AGRICULTURAL METEOROLOGY

by

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Introduction

By Lionel P. Smith

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Beyond any doubt, man's first application of meteorology was to the problems of agriculture. In fact, the whole history of agriculture has been one of continuous field experiment, with husbandry, seeds, animals and the weather as the ill-defined variables. The progress that was made depended largely on the intelligence of man; but as the process was essentially one of trial and error, even the most unintelligent man did not persist, and indeed could not persist, in the face of continual failures.

Bad practices had to be discarded; acceptable procedures prevailed. In the more advanced countries, land use and husbandry techniques reached a reasonably high standard. In a less favourable mental environment, at very least the worst mistakes were generally eliminated by the brute force of attendant circumstances such as bankruptcy or starvation.

Science as we know it today, especially the sciences of mathematics and physics, hardly entered consciously into the evolutionary process. Although weather was recognized as a potent factor in agricultural success, meteorological science played a very small part. Nevertheless, the meteorological services of many countries did pay considerable attention to the needs of agriculture, without perhaps having the time, money, or inspiration to make any major contribution to the advancement of the basic knowledge.

Outside agriculture, urgent demands were made on meteorology in the interests of human safety. These demands were first made by maritime transport and subsequently during the present century by aviation. Due to these demands the meteorologist has been largely preoccupied by the need to produce forecasts to suit the precise needs of such categories of interest. Agricultural needs have tended to lose priority, and agricultural meteorology did not share in the rapid progress made in the other branches of meteorology. This, however, does not imply that the subject was stagnating. Agriculturalists with a knowledge of meteorology, and meteorologists with a knowledge of agriculture were continuously adding facts and experience to the dual subject. Their results and opinions appeared in a multitude of scientific papers scattered throughout the technical journals of the world. The citadel of ignorance was being attacked by a system of erosion rather than by overwhelming frontal assault.

Furthermore, because meteorology itself was somewhat of an imperfect science and one in which it was extremely difficult to attain anything resembling perfection, and because relatively little was fully understood about the effect of weather on plants and animals, much of the work in agricultural meteorology proceeded on a semi-empirical basis. As a result, it was dangerous to extrapolate the findings established in one area to problems arising in another. Methods which worked extremely well for all practical purposes in the zones where they had been investigated could not be applied elsewhere with a certainty of success, and a degree of scientific caution had to be exercised.

Both these sets of circumstances, the individual approach and the individual solution, militated against the possibility of writing reliable textbooks on the subject. Such books were, in fact, practically non-existent, while publications on popular and aviation meteorology sprang up like mushrooms. A time was bound to arrive, however, when it would be possible to combine the scattered information into a more comprehensive volume, even though it is still true that in some aspects such volumes must inevitably be regional in character.

In an era when the so-called underdeveloped countries are awakening rapidly and when the frightening increase of world population is raising the problem of food production to the highest possible priority, the meteorologist can and must play an essential role.

The advent of a book such as this is therefore an event of considerable importance, and agricultural meteorologists the world over will join me in welcoming a much-needed addition to the literature.

My own opinion is perhaps best summarized in the words I used in "Weather and Food" Basic Study No. 1 of the Freedom from Hunger Campaign:—"Much can be done by the application of existing knowledge, much more could be done if we knew a little more.". . . . "As the value of applied meteorological help becomes realized and its capabilities improve, the present trickle can become a flood which could carry away to oblivion centuries of hunger and want. The treasure chest lies before us, the key is in our brains, the determination to insert it in the lock and to turn it to obtain the contents in the new responsibility of us all."

Bracknell, Berks., England
June 1963

Preface

This textbook is written as an introduction to the field of agricultural meteorology on the college level. In its original form, this book was a collection of class lecture notes which the author has used at the Fukien Christian University in China as well as at the University of Wisconsin in the United States. The content has been changed and extended to incorporate as much as possible of the recent progress in this branch of science, and on the basis of the author's teaching experience. As a horizontal science, the field of agricultural meteorology involves many subject areas in agriculture and some in the biological and physical sciences — ranging from construction design of plant and animal houses to phenology and weather forecasts, as represented in a great variety of research topics. It is the author's intention to present this work not merely as a description of the microenvironment, but also as a study of relationships that exist between plants (or animals) and the microenvironment, with emphasis on methods of approach to various problems in order that the reader may follow the principles and schemes as guides in developing his own specialized area of study. The materials included are by no means exhaustive, but an attempt has been made to include sufficiently varied topics. Moreover, some areas which are in their beginning stage of development are also included so as to present, hopefully, germs of ideas for future investigation. As an old Chinese saying expresses, "throw a piece of brick and hope for a gem to return."

The present volume consists of twelve chapters divided into two parts. Part I occupies the first four chapters and deals with the fundamentals of agrometeorology. Such basic subjects as micrometeorology, ecology, pedology, and plant and animal physiology are reviewed. Part II presents methodology and applications—the former being dealt with largely in chapters 5 through 9, and the latter in the remaining three chapters. Each chapter is given as much independence as possible. Three appendices offer a glossary of terms and brief summaries of fundamentals in mathematics and statistics. Terms defined in the glossary (Appendix A) exclude those already defined in the text; those defined in the text can be found in the subject index.

As always, it is extremely difficult to repay in words the contributions which the author has received in the form of advice, assistance, and encouragement, toward the completion and improvement of his manuscript. First of all, the author wishes to express his sincere gratitude and appreciation to Professor James E. Newman of Purdue University, who at the start of the writing was at the University of Wisconsin on sabbatical leave. It was with his assistance that the organization of the text and the first two chapters were put into shape. For any recognition this book may gain, the author is indebted to the contribution of Professor Newman. Many thanks to those who have spent time in reviewing and rendering valuable suggestions on specific portions of the manuscript. Appreciation is especially due to Professors Victor H. Regener of the Department of Physics, University of New Mexico; Harold A. Senn, Director of the Biotron, University of Wisconsin; Robert P. Hanson and Mervin L. Frey of the Department of Veterinary Science, University of Wisconsin; Hudson H. Kibler of the Department of Dairy Husbandry, University of Missouri; Norman J. Rosenberg of the Department of Horticulture and Forestry, University of Nebraska; Frederic G. Teubner, the late professor of horticulture, University of Nebraska; Sylvan H. Wittwer of the Department of Horticulture, Michigan State University; Burdean E. Struckmyer and Theodore W. Tibbitts of the Department of Horticulture, John T. Medler of the Department of Entomology, Herman W. March and James H. Torrie of the Departments of Mathematics and Agronomy, respectively, of the University of Wisconsin; Herbert B. Schultz of the Department of Agricultural Engineering, University of California—Davis; Heinz H. Lettau and Verner E. Suomi of the Department of Meteorology, University of Wisconsin; and Robert H. Shaw of the Department of Agronomy, Iowa State University. Special appreciation is also due to the following persons for their valuable review comments and assistance: Dr. Oskar M. Essenwanger, Chief of the Aerophysics Branch, Physical Sciences Laboratory, Directorate of Research and Development, U.S. Army Missile Command, and Professor of the University of Alabama Extension Center in Huntsville; Dr. Christian E. Junge of the Office of Aerospace Research, Air Force Cambridge Research Laboratories; and to several officials of the U. S. Weather Bureau, particularly to Dr. Gerald L. Barger, Director of the National Weather Records Center; Mr. Lynn L. Means, Chief of the Public and Agricultural Forecasting Section; Mr. Robert F. Dale, North Central Area Climatologist; Mr. Marvin M. Burley, Wisconsin State Climatologist; and Herbert H. Bomalaski, Meteorologist-in-charge of the Green Bay Weather Bureau.

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PART I

FUNDAMENTAL CONSIDERATIONS

CHAPTER 1

The Field of Agricultural Meteorology

1.1 DEFINITION AND GOAL

Agricultural meteorology in its broad sense is that branch of applied meteorology which investigates the responses of living organisms to the physical environment. The ultimate goal is to improve agricultural production by more accurate forecasting and by control of the physical environment. Forecasting may range from predictions of crop yield and quality on the one hand to the estimation of livestock production and climatic hazards on the other. Control of the physical environment may include frost prevention, flood control, and temperature regulation of animal houses.

In a narrow sense, agricultural meteorology may be defined as the study of the physical processes in the atmosphere that produce weather, as related to agricultural production. It is a horizontal science which applies the physics of the air and soil to agriculture. In fact, many workers in this field believe that investigations on the microclimate of plants and animals as well as statistics of weather elements are properly subjects of agricultural meteorology. However, we stress the broad sense of the definition, which is the study of the responses of living organisms to the physical environment, for this is the link between meteorology and agriculture, and is the fundamental aspect of the subject.

The physical environment involves one or more properties of the physical surroundings in which living things are produced, such as air, soil, water, plants, animals, microbes, and foreign matter. The living organisms studied in agricultural meteorology are restricted to cultivated plants, livestock and domestic fowl, and insects and microorganisms of economic importance. Finally, the subject matter of agricultural meteorology is concerned mainly with quantitative relationships between the physical environment and the biological responses of domestic species.

1.2 BRIEF HISTORICAL REVIEW

Primitive knowledge of agricultural meteorology may be found in the records of the ancient Chinese, Mesopotamians, and Egyptians, and also in the form of folklore, poetry, and songs. However, the scientific era of agricultural meteorology began rather late. It is customary to say that agricultural meteorology as well as meteorology developed mainly as a result of the invention of the barometer, the thermometer, and the telegraph. Shortly after René Réaumur proposed the Réaumur scale of the thermometer in 1730, he began his study on crop-temperature relationships. His findings, known as Réaumur's thermal constant, were published in 1735.[1] Having been improved through the years, his constant is currently referred to as the heat unit and is widely used in certain large scale farming operations. However, the study of single weather elements such as temperature, as used in Réaumur's thermal constant approach, has been accomplished largely through the use of statistical methods, and little consideration has been given to the importance of physiological principles and physical laws. It should be emphasized that the development of agricultural meteorology depends more upon understanding of biological responses to the physical environment than simply on knowledge of that physical environment. Any progress made in the study of biological responses contributes more to agricultural meteorology than does any advance of pure meteorology. Some important discoveries and scientific achievements relating to biological responses, particularly in plant science, are listed briefly as follows.

In 1919 Garner & Allard discovered "photoperiodism," which is the response of plants to daylength or light duration. They grew Maryland Mammoth tobacco plants in both lighted and unlighted greenhouses. The plants in unlighted greenhouses remained vegetative, whereas those in lighted greenhouses flowered. This added a new and useful environmental factor — the duration of daylight — to the study of agricultural meteorology. Numerous experiments on photoperiodism have since been done. Other studies which are related to photoperiodism involve "photoperiodic induction," in which either light intensity or light quality have been investigated together with light duration and the associated biological responses. Much work has also been done on thermoperiodism.

In 1935, Lysenko, who borrowed Klebs' idea originated in 1918, postulated the theory of phasic development. He theorized that plants respond differently to the physical environment during various phases or stages of their life cycle. Thus, a distinction between growth and development was established, and differential responses of various

[1] A more detailed discussion of Réaumur's work will be found in Section 4.2.3.

stages in the life cycle of the plant were emphasized. Many European workers, and in particular the Russians, have made use of the theory of phasic development in studying different kinds of crops, with varying degrees of success.

In 1949 Went developed a special installation known as a "phytotron," comprised of a series of light- and temperature-controlled rooms in conjunction with several air-conditioned greenhouses, in which he could achieve considerable control of plant growth and development. His work in the past decade has laid a cornerstone for the scientific development of modern agricultural meteorology. Similar facilities have been developed in a number of countries and have proved to be powerful tools in plant research. A large, nearly completely controlled house designed for both plants and animals at the University of Wisconsin will be available in 1965 and will be called the "biotron." At the same time, many research studies involving control of the physical environment in a limited area of the open field have been carried on. These studies, mainly applications of micrometeorological principles, have drawn worldwide interest. This type of research will continue to be of importance.

In the last decade radioisotopes have been used in studying the physiology of plants. Through the use of these isotopes, physiological processes, such as the foliar absorption and leaching of nutrients, have been better understood. It has been found that considerable amounts of both mineral nutrient and organic substances are removed from the above-ground parts of plants when there is a steady, light rainfall. Therefore, it is necessary to consider the intensity of rainfall, as well as its duration and perhaps the time of day at which it occurs. This type of research has opened new horizons for the development of plant science.

Discoveries on the biological transformation of energy form one of the most exciting chapters in modern biological science. Scientists have performed and are still working on important basic research on various aspects of photosynthesis. Processes in the storage of solar energy by green plants and the transformation of energy by microbes and animals into living tissue and other products need to be fully understood. More knowledge on efficiency in transformation of energy will eventually lead to further development and improvement of agricultural meteorology.

Aside from the progress of the biological sciences, developments in the physical sciences—particularly electronic aids to instrumentation and advances in microclimatic research—give a better understanding and interpretation of the physical environment. Success in measurements and studies of the physical environment, together with the progress of biostatistics, have paved an avenue for the development of agrometeorology.

Volumes of papers have been published as a result of the studies mentioned above, but there are few satisfactory textbooks on agricultural meteorology. In fact, only one well-known English textbook exists on this subject, written by Smith in 1920. Smith's book, published before the discovery of photoperiodism and other modern findings, is obsolete.

In 1905, Abbe published a report on the relationship between climate and crops. It is a compilation of studies by various authors all over the world, particularly in Europe. In 1941, the U.S. Department of Agriculture published a yearbook entitled ***Climate and Man,*** which summarizes many studies on domestic animal- and crop-weather relationships. Another U.S. Department of Agriculture yearbook, ***Water,*** published in 1955, summarizes many studies on irrigation and conservation. In 1952, 1953, and 1954 Searle published three books on plant climate, entitled ***Plant Environment and the Grower, The Measurement of Plant Climate*** and ***Plant Climate and Irrigation.*** Shaw's book (1952) on ***Soil Physical Conditions and Plant Growth*** has a comprehensive treatment of soil temperature, soil moisture, and aeration. In 1958 Smith published ***Farming Weather*** and during the same year Smith & Searle published ***Weatherwise Gardening.*** These publications deal mainly with a single weather element at a time, in a simple manner, and for a certain region or for a certain crop, and may be used as references for agricultural meteorology.

There are many agricultural meteorology textbooks in Russian, German, French, Japanese, Italian, and several other European and Asiatic languages. The Russian workers emphasize estimates of such factors as evaporability and soil moisture, climatic indices, instrumentation, and the utilization of meteorological and micrometeorological knowledge. Some foreign books also report the use of phenology.[2] Most of these books have been published since World War II. Common drawbacks of these textbooks in agricultural meteorology are: (1) they are regional — pertaining to material of a certain locality; (2) they are descriptive—lacking in quantitative expressions; (3) they are repetitious — duplicating material appearing in general textbooks of meteorology, ecology, physiology, and sometimes crop geography; and (4) they include little information on livestock.

In this book no attempt is made to review these agricultural meteorology texts, but most of them are listed at the end of the present chapter as references.

[2]Phenology is the science which treats of periodic biological phenomena with relation to weather and climate, especially seasonal change; emphasis is placed on the dates of occurrence of events in the cycles of plants and animals. Detailed studies in phenology will be given in Chapter 6.

1.3 THE ROLE OF AGRICULTURAL METEOROLOGY

Agricultural meteorology is a combination of physical and biological sciences and, in fact, forms a valuable link between them. In recent decades the use of meteorology in agriculture has increased. This has been due largely to laboratory, greenhouse, and field studies in which biological responses have been measured under controlled conditions. The transfer of laboratory and greenhouse results to the open field is largely the task of the agricultural meteorologist. To date, most of the field applications of laboratory findings have been accomplished through the use of empirical field tests.

There have been several applications of meteorological techniques to field operations during the past century. This is also partly true of micrometeorological techniques. Some important examples are: (1) frost forecasting and protection, (2) forest-fire warning, (3) conservation and irrigation control, (4) scheduling of planting and harvesting dates, (5) selection of cropping and building sites, (6) insect control, (7) disease control, and (8) many other microclimatic modifications such as the utilization of wind shelter practices. A great many experiments have been performed in the open field in an attempt to improve agricultural production. However, these experiments are complicated due to various factors of the natural physical environment. New theory, methodology, and instrumentation need to be developed in order to overcome complications of open field research.

Another phase of agricultural meteorology is concerned with livestock and domestic fowl. This phase involves the design and control of animal and poultry houses, the selection of pasture fields, the prediction and prevention of animal diseases, and other related activities.

Thus, the role of agricultural meteorology includes the transfer of laboratory and greenhouse techniques and findings to the open field, the control or modification of the local climate of a field, and, finally, the forecasting of weather for crops and for animals.

1.4 DIFFERENTIATION FROM SOME RELATED SUBJECTS

There exists considerable confusion between the study of agricultural meteorology and its allied subjects, such as agroclimatology, agricultural ecology, agrophenology, agricultural geography, bioclimatology, agrobiology, and crop and animal physiology. Although they are interrelated and have similar objectives, the main difference between them lies in their method of approach. A differentiation of these subjects from agricultural meteorology is thus necessary to establish the boundaries and to describe the scope of the subject.

Agricultural meteorology, better termed "agrometeorology," should be differentiated from "agroclimatology," and to do so, one must first consider the difference between meteorology and climatology. Meteorology may be defined as the study of physical processes in the atmosphere that produce weather, while climatology is the study of the totality of weather. Hence, while the study of agroclimatology deals partly with the relationships of climatic regimes and agricultural production, agrometeorology deals with the entire field of study including agroclimatology, instrumentation, crop forecasting, and many others.

Agricultural ecology, on the other hand, is concerned with the interdependence between crops and environment. Factors controlling the habitat of a crop during the entire life cycle, such as regeneration of nutrients, cultural practices, planting rate, mortality, etc., are considered. Hence, the central aim of agricultural ecological studies is to delineate the external conditions under which agricultural crops reach optimum production.

Another closely related area, agrophenology, emphasizes the date or time of appearance of certain periodic events in the life cycles of crops and domestic animals. Germination, flowering, and maturity of crops are examples of crop phenology; breeding seasons, birth of the young, and death of the old are examples of animal phenology. They are the results of weather influences over a period of time. The combination of crop and animal phenology is a study of agrophenology.

Agricultural geography, which covers the historic evolution of agricultural patterns as well as present distribution, refers to the spatial arrangement and differentiation of agriculture. When related to cultivated plants, it may be termed crop geography, which treats the climatic, soil topographic, and latitudinal effects on crop distribution over long periods of time and over large geographical areas. This also applies to animal geography.

In times past, bioclimatology has consisted primarily of studies of human responses to climatic conditions. Recently, however, bioclimatology has been broadened to include many climatological-biological response studies, and has been termed "bioclimatics." Still another subject, known as agrobiology and commonly referred to in European literature, is primarily concerned with crop responses to the application of fertilizers. The approach used in crop and animal physiology differs greatly from that of agroecology, agrophenology, and agricultural geography in that the biological influences studied are of an internal rather than an external nature. In other words, physiological studies deal largely with biological responses within the individual plant or animal (or even an organ of them) to the physical environment.

1.5 RELATIONSHIP TO OTHER FIELDS

As has been indicated, agrometeorology is a horizontal science making use of several physical, biological, and applied agricultural sciences. In this connection, it is desirable to define the relationship of agrometeorology to these different fields.

Physical Sciences. Among the physical sciences, meteorology is the closest subject to the field of agrometeorology. However, caution must be taken lest agrometeorology become just another form of general meteorology, even though it is an "applied meteorology." While agrometeorology makes use of many techniques of meteorology, emphasis is of necessity placed on the agricultural application of these methods. Because of this, there are many areas which are primarily the concern of meteorologists, but not of agriculturists, and vice versa. Nevertheless, meteorology itself is an applied study of physics, and all fundamental physical principles and theories are equally important to agrometeorology.

Many climatologists have made intensive studies of climatic factors such as rainfall and temperature, and have made these studies available to agriculturists. These studies may be important to agricultural operations; however, they may not be agrometeorological investigations. Unless these investigators can apply their climatic studies to biological responses of organisms (e. g., the relationship between rainfall and crop yield), their findings are of little importance to the agrometeorologist. On the other hand, the establishment of photothermal units, the measurement of the microclimate of a wind shelter, the study of energy balance in a microlayer, and the observation of the interception of rainfall and light under a crown would be valuable contributions to agrometeorology.

It is well known that the daily fluctuation of moisture in the air, as well as in the soil, is a vital problem which must be solved. This study involves meteorology and hydrology. The boundaries between these two are a matter of emphasis. Meteorological studies are primarily concerned with the formation of rain, snow, dew, and water vapor in the atmosphere, and the processes of evaporation, condensation, and evapotranspiration from the earth's surface. Hydrological studies are confined largely to the processes of interception, runoff, percolation, ground water, and soil-water storage changes. Hydrology is as important in some types of agricultural problems as is meteorology. Irrigation and drainage of agricultural lands are excellent examples of this. Therefore, hydrology, meteorology, and the parent science physics are three important physical sciences which are closely connected with agrometeorology.

Agrometeorology is also related to chemistry. The chemical content of rainwater, the formation of smog, condensation nuclei, aerosol, and hailstones, the distribution of atmospheric carbon dioxide and other elements, are all problems involving chemistry. At present this relationship is not well developed, although considerable information has been obtained relating biochemical changes to crop re-

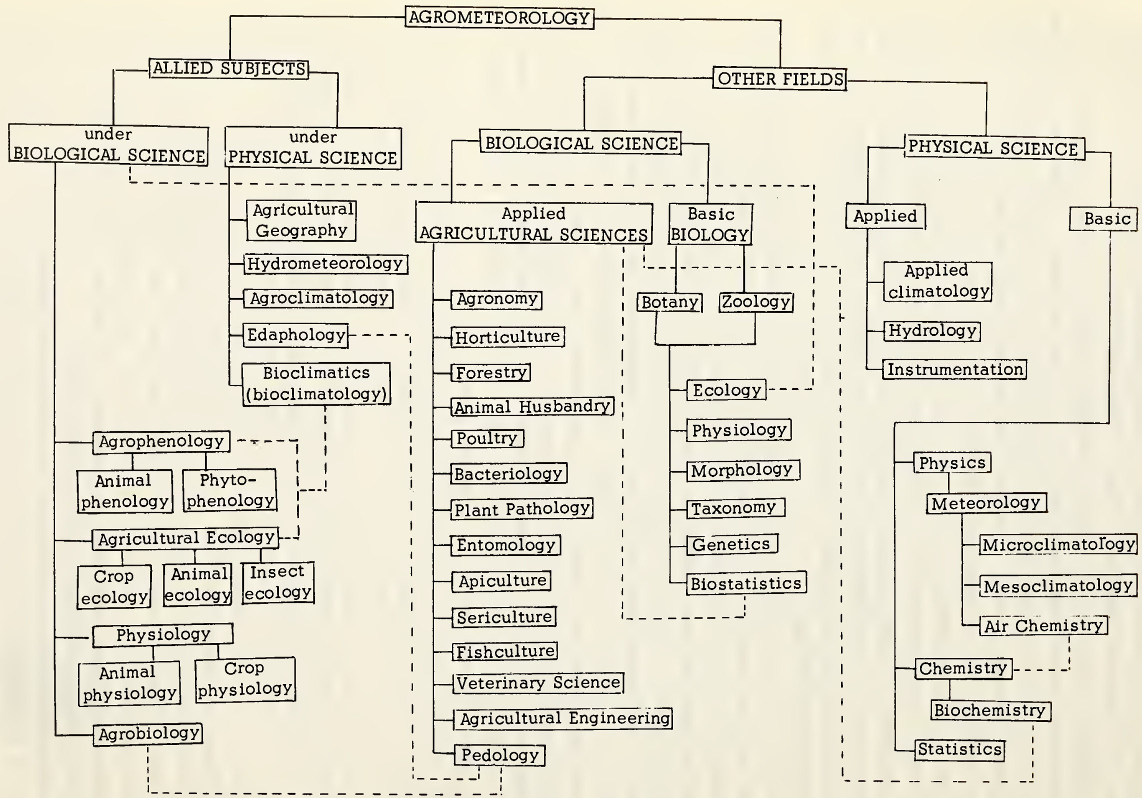

Fig. 1-1. Agrometeorology and its related sciences.

sponses. This field will undoubtedly yield significant findings in future studies on the responses of plants and animals to their environment. Last but not least, modern statistics, particularly biostatistics, is a vital tool in the study of agrometeorology.

Agricultural Sciences. Since the growth and development of both animals and plants depend basically upon the physical conditions of the media in which they live, agrometeorology enters into the realm of the individual agricultural sciences. In fact, few of the applied agricultural sciences are complete without the incorporation of agrometeorological information. The soil scientist is concerned with soil water and soil erosion; the plant pathologist with those weather factors that affect the spread of plant disease; the agronomist and the horticulturist with the relationship between crop production and weather; the animal and poultry scientist with the design of barns and poultry houses; the agricultural engineer with irrigation design, land drainage and wind shelter and farm building design; the entomologist with the climatic conditions for outbreaks of insects. Naturally, the basic research in the above fields depends upon the contributions of the related biological sciences.

A schematic diagram which indicates the functioning of agrometeorology in relation to allied and other subjects is shown in Fig. 1-1.

1.6 AGRICULTURAL METEOROLOGY AS A SCIENCE

As stated previously, agrometeorology is based on a definite approach related to theory and methodology. Its independent theory, hypotheses, and methodology (which cannot be obtained totally from any allied subjects as listed in Fig. 1-1) are given in this book. Constancy of biotic factors is an example of an hypothesis, and crop rainy day criteria is an example of methodology. Agrometeorology might well be termed an independent science, consisting of subject matter which links the physical environment to the biological responses under natural conditions. This makes it independent of both the physical and the biological sciences. Currently, there is a very real need to bring these two spheres of knowledge together. Greenhouse experiments, controlled climatic studies, and field tests appear to be the best way to fill this need. Controlled environment installations (the phytotron for plants, and the biotron for plants and animals) enable investigators to study biological responses to experimentally manipulated conditions. Also, more agricultural weather stations, located at proper sites and equipped with appropriate instruments, are needed to record the specific data required in agrometeorological research.

The agrometeorologist must first formulate an accurate description of the physical environment and biological responses. He should then proceed to an interpretation and understanding of these phenomena.

The final step should be the improvement of weather and crop forecasting, and control of the environment.

From this introductory discussion, it is obvious that many difficulties are inherent in this field of study. A discussion of all the problems in agrometeorology is impossible, but it is hoped that the reader will find the methods suggested in this book helpful guides in solving his problems.

Since agrometeorology is related to many different subjects, a "Glossary of Terms" has been appended to this work. The reader may consult the glossary from time to time for those terms which have not been defined in the text.

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CHAPTER 2

The Physical Environment

2.1 THE ENVIRONMENT

The environment of plants and animals is the biological and physical system of the medium surrounding them—the biological including microbes, plants, and animals, and the physical including air, soil and water. In this chapter, we are concerned with the physical and biological materials of the environment and the factors controlling them. A description of the environment will be found in Chapter 4.

2.1.1 *Physical medium*

Normally, the physical material surrounding crops and livestock is a mixture of air, water, and soil. Air and water are found in the soil; water and soil particles are found in the air. Aeration and soil moisture are phenomena of air and water in the soil, while atmospheric humidity and dust are those of water and soil in the air. The degrees of association of the various constituents comprise different types of physical environments. For example, too much water in a field of crops may cause waterlogging or even a flood, while too little produces drought. Therefore, fundamental concepts of the physical and chemical properties and the composition and distribution of air, water, and soil should be understood by the student.

(a) Air. The air has long been recognized as a colorless, odorless, and tasteless fluid. It is a mixture of gases, present both as single elements and as compounds, and comprises the earth's atmosphere. Some of these gases are inert, others active. The chemical and physical properties of each individual gas differ widely. Information on these can be found in textbooks on physics, chemistry, and air chemistry.[1]

[1]A study of the origin, evolution, composition, and life cycle of the elements pertaining to air includes problems of the distribution and migration of the elements as well as radioactive elements and air pollution. Chemical analyses of dew, fog, frost, rainwater, and other precipitates are also included.

Under natural conditions, the dry atmosphere (denoting air from which all water vapor has been removed) at the surface of the earth, when measured by volume, is composed of 78% nitrogen, 21% oxygen, and 1% of a combination of several rare gases (A, Ne, He, etc.) and chemically active trace gases (SO_2, NH_3, N_2O, NO_2, etc.). Except for the constituents of the 1% fraction, which vary considerably among themselves, the fractions of nitrogen and oxygen remain constant up to an altitude of about 45 miles above the earth's surface. Slight variations occur in the proportions of nitrogen and oxygen, however, with respect to latitude, altitude, geographical locality, and season. From 45 miles up to the top of the atmosphere (around 18,600 miles), large variations occur. At a height of 370 miles, the density of the atmosphere becomes so low that the typical properties of a gas cease to exist. Since plant and animal life is only concerned with tropospheric air, discussion will be restricted to the troposphere.

The variable and non-variable constituents of air, as described by Glueckauf (1951), Paneth (1937), Brown (1952), Goody (1958), and others, are listed in Tables 2-1 and 2-2.

Each of these variable constituents of dry air, including carbon dioxide,[2] has a cycle of its own. The nitrogen cycle involves complex processes of nitrogen fixation, ammonification, nitrification, aminization, denitrification,[3] and return to free nitrogen gas. It produces various complex organic compounds and ammonia gas. The well-known carbon dioxide cycle is likewise complicated and yet involves only two main processes, photosynthesis and respiration. Although the nitrous oxide (N_2O) cycle has not been fully explored, nitrous oxide is most likely produced in the soil by the transformation of nitrogen compounds through bacterial activity (see Kriegel, 1944; Goody & Walshaw, 1953). When it reaches the stratosphere, it is dissociated by photochemical action. In the sulfur cycle, most natural sulfur is originated from soil and swamps as hydrogen sulfide and subsequently oxidized. Volcanoes are a minor source. A considerable concentration is produced by industry. The residence time of sulfur is 40 days, and that of sulfur dioxide is five days, as estimated by Junge (1960).

The significance of the cyclic processes of gases as indicated above is that the total amount of each of these gases remains constant if taken over a sufficiently long period of time.

[2]For the geographical distribution of carbon dioxide, see Takahashi (1961); for classical treatments of carbon dioxide, see Lundegårdth (1931).

[3]For definition of terminology hereafter, see the Glossary of Terms in the Appendix. For a complete description of the life cycle of nitrogen, see Ensminger & Pearson (1950). For the composition of nitrogen compounds in dew, fog, frost, rainwater, and other precipitates (mostly in the form of nitrate and ammonia), see Eriksson (1952), Junge (1958), and Ångström & Högberg (1952).

Table 2-1. The Constant Constituents of Dry Atmospheric Air

Constituents	Sources	Contents[4] (Percentage by Volume)	Density Relative to Air
Nitrogen (N_2)	Denitrification of organisms; biological residues; lightning discharges.	78.084 ± 0.004	0.967
Oxygen (O_2)	Photosynthesis of plants; reduction of various oxygen compounds.	20.946 ± 0.002	1.105
Argon (A)	Volcanic eruptions.	0.934 ± 0.001	1.379
Carbon dioxide (CO_2)[5]	Primary sources: respiration and combustion of organisms of land and sea. Secondary sources: volcanoes, mineral springs, combustion of coal and oil.	0.033 ± 0.001	1.529
Neon (Ne)	Originally existed in the air.	0.00191	0.695
Helium (He)	Oil wells and radioactive substances.	0.00052	0.138
Krypton (Kr)	Originally existed in the air.	0.00011	2.868
Methane (CH_4)	Biological residues; mines.	0.00022	0.558
Hydrogen (H_2)	Oil wells and volcanoes; decomposition of raindrops and water vapor.	0.00006	0.070
Nitrous oxide (N_2O)	Primary source: activity of soil bacteria. Secondary sources: homogeneous photochemical reaction, lightning discharges, ultraviolet radiation, industrial products.	0.00005	1.529
Xenon (Xe)	Originally existed in the air.	0.00001	4.524

[4]Figures in Tables 2-1 and 2-2 refer to sea level observations, based upon the results up to 1960.

[5]A variable under some conditions.

Significant changes often occur in the contents of certain constituents at a specific time and under specific environmental conditions. The presence of atmospheric ozone in polluted air as related to plant diseases, for example, is sometimes detrimental to vegetables. It comes from the stratosphere and reaches the ground by wind turbulence. On days with little turbulence, ozone decreases near the ground after nightfall, but remains unchanged in high winds. Another example is the winter killing of plants under ice sheets where carbon dioxide concentration is high (Sprague & Graber, 1943). In this case, oxygen is insufficient and respiration is retarded. Therefore, a study of the magnitude of the diurnal, annual, and geographical variation of a certain constituent in a microenvironment would be useful. Factors governing the changes of air composition as related to microenvironments are numerous. Soil types, radiation, wind, rainfall, and air masses are the major factors. Many other important constituents of microenvironments, such as carbon dioxide, oxygen, nitrogen, etc., which are closely related to plant-animal responses, have not been extensively investigated under natural conditions. For instance, the concentration of carbon dioxide with respect to soil physical condi-

Table 2-2. The Variable Constituents of Dry Atmospheric Air[6]

Constituents	Sources	Contents (ppm)[7]
Ozone (O_3)	Major source: ultraviolet radiation on stratospheric gas. Minor source: lightning discharge in tropospheric air.	0 to 0.04 (spring) 0 to 0.02 (fall)
Nitrogen dioxide (NO_2)	Soil and industrial products.	0 to 0.02 (urban)
Sulfur dioxide (SO_2)	Ocean, soil, and the oxidation of the gaseous compounds.	0 to 1.00 (urban)
Hydrogen sulfide (H_2S)	Coastal areas of ocean, soil, and some from volcanoes.	0 to trace
Ammonia (NH_3)	Soil and some industrial products	0 to trace
Carbon monoxide (CO)	Industrial products.	0 to trace
Iodine vapor (I_4)	Industrial products.	0 to trace
Radon (Rn)	Radioactive substances.	0 to trace
Other gases (CH_2O, HBr, HCl, HF, etc.)	Biological activities; industrial products.	0 to trace

[6]The variable constituents of moist air include, in addition, water vapor, which will be studied later in this section under the heading "Water."

[7]Parts per million.

tion,[8] air mass movement, radiation, and wind is not thoroughly understood. One would assume that the carbon dioxide concentration of a given locality would be greater under any or all of the following conditions: warm air masses, southerly winds, sea breezes of warm ocean surfaces, and/or organic soil of high temperature. This assumption is made on the basis of the strong dependence of the solubility of carbon dioxide upon temperature. In short, the production and consumption of carbon dioxide over land by plants, animals, and microbes are the controlling factors.

The composition of contaminated air is obviously much different from that of dry air, and is even more so in an artificial environment. When the air is contaminated in a greenhouse, for example, it may have a very small fraction of ethylene present. This minute amount of ethylene has a lethal effect upon most plants. In the case of animal quarters, carbon dioxide and ammonia concentration can be very high without any noticeable damage. However, the presence of a minute amount of carbon monoxide may be fatal to turkeys, as has been reported. Other contaminating materials, both natural and man-made, are radioactive materials, complex organic materials, and a great variety of inorganic materials such as halides.

On the other hand, aerosols which are composed of either solid particles (such as haze, smoke, salt particles and pollens) or liquid particles (such as fog, mist, and smog) are dispersed in the polluted air. When, for example, the sea salts occur, aerosols have a profound influence on plant growth and composition along the coasts. Smog, which is a natural fog contaminated by industrial pollutants forming a mixture of smoke and fog, has been studied in association with synoptic weather patterns. It has been reported that half a million dollars' worth of vegetable crops is damaged annually in the Los Angeles area of the United States.

Furthermore, the air in the soil, or soil atmosphere within the zone of aeration, has the same kinds of gases such as N_2, O_2, and CO_2, and inert gases, as does the free atmosphere above the ground. The main difference is that soil atmosphere contains a high carbon dioxide and water vapor concentration and a lower concentration of oxygen. This phenomenon is caused by the consumption of oxygen and liberation of carbon dioxide by soil organisms and plant roots. For most soils, the carbon dioxide concentration is usually 10 to 50

[8]The porous nature of soil determines the rate of gaseous diffusion into and out of the soil. Other factors governing the concentration of carbon dioxide are the chemical and moisture contents of the soil, the pH of soil water, and organic activities in the soil. Lundegårdth's classical studies of carbon dioxide (1931) in terms of soil respiration are an important reference for beginners. He studied all kinds of microenvironmental factors influencing soil respiration in connection with diurnal and seasonal variations of carbon dioxide. Factors considered are soil type, artificial fertilizer and farmyard manure, vegetable covers, soil and air temperature, solar intensity, rainfall, and soil moisture.

times as much as in the air above it. As an average, carbon dioxide occupies 0.03% (near the ground) in dry atmospheric air; it is 0.20 to 1.00% (surface layer of soil) for soil atmosphere. With high aeration an equal distribution of air composition both in the top soil and free atmosphere will occur. The gas exchange in the air-soil interface depends upon the variation of air and soil temperature, air pressure, wind, and rainfall in terms of two physical processes: mass flow and gas diffusion.[9] Gases produced in the soil besides carbon dioxide are ammonia, hydrogen sulfide, nitrous oxide, methane, and other hydrocarbons of measurable quantities, together with traces of helium, radon, thoron, and actinon.

The composition of soil air is subject to change with time and space, particularly seasonal changes within the root zone layer. These changes are conditioned mainly by fluctuation of soil-air temperature, soil moisture, and the presence of living organisms. The biological processes, in terms of respiratory activities in the soil, tend to accentuate differences in composition of soil air and atmosphere; the physical processes in terms of gas diffusion tend to eliminate these differences. It is imperative to have more knowledge about soil air. The present inadequacy is due to insufficient and inaccurate measurement of soil air, especially the lack of reliable instruments for the measurement of the *change of soil air in the root zone.* Records of the past were restricted to volumetric measurement; thus, most of the data represent the gross change of soil air of the pore space. Since aeration as related to soil air composition is extremely important to the growth and development of plants,[10] *measurement of the change of varying soil air composition with time at the root zone is invaluable.*

(b) Soil. Soil, as used here, is defined as the assemblage of natural bodies of the earth's surface containing living organisms, organic materials and minerals, which is the medium for plant growth. At its upper limit is air, water, or vegetation. At its lower limit is bedrock. At its lateral margin it grades to deep water or to barren areas of rock, ice, salt, shifting desert, and sand dunes.

Soil is a dynamic body, ever changing in its responses to the environment and at the same time influencing that environment. Thus, it is recognized in genetically related layers or horizons, developed from parent materials, under the influence of climate, organisms, topography, and time.

[9]The major meteorological factor governing gas exchange is rainfall. The effects of meteorological factors on the renewal of soil air are intermittent. Diffusion, which depends primarily upon the ratio between mass changes and partial pressure changes, is the major process which dominates the gas exchange.

[10]Root morphology, nutrient and water absorption by the root, plant diseases, etc., are all related to soil aeration.

The undecomposed and partially decomposed leaf and litter on the surface layer and rocks of the bottom layer in a natural soil profile do not constitute soil.[11] The uppermost layer of an undisturbed soil profile, known as the duff layer (or A_0 layer), consists of partly decayed organic debris. The layer adjacent to the duff, generally known as the topsoil, or the A horizon, is followed in descending succession by the subsoil B and C horizons. Usually, the C horizon constitutes the parent material.[12] Each horizon can also be divided into subhorizons (e.g., A_1, A_2, A_3 of A horizon; B_1, B_2, B_3 of B horizon, and the like), with the number and depth of horizons present depending upon the soil material and soil genesis. The pattern of horizons and their observable properties that make up the soil is soil morphology.

Studies of soil sciences in relation to soil environment, which have been termed "edaphology," are essential to agrometeorology. These studies involve the subjects of physics, chemistry (soil analysis, etc.), microbiology, genesis, morphology, fertility (fertilization and management), taxonomy (classification and identification, which includes cartography), and technology (drainage, irrigation, erosion control, and soil conservation) of the soil. These essentials have been summarized here. The terminology for this summary is given in the Appendix. For details, students may refer to any textbook on soils.

The conventional classification of soil taxonomic units has followed the system of (1) soil order, (2) great soil group, (3) soil family, (4) soil series, (5) soil type, and (6) soil phase. There are three orders, namely, Zonal, Intrazonal, and Azonal.[13] There are many great soil groups. A great soil group among the Zonal soil may be defined as a group of soils which has developed under similar climatic conditions and vegetative cover and the same predominating soil-forming processes, such as podzolization, calcification or laterization. The chief processes responsible for the development of Intrazonal soils are gleization due to hydromorphic conditions, salinization and/or alkali deposition. Under the Azonal soil group, or the young soil, there are no true soil-forming processes. Just as climate con-

[11]Strictly speaking, it is very difficult to define soil and its boundaries. However, the definition given here is the most suitable one for agrometeorological usage.

[12]The "A Horizon" is collectively referred to as "Major Zone of Leaching;" "B Horizon," "Major Zone of Deposition;" and "C Horizon," "Zone of Parent Material." Both A and B horizons are usually referred to as "Solum," which is the layer influenced by climate and vegetation. The unweathered rock, known as bedrock, below the C horizon, has been referred to as "D Horizon."

[13]A new classification is being developed by the USDA, and the "7th approximation" of it, published in 1960, groups soils of the world into 10 orders, 40 suborders, about 200 great groups, 400 subgroups, 1500 families, and 7000 series. Soil type is not being retained as a category of the natural system in this classification.

trols the development of the soil, their ultimate productivity is a function of climate. For example, the podzolic soil of low inherent fertility is important because of its location in the arid, cool temperature climate. The fertile chernozem soil reaches its maximum productivity when irrigation is employed to compensate for the semi-arid climate.

Among these classifications, the lowest three units, i. e., *soil series*, *soil types*, and *soil phases*, are commonly used for practical agricultural purposes. *Soil series* is a subdivision of soil family and consists of groups of soils which have all been developed from the same type of parent material and are similar in differentiation of horizons. However, the texture of soils is not considered. The *soil type* is a textural subdivision of a soil series. *Soil phase* is a subdivision of soil type. To differentiate[14] series, types, and phases, for instance, the "Miami Series" (a soil series) may be subdivided into "Miami Silt Loam" (a soil type) and others, and further subdivided as "Miami Silt Loam, Steep Phase," "Miami Silt Loam, Stony Phase" (a soil phase), and the like.

The soil texture of mineral soils (inorganic soils) is usually determined by the percentage of sand, silt, and clay. This is shown in Fig. 2-1. Organic soil is defined as having more than 20% organic matter. The physical and chemical properties of soil owe their origin mainly to the different proportions of sand, silt, and clay in the total soil mixture.

The soil, as a physical system, can be described in terms of such properties as mechanical, thermal, optical, chemical, and hydrological.

MECHANICAL PROPERTIES

Texture: diameter of particles for sand (2.0 to 0.02 mm); silt (0.02 to 0.002 mm); clay (0.002 to 0.0002 mm); and colloid (0.002 to 0.0000001 mm).[15]

Structure: simple structure (massive and single grain); compound structure (granular, blocky, platy, prismatic, and columnar).

Density: bulk density (volume weight); specific gravity; particle density (grain density).

Other properties: consistency (resistance to deformation); plasticity; viscosity; porosity; permeability; and capillarity.

[14]This differentiation applies only to the Zonal and Intrazonal Soils. For Azonal soils, the soil profile is too young to be adequately described.

[15]This is the Atterberg System, known as the International System. Most colloid chemists have considered 0.002 mm as the maximum size of colloidal particles. Accordingly, the particle size of clay is within the colloidal range.

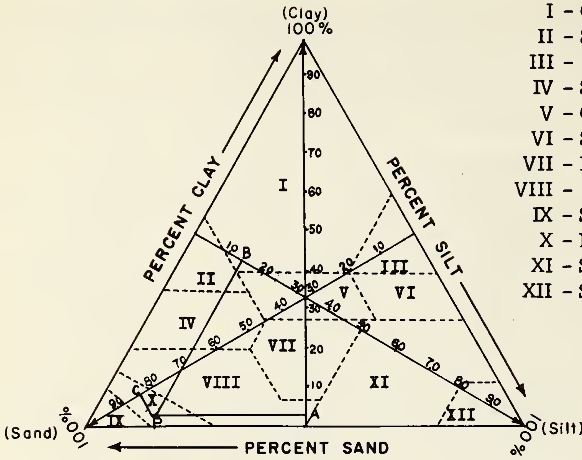

Fig. 2-1. Triangular coordinates of soil texture classes by mechanical analysis. For illustration, point P represents loamy sand, where PA + PB + PC = 3% clay + 13% silt + 84% sand.

THERMAL PROPERTIES

Heat storage: heat capacity (amount of heat absorbed per unit temperature rise or vice versa); specific heat (heat capacity of a system per unit mass).

Heat transfer: conduction; radiation; convection (laminar flow and turbulence flow).

Soil temperature: space variation (horizontal and vertical gradient); time variation (hourly, diurnal, nocturnal, seasonal, etc.).

Other properties: thermal effect on mechanical properties may be illustrated by such phenomena as: expansion (the opposite of compression); thermal stress; thawing and freezing; frost heaving; frost line; chemical reaction and color changes.

OPTICAL PROPERTIES

Albedo: bare ground, 10-20%; green forest, 3-10%; wet sand, 9%; dry sand, 18%; fresh snow, 80-85%; earth as a whole, 35-43%. (These are the approximate values of the albedo for visible wavelength.)

Color: varied shades of gray, yellow, brown, red, and black. These are the most common colors of the soil surface.[16]

Other properties: absorption, emission, transmission, and reflection (direct, diffuse, and scattering).

[16]For specification, see R. L. Pendelton & D. Nickerson, 1951, Soil colors and special Munsell soil color charts, *Soil Science* 71: 35-43.

The chemical, biochemical, and microbiological properties of soil will not be discussed here. The reader may refer to textbooks on soil chemistry and soil microbiology. However, certain phenomena are enumerated below, an understanding of which will be beneficial.

ACIDITY AND ALKALINITY

pH values: neutral, 7.0 pH (decreasing acidity from 3.0 to 6.0 pH, and increasing alkalinity from 7.0 to 10.0, sometimes to 11.0 pH); acid soil (below pH 7.0); alkali soil (pH 8.5, or higher).

Buffer capacity.

Degree of base saturation, etc.

COLLOIDS

Colloid fraction (colloid vs. noncolloid)

Cation exchange capacity and percentage base saturation (two phases).

ELEMENTS

Carbon-nitrogen ratio; phosphorus (chemically precipitated, chemisorbed): *potassium* (fixation, exchange); *silica-sesquioxide ratio.*

SALINITY

Units: conductivity of saturation extracts expressed in mhos per centimeter.

Types: saline, saline-alkali (or sodic), non-saline-alkali (or non-sodic) soils.

MICROBIOLOGY AS RELATED TO SOIL FERTILITY

Edaphon: macroanimal, microanimal, algae, fungi, molds, actinomycetes, bacteria, funa.

Availability of nutrients: nitrogen, potassium, calcium, and phosphorus.

Processes of nitrogen: nitrogen fixation (the opposite of denitrification); aminization; ammonification; nitrification.

The terminology used in soil technology, soil management, and landscaping in practical farm operation is listed as follows:

HYDROLOGIC TERMS

Irrigation: types — sprinkling, subirrigation, and flooding (e.g., basin, border, and furrow). *Scheduling of irrigation* — amount, intensity, time, and duration. *Quality of irrigation* (chemicals dissolved in water, such as Ca, K, Na, etc., and even Strontium 90).

Drought: types — agricultural drought, partial drought, absolute drought, dry spell, etc. *Related measurement* — soil moisture stress, water deficiency, water vapor deficit, wilting point (coefficient, percentage), permanent wilting, etc. *Drought criteria* — indices, aridity. *Drought control.*

Water movement: percolation; infiltration — penetration (infiltration rate), leaching; *capillary action* (capillary conductivity, capillary fringe); *drainage* (tile, open ditch, mole); *run-off* — surface and subsurface (inflow and outflow); *erosion* (accelerated, normal, gully, rill, and sheet); *permeability; hydraulic conductivity* (gradient).

Soil and water conservation: soil moisture; ground water; surface water; water table; water storage; snow cover; flood control; erosion (soil, water, and wind); *water retention; evaporation; field capacity* (available water); *hygroscopic coefficient; equivalent pF values* (equivalent values ranging from 0 to 7 pF); *waterlogging; water contamination* (pollution).

SOIL MANAGEMENT TERMS

Cultivation: tillage; manuring (animal and green); *mulching* (artificial and natural, e.g., snow cover); *cropping system; weed control* (herbicides).

Miscellaneous: fallowing; rotation; fertilization; liming; salinity; erosion control; flooding; drainage; sanding.

As has been mentioned previously, the above summary serves as a guide to students who have had a basic knowledge of soil science. Those who have not had enough knowledge of soils should consult the Appendix for definitions and other aids.

It is obvious that the composition of soil is far more complex than that of air, due to the fact that soils are heterogeneous in nature. One may find many types of soil in an acre of land. For convenience, however, the major components of soils may be grouped into five principal classes: (1) inorganic materials, (2) organic materials, (3) soil water, (4) soil atmosphere, and (5) soil organisms. Under ideal conditions, the soil water (liquid phase) and soil atmosphere including water vapor occupy about one-half of the soil volume; the other half is made up of organic-inorganic particles. Organic materials, such as humus, form only a very small fraction of the total soil volume, most of which is occupied by inorganic materials. The colloidal materials (clay and humus) are the most chemically active soil fraction and contribute to the formation of secondary particles (e.g., aggregation and structural development). Silt and sand, although not inert, are of greater importance for their role as framework. Soil organisms are important to the growth and development of plants. Though abounding in the soil, they constitute only a small fraction of the total soil mass. Environmental effects on their development will be treated later. The soil properties of organic and inorganic material and soil atmosphere have already been mentioned, while soil water will be discussed in the following section.

(c) Water. Three physical states of water (vapor, liquid, and solid) exist both in the air and in the soil. When atmospheric water vapor is cooled down it may be condensed into clouds, fog, dew, or rain. Upon further cooling, it forms ice crystals which can remain in the clouds or fall to the earth's surface in the form of hail, sleet, or snow. In the soil, it may be sublimed or condensed into rime, frost, or ice sheets. These involve the processes of condensation and precipitation. In meteorology, the differentiation of condensation from precipitation is necessary. The former involves the change from water vapor to water, the latter, the falling out of that water as rain, snow, hail, or some other hydrometeor (Greek, "water of the air"). Sublimation is the change of ice directly to water vapor or vice versa.

Hydrometeors which influence crops and livestock have recently been defined by Huschke (1959) in the *Glossary of Meterology* as: "Any product of condensation or sublimation of atmospheric water vapor, whether formed at the free atmosphere or at the earth's surface; also, any water particles blown by the wind from the earth's surface." A katahydrometeoric process has been defined by Buettner (1958) as one by which water reaches the earth's surface. Buettner's clear-cut definition and description of hydrometeors follows:

(1) Precipitation — atmospheric water, in any of its phases, deposited on the earth's and biotic surfaces.

If the deposition is accelerated by gravity, it is termed falling precipitation. Examples of this type are: *Rain* — water droplets of about 0.01 to 0.25 inches in diameter; *Freezing rain*— falling droplets which freeze upon striking the ground; *Snow* — hexagonal crystalline systems of ice, including simple needles and columns, flat plates, capped columns, stars, and irregular forms; *Hail* — balls or irregular lumps of ice, hailstones ranging from 0.25 inches up to several inches in diameter; *Sleet* — transparent, more or less spherical, hard pellets of ice about the size of raindrops; *Drizzle* — uniformly dispersed droplets of about 0.002 to 0.02 inches in diameter; *Freezing drizzle* — falling drizzle which freezes upon striking the ground; *Glaze* — falling supercooled water (raindrops or drizzle droplets) which solidifies upon contact with freezing surfaces, forming a homogeneous and transparent deposit of ice.

Atmospheric water of liquid or solid forms suspended in the air is not precipitation unless it is falling to the ground. A suspension of very minute water droplets around the visible horizon (frequently less than 500 feet above the ground) is termed *fog*. Fog droplets have a diameter of 4×10^{-3} to 4×10^{-5} inches. A suspension of numerous small ice crystals in the air is *ice fog*. Those above the visible horizon are *clouds*. The lowest types of clouds are higher than 1,000 feet. *Mist* is a thin fog, and should be differentiated from *haze* which is mainly atmospheric dust.

Deposition caused by interception is known as intercepted precipitation. An example of this is *rime*, which results from the interception of supercooled fog droplets, possibly mixed with ice particles, by vertical surfaces. Intercepted low fog is termed dew-fog (German:

"Nebeltau") because it cannot be distinguished from dew and fog. Other terms for this intercepted precipitation are *occult rain, horizontal rain, fog precipitation, fog drip,* and *filtered precipitation.*

(2) Condensation-sorption — atmospheric vapor which is deposited on or below the surface in solid or liquid form. The condensation products are *dew* and *frost.* The two conditions which permit the condensation processes to occur are (i) the condensation surface is non-hygroscopic; (ii) the temperature of the condensation surface is lower than the dewpoint of the adjacent air. When the surface is cooled by radiant heat loss, dew is formed by condensation of water vapor. When the surface is cooled from below by conduction, *sweating-dew* results. When the surface is cooled below freezing, frost is formed through sublimation. Various terms have been used in describing frost: *white frost* refers to frost in white crystalline form; *black frost* usually occurs in dry autumn air when the temperature reaches 32°F or below, blackening tender vegetation—no actual frost formation occurs;[17] a *killing frost* is a frost which causes damage to vegetation — usually occurring when the air temperature is two or more degrees below freezing, depending upon the plant species concerned; *hoarfrost* is a light frost deposited upon freezing surfaces in the form of scales, needles, and feathers — however, the temperature of the surrounding air can be above freezing.

When the surface upon which water vapor is deposited is hygroscopic in nature and its temperature is higher than the dewpoint of the surrounding air, sorption processes rather than condensation processes occur. Such sorption processes include: liquid sorption—dissolving of vapor in water soluble solids; adsorption — adhesion of water vapor to nonsoluble solid surfaces; absorption—intake of water vapor by organic substances, such as straw mulch, without being dissolved; and chemical-sorption processes — reaction of water with certain types of chemicals, such as CaO, P_2O_5, to form new compounds.

Although water is far simpler in composition than either air or soil, it is subject to change in form and amount with respect to time and space. The amount of rainfall, for example, varies greatly over a distance of one mile and a period of a few hours; this is particularly true during the summer months. This variability is one of the most important and difficult problems in the field of agrometeorology. Various approaches to it have been attempted by meteorologists and hydrologists; they will be treated in detail in Chapter 4.

In the present section, only atmospheric water has thus far been discussed. Soil water, on the other hand, is of fundamental importance to agriculture. With respect to gravitational and capillary

[17]In the past decade the growing season has been defined in terms of white and black frost (e.g., Wang, 1957).

forces, it is customary to divide soil water into four categories:

(i) Gravitational water — that which percolates through the soil under the force of gravity.

(ii) Capillary water — that which moves toward the region of greatest capillary tension, regardless of direction.

(iii) Hygroscopic water—that which remains in the soil and is influenced by neither capillary tension nor gravitational force.

(iv) Combined water — that which remains after the hygroscopic water evaporates, held by chemical combination.

2.1.2 *Biological community*

As stated above, the environment consists of both biological and physical media. Thus, it seems that living organisms occupy the other half of the environment, even though they are seldom considered a part of it.

From the standpoint of agrometeorology, the biological community may involve crops, diseases, insects, and soil microorganisms. All are subject to change, and there are no existing methods for accurate measurement of these changes on a quantitative basis. Such changes include the propagation of soil microorganisms, competition of crops, diseases, and insects for light, moisture, and nutrients. Collectively, these are considered as biotic factors. Most studies in agrometeorology have assumed that biotic factors are constant under uniform cultural practices; otherwise, they must be considered separately. *The constancy of biotic factors is an important assumption in agrometeorological studies.* This assumption can be applied more effectively to cultivated plants than to native plants. The validity of this assumption lies in the fact that changes of the microenvironment by biotic factors are more consistent in a cultivated field than under natural conditions. The space and depth of planting, rotation system, plowing and mulching, weed control, and many other cultural practices are uniform for the former, but this is not true for the latter. This can readily be seen by contrasting an orchard to a natural forest.

The way in which the biotic factors influencing the growth of a crop can be treated as a constant without introducing much error can be illustrated as follows. Suppose a field of Golden Cross Bantam sweet corn is grown under the same cultural practices in each of three years. The variation in competition for moisture and light between the plants during the tasseling stage will then be of the same magnitude during each of the three years and can therefore be neglected. A similar year-to-year identity will exist for any other biotic factor so long as the same variety of corn and the same cultural practices are used each year and identical developmental stages are compared. The necessity of comparing identical stages lies in the fact that the degree of interplant competition varies with the size and age of the plants. To insure this uniformity, crop data from fields showing excessive disease and insect injury should be discarded; an arbitrary rejection limit (say 5%) can be established for this purpose. In this way, the biotic factors of diseases and insects can be eliminated. Variability in the soil organic matter and fertility, as influenced by soil microorganisms, will automatically be eliminated partly through constant cultural practices (cropping system, tillage, weed control, mulches, fertilization, etc.), and partly by the selection of the same field from year to year in the study. Edaphic factors (soil moisture, soil temperature, aeration, etc.) of the physical environment are recognized as the only variables.

Under the above considerations, the assumption of the constancy of biotic factors is valid and necessary for the study of agrometeorology.

A knowledge of the organisms of the soil, however, is still necessary. Although it is not considered as a factor it might be a problem. Environmental conditions affecting the growth of soil bacteria, for example, are supplies of oxygen and soil moisture, soil temperature, amount and nature of soil organic matter, and H-ion concentration of the soil solution as well as the amount of exchangeable calcium present. The organic matter contents, the exchangeable calcium and pH relationship are dependent on the variation of physical environment. The optimum soil moisture level for higher plants is usually the best for most bacteria. The oxygen supply is conditioned by the variations of soil moisture and soil temperature. The suitable soil temperature range for the greatest soil bacterial activity is 70° to 100°F, and ordinary temperature extremes seldom kill bacteria.

The important groups of soil organisms commonly present in soils have been grouped by Lyon, Buckman & Brady (1952) as macroanimals, microanimals, and plants. Under macroanimals, those subsisting largely on plant materials are: small mammals (squirrels, gophers, mice, etc.), insects (beetles, springtails, grubs, etc.), millipedes, sowbugs, mites, slugs and snails, and earthworms; those subsisting largely on animals and plants are: moles, insects (ants, beetles, etc.), centipedes, and spiders. Under micro-animal, we have nematodes, protozoa, and rotifers. Under plants we have roots of higher plants, algae, fungi, actinomyces, and bacteria (aerobic and anaerobic, autotrophic and heterotrophic).

Biotic factors other than soil organisms, such as insects and diseases pertaining to the air, are also important. Again, an agrometeorologist will not consider them as a factor, but sometimes as a problem.

2.2 THE CONTROLLING FACTORS OF THE PHYSICAL ENVIRONMENT

The physical environment of plants and animals is governed by several major processes. Through the radiation process, energy in the form of heat and light reaches the earth from the sun — the sole heat source.[18] It is followed by such processes as heat transfer, re-radiation, conduction, convection, and diffusion. Finally, these processes reach a state of equilibrium, energy changes and exchanges become balanced between the earth's surface and the atmosphere immediately above it. This equilibrium condition, established at a fixed time and locality, forms the microenvironment of that specific place. However, for an accurate description of a microenvironmental equilibrium, it is necessary to measure all the other factors involved, such as heat, light, moisture, and mass exchanges in the air, vegetative cover, and soil profile.

2.2.1 *Radiation*

Radiation is the principle type of propagation of energy (in the form of heat and light) accomplished without the aid of any material medium as a carrier. Solar radiation, as the main source of radiation to the earth, passes through the vast universe without a material carrier, such as air, water, or soil. It links the "heat source" — the sun, and the "heat sink" — the earth.[19] This is one form of short wave radiation. The reverse of direct solar radiation is re-radiation, also termed back radiation, and is the major factor controlling night temperature. Net radiation is the difference between the incoming solar radiation and the outgoing back radiation of the earth. As far as the earth's surface is concerned, a positive value of net radiation means that more heat flows toward the earth's surface, while a negative one indicates that more has been removed from the earth. The study and measurement of net radiation is one of the most important facets of agrometeorology.

Since heat and light are closely related in a natural environment, they will be conveniently studied under the same heading, "radiation."

(a) Heat. In the past two hundred years, temperature instead of heat has been employed in the study of plant responses. Temperature is the hotness of a body in terms of a fixed scale, namely, Fahrenheit or Centigrade scales. Of two bodies, the hotter is said to be at a higher temperature. This is a qualitative expression. For the expression to be quantitative a fixed scale must be used. In reality there is no rigorous definition of temperature.[20]

[18]This is referred to a global scale. There are minor heat sources, such as chemical heat, combustion heat, ground heat, and even heat from other planetary sources.

[19]Strictly speaking, the space of the universe is the heat sink.

[20]In physics, according to the second law of thermodynamics, temperature has been precisely defined in terms of the work done by an ideal reversible engine. Two temperatures T_1 and T_2 on the Kelvin scale are given by the ratio of the heats added Q_1 and rejected Q_2 and by a Carnot cycle operating between the temperatures, $T_1/T_2 = Q_1/Q_2$. In principle, it may be measured as accurately as possible by means of a gas thermometer.

Heat, or rather the thermal capacity of a body, is known as the product of the specific heat of, the temperature change in, and the mass of that body. Describing the thermal relation of a plant to its environment by temperature and neglecting heat or energy exchanges is misleading. For example, the thawing date of a lake, which is a change in the thermal capacity of the lake, is a much better indication of the thermal plant responses than are temperature records. As indicated above, it is incorrect to use the terms temperature and heat interchangeably. However, temperature is still used in plant response studies.

Temperature scales are familiar to all, but for the sake of convenience, a review of these scales and conversion formulas is included.

Table 2-3. Temperature Scales and Conversion Formulas

Temperature Scale	Freezing and Boiling Range	Simplified Conversion Formula	Remarks
Kelvin, K	273-373	$K = C + 273$	Usually for theoretical studies.
Centigrade, C	0-100	$C = (\frac{1}{2} + \frac{1}{2}\frac{1}{10} + \frac{1}{2}\frac{1}{100} + \ldots)(F - 32)$	Adopted by most countries in the world.
Fahrenheit, F	0-212	$F = \frac{1}{10}(20C - 2C) + 32$	Adopted by U. S. A. and Great Britain.
Réaumur, R	0-80	$R = \frac{5}{4}C$	Nearly out of date.

In Table 2-3 the simplified conversion formula $C = (\frac{1}{2} + \frac{1}{2}\frac{1}{10} + \frac{1}{2}\frac{1}{100} + + \ldots)(F - 32)$, for example, is much easier to use than the usual $C = \frac{5}{9}(F - 32)$. To convert 86°F to centigrade, for example, subtract 32, leaving 54. Then multiply 54 by $\frac{1}{2}$, giving 27; then add to 27 a tenth of 27, then a hundredth of 27, etc., giving a total of 29.97 or 30°F. These formulas can similarly be used for the other scales; although they look complicated, they are actually much simpler than the classical methods.

Various ways of expressing temperatures have been used. The daily mean temperature is conventionally designated as half of the sum of the maximum and minimum temperatures occurring on a single day, but it does not give an adequate representation of the actual temperature conditions. An average of the 24 hourly temperature observations of the day is better, if hourly data are available. If three daily observations are made at 7, 14, and 21 o'clock local time, an approximation of the mean can be found by adding the 7 and 14 o'clock readings to twice the 21 o'clock reading and then dividing the total by 4. Actually, no one method is perfect because no single temperature can adequately represent an entire day's record. The discrepancy becomes even more apparent if a longer range of time is considered, such as weekly, monthly, or annual temperatures. Therefore, the best way of expressing such temperatures is in terms of frequencies of their occurrence. The diurnal temperature variation refers to the temperature changes occurring within a 24-hour period. The interdiurnal temperature range is the difference between the daily mean temperatures of two successive days. The difference between the maximum temperature of the first day and the minimum temperature of the following day represents the interdiurnal cooling, and the reverse of this, the warming. This is another way of expressing the interdiurnal temperature range and can be termed the interdiurnal maximum-minimum range. The highest and lowest monthly or annual temperatures of a state as reported by the U. S. Weather Bureau refer to the absolute extremes of temperature at a specific time and locality within that state. This expression has little value as far as agrometeorology is concerned, although it gains much popular publicity. The maximum or minimum temperature of a single day, on the other hand, is much more useful in agrometeorology than the daily mean, monthly mean, or highest and lowest temperatures. The night temperature, which has been recognized as an important factor in plant response, is the mean value of the night-time temperature observations. However, if these observations are not available, the minimum temperature of the day may give the best approximation of the night temperature. Similarly, the maximum temperature might be useful to represent the daytime temperature, but not as representative as the minimum temperature is to the night temperature, because a typical diurnal temperature curve shows that a much longer period of a minimum temperature holds constant during the night than the maximum during the day. Went (1958) has approximated the effective day temperature as

$$T_M - \tfrac{1}{4}(T_M - T_m)$$

and the effective night temperature as

$$T_m + \tfrac{1}{4}(T_M - T_m)$$

where T_M and T_m are the daily maximum and daily minimum temperatures, respectively. He labelled the day temperature phototemperature, and the night temperature as the nyctotemperature. However, one can get a different relationship rather than what Went has formulated, for the relationship depends upon seasonal and regional variations. Therefore, each region has to establish its own relationship according to seasonal differentiations. Further significance of maximum and minimum temperatures will be discussed later.

The media by which temperatures are measured define the type of temperature involved: air temperature, soil temperature, water temperature, and plant temperature. The time and place of observation of these temperatures must be specified in detail. The "time" should be recorded at least to the nearest hour and expressed as local solar mean time; the "place" should be specified in inches (or other units) above the ground. Other specifications as to instruments used, type of microenvironment, and techniques of observation should likewise be given, and will be treated later in this book.

(b) Light.[21] Intensity, duration, and wavelength are the three major characteristics of light which are of importance in the growth and development of plants and animals. In natural environments, only the intensity and duration of solar radiation and the accompanying heat are the characteristics of general concern.

The intensity of solar radiation is greatly reduced by the earth's atmosphere before the radiation reaches the earth's surface. The generally recognized value of 1.94 cal cm^{-2} min^{-1} (i.e., 1.94 langley per minute)[22] at the upper limit of the earth's atmosphere, known as the solar constant, was principally determined by the Smithsonian Institution and has been continually revised since 1902. This value is obtained by assuming that the surface (1 sq cm) involved is perpendicular to the solar beam at the mean solar distance, and that the earth's atmosphere is absent. Nevertheless, the solar intensity value, 1.94, is no longer constant following the processes of absorption, reflection, and transmission by the atmosphere and the earth's surface. In the atmosphere, clouds, water vapor, gas molecules (particularly carbon dioxide), and dust and other foreign matter are the media in which absorption and scattering[23] of radiant energy occur. Energy which is absorbed will be re-radiated as sky radiation in longer wavelengths; that which is transmitted will reach the earth's surface and will again be absorbed, reflected, and transmitted, even though transmission will be obviously much less here than in the atmosphere. Energy scattered by the earth's surface is the principal source of long wave or terrestrial radiation. The percentage of radiant energy which is reflected from a surface is known as its albedo. For example, the albedo of the earth's surface is the ratio of the incoming radiant energy of the sun to the outgoing radiant energy of the earth. A knowledge of the earth's albedo, although complicated by the heterogeneity

[21]Actually the word "radiation" is a better term here than "light," because the latter refers to visible radiation (about 0.4 to 0.7 microns in wavelength) and the former includes all wavelengths. Wavelengths such as "ultraviolet" and "infrared" are all-important to plant response.

[22]One calorie equals 4.184×10^7 ergs; one calorie per square centimeter equals one langley (ly). Thus, one ly per minute = 1 cal cm^{-2} min^{-1} = 4.184×10^7 ergs cm^{-2} min^{-1}. The generally accepted value of 1.94 ly min^{-1} for solar constant has been suggested by Johnson (1954) as 2.00.

[23]Such scattering is responsible for other optical phenomena, such as reflection, diffraction, and some polarization.

of the earth's surface,[24] is important to meteorological studies. The radiation balance, heat balance of the earth's surface, as well as soil temperature and evaporation, depend in part upon the earth's albedo. Radiant energy is transmitted through cloud layers as short waves and is re-radiated by the earth's surface as long waves, most of which return to the earth. This causes a heating of the earth's atmosphere under the clouds and is known as the greenhouse effect.

In many biological studies on radiation, foot-candles (f.c.)[25] instead of calories per square centimeter are commonly used. These were converted in 1924 by Kimball at Washington, D. C., to the following cloudiness values: for overcast skies, a mean value of 7,440 f.c. min^{-1} is equivalent to one calorie cm^{-2} min^{-1}; for cloudy skies, it is 7,000; and for cloudless skies, 6,700 ± 5. These equivalents are a function of solar altitude and zenith distance, and are true insofar as solar radiation and sky radiation at daylight intensity are concerned. The following factors must be considered in order to apply these conversions accurately: the latitude of the observer, the time of day (hour angle of the sun or angular distance from the meridian of the observer), and the date of the year (the declination of the sun). For example, at 25° sun's zenith distance, 1 cal cm^{-2} min^{-1} is equivalent to 7,000 f.c. min^{-1}; at 78.7°, 6,200 f.c., for a cloudless sky. At noon on a clear summer day in regions of low latitude, this value can be as high as 8,000 to 10,000 f.c.; 6,500 foot candles per minute is equivalent to 1 cal cm^{-2} min^{-1}, an approximate but useful conversion. Thus, 100 langley per day represents about 650,000 f.c. per day or 100 calories per square centimeter per day. Another unit which is useful in controlled environments is the watt per square meter. One langley per minute is equivalent to 698 watts per square meter.

The duration of light is just as important to the growth and development of plants as is the intensity of light, and sometimes even more so. The length of daily exposure to light is termed the photoperiod. The response of plants to photoperiod is called photoperiodism; that of animals, photoperiodicity. Garner & Allard (1920, 1925) classified plants into four types according to their photoperiodic requirements for floral initiation: long-day, short-day, day-neutral, and indeterminate. Generally, the earliness of blossoming of a long-day plant requires longer light exposure (usually more than 14 hours). A short-day plant requires short exposure (less than 10 hours). Day-neutral plants are indifferent to light duration within a daily range of 10-18 hours duration. Indeterminate plants must receive 12-14 hours

[24]The mean albedo of the earth's surface is 35-43%; of fresh snow, 80-85; of a green field, 10-15; and of overcast stratus clouds 0-500 ft. in thickness, 5-63. The albedo of water surfaces at different solar elevations ranges from 3 to 46%.

[25]A foot-candle is generally defined as the amount of illumination produced by a standard candle at a distance of one foot.

of light daily if flowering is to occur. In some plants, the photoperiodic requirements for flowering differ in the various developmental phases. The strawberry requires short days for initiation of flowering, but long days are needed for fruiting. Spinach and wheat are day-neutral for floral initiation, but require long days for fruiting. Soybeans, on the other hand, require short days for both flowering and fruiting. Both the age of the plant and its stage of development, as well as external factors such as light intensity, light quality, and temperature, which is interrelated with light duration, are all important factors which must be considered in the classification of plants as to their photoperiodic requirements. Complications in plant and animal photoperiodic responses will be studied in later chapters.

The duration of daylight in a natural environment may be defined as the length of time between sunrise and sunset, or the length of time between the beginning of morning civil twilight and the end of evening civil twilight. The latter is the preferred definition as far as photoperiodism of plants is concerned.[26] Civil twilight time is the time interval between sunrise or sunset and the time when the true position of the upper limit of the sun is 6° below the horizon, at which time stars and planets of the first magnitude are just visible. The maximum annual variation in twilight time between the equator and a latitude of 30° is only 12 minutes per day, which is negligible for photoperiodic studies. At 60° latitude, it is as much as two hours and 10 minutes. At latitude 65° or more, it lasts for 24 hours during the months of June and July. Table 4-5 gives the longest and the shortest duration of daylight and twilight for all latitudes; Fig. 4-3 gives the day-to-day variation of the durations throughout the year for latitude 45°. The extension of the duration of daylength by moonlight is of significance to some plants.

The daily duration of sunshine is more commonly observed than is the intensity of sunshine. The ratio of the actual (or recorded) duration of sunshine to the maximum possible duration (in percent) at a given time and locality is termed the percentage of possible sunshine. This expression has proven to be a useful parameter insofar as the evaluation of solar intensity, potential evapotranspiration, cloudiness, and net radiation are concerned. Other studies which deal with the effect of this parameter on the growth and development of plants will be described in later chapters.

Wavelength or quality is another important aspect of light. Almost all studies of light quality have been performed under controlled environments. Monochromatic light such as red, yellow, blue, etc., has been utilized in researches on plant and animal responses. Many important and useful findings have been published from time to time.

[26]Of course, this depends upon the radiation intensity requirements of each species of plant.

Particularly, many contributions have dealt with the biological effects of the ultraviolet and infrared regions of the spectrum. Nevertheless, little work has been done in natural environments. Differences in air masses, types and coverage of clouds, intensity of air pollution, and even the color of leaves decidedly influence the quality of light.[27]

Solar radiation covers only a small portion of the entire electromagnetic spectrum. The total spectrum ranges from 0.15 microns in the ultraviolet region to over 4.0 microns in the infrared, of which visible light occupies only 0.40 to 0.70 microns. The maximum intensity is located at about the 0.50 micron region. Lunar radiation, which is mainly reflected solar radiation, bears the same spectrum as sunlight and is modified only by the orange tint of the moon's surface which causes its reflected blue, violet, and ultraviolet light to be weaker than that of the solar spectrum. The intensity of light from a full, bright moon has been estimated to be on the order of 0.05 f.c. Terrestrial radiation, which consists of sky radiation and earth radiation, is mostly long wave spectrum. Its total spectrum ranges from 4.0 to 34 microns, with a maximum radiation intensity of 10 microns. The solar radiation contributes almost all the light intensity and heat energy needed by plants and animals. Since lunar radiation is essentially a reflection of solar radiant energy, it contributes a light intensity which is only 5 parts per million or less of the solar intensity, and is accompanied by only a negligible amount of heat energy.[28] Terrestrial radiation contributes mainly heat energy and some light intensity, e.g., the twilight of the sky radiation.

2.2.2 *Moisture*

The term "moisture" is used to designate the presence of water in its vapor, liquid, and solid forms both in the atmosphere and in the soil. Water in solid form, such as ice (hailstones, for example) and snow, represent potential moisture. Snow is usually measured according to the depth accumulated on the ground. According to the U. S. Weather Bureau, one inch of freshly fallen snow is equivalent to one-tenth of an inch of water, but according to the Royal Meteorological Office of Great Britain, one foot of snow is equivalent to one inch of water. Because of the great variation in the density of snow, this conversion is only an approximation. Several samplings of the actual water equivalent (w) of freshly fallen snow (i.e., measured in

[27]The quality of light may vary with a certain persistence of weather pattern during a certain season of the year. For example, a given weather pattern gives successive days with clear skies during sunrise and sunset and clouds during the day, while another weather pattern contributes a cloudy dawn followed by clear sunny day and sunset. Also, under the shade of crowns in a field or under different types of glass in the greenhouse, the quality of light is different. This gives rise to the diurnal and seasonal variation of light quality.

[28]However, the effect of moonlight on plants cannot be ignored. A considerable literature covers this area of study.

inches of water after melting) must be made over a large area. Since the density of snow changes as time goes by, the water equivalent changes correspondingly. The amount of freshly fallen snow yielding one inch of water may vary from 5 to 20 inches. The variation is further increased by evaporation, compaction, wind, thawing, and freezing. A measurement of snow density, D_S, as defined below, is sometimes useful:

$$D_S = \frac{\text{actual water equivalent of snow}}{\text{depth of freshly fallen snow}} = \frac{w}{h} \qquad (2\text{-}1)$$

A successive weekly accumulation of the actual water equivalent during the period previous to the growing season would be useful for winter evaporation and soil moisture studies. Wang (1961) has made such a study for Wisconsin. Various diagrammatic presentations have also been prepared. The total snowfall and rainfall accumulated during the winter prior to the planting as well as the snow-rain ratio have been established. When snowfall accumulation alone is considered, the snow threshold probability at various time intervals is easily computed. Snow cover is both beneficial and detrimental to agriculture. It usually serves as a natural mulch if the duration of coverage is long and persistent. But at the same time, it may cause agricultural hazards as well. The study of hail, its distribution and intensity, is another important aspect of research.

Moisture in the plant, on the other hand, has been studied more extensively by plant physiologists. Studies of water movement within plants are promising guides to research in agrometeorology. As far as crop-weather relationships are concerned, moisture in the soil is a far better indicator of the available moisture than is precipitation. This is because considerable moisture is lost as percolation, surface and subsurface runoff, evaporation, and interception by the leaves of plants. A further discussion of soil moisture will be found in Chapter 4.

Water in the atmosphere, in its liquid form, can be received by the earth either as dew or as rain. Dew, which is not regularly measured, is an important source of moisture, particularly in arid and semi-arid areas. Rainfall is usually expressed as the depth of rain accumulated in a definite interval of time. It may be expressed in inches, to hundredths of an inch, in English-speaking countries. Thus one inch of rainfall to the acre is equivalent to 101 tons of rainfall.[29] The daily rainfall, for instance, is the number of inches of rain which has fallen during a 24-hour period. Effective rainfall, that portion of the total rainfall used by plants, is another important

[29]This is useful for irrigation estimates. Since one acre is 43,560 sq. ft., one acre of one-inch rainfall occupies 3,630 cubic feet. Since 1 cu. ft. of water is 62.43 pounds, and 1 long ton equals 2,240 pounds, one inch of rainfall to the acre is 3,630 × 62.43 / 2,240 = 101.17 or 101 tons of water. This is about 27,000 gallons of water per acre.

expression, but one difficult to estimate. A rainy day is customarily defined as one on which 0.01 inches or more of precipitation has fallen. Since this simple definition does not take plant responses into account, a more appropriate criterion is necessary. The crop-rainy day R_c criterion has been devised by Wang (1956) for this purpose (see Chapter 4).

Water of the atmosphere, in its vapor form, may be represented in several ways: vapor pressure (e), relative humidity (r), vapor pressure deficit (d), absolute humidity (a), specific humidity (q), mixing ratio (m), dew point temperature (T_d), wet-bulb temperature (T_w), and the virtual temperature (T_v). These expressions may be defined as follows:

a. Vapor pressure (e) is the pressure of water vapor in the air during the transformation of water to vapor or ice to vapor. The former is known as vapor pressure over water, and the latter as vapor pressure over ice. Vapor pressure over water is always greater than over ice. When saturated, it is known as saturation vapor pressure (e_s), which is determined by the air temperature. The higher the air temperature, the larger the saturation vapor pressure. Values of saturation vapor pressure over water and over ice with respect to various temperatures can be obtained, for example, from the Smithsonian tables.

b. Relative humidity (r) is the ratio of the actual vapor pressure to the saturation vapor pressure *over water* at the same temperature. It is expressed as

$$r = e/e_s , \tag{2-2}$$

or, more often, as a percentage,

$$r = e/e_s \times 100 . \tag{2-3}$$

Thus, when $r = 100\%$, then $e = e_s$.

c. Vapor pressure deficit (d) is the difference between the actual vapor pressure and the saturation vapor pressure; thus

$$d = e_s - e . \tag{2-4}$$

From equation (2-3), then,

$$d = e_s (100 - r) . \tag{2-5}$$

The well-known Meyer precipitation-saturation deficit or simply N - S quotient of Germany is a combination of precipitation (P) and vapor pressure deficit ($e_s - e$). It is expressed by

$$\frac{N}{S} = \frac{\text{Precipitation}}{\text{Vapor pressure deficit}} = \frac{P}{e_s (100 - r)} . \tag{2-6}$$

This expression has been widely used by European and American workers for the study of climate-soil relationships.

d. Absolute humidity (a) is the density of water vapor or mass of water vapor present in a unit volume of moist air. It is usually expressed in grams per cubic centimeter, or grains per cubic foot.

e. Specific humidity (q) is the mass of water vapor present in a unit mass of moist air. It is usually expressed as grams per kilogram, and can be calculated by a simplified equation from the existing air pressure, air temperature, and relative humidity, with the aid of equation (2-2) and the saturation vapor pressure curve,[30]

$$q = 622\ e/p, \qquad (2\text{-}7)$$

where e is the partial pressure of water vapor and p the total atmospheric pressure of moist air.

f. Mixing ratio (m) is the mass of water vapor present in a unit mass of absolutely dry air. The simplified equation is

$$m = 622\ e/(p - e) \qquad (2\text{-}8)$$

and is expressed in the same units as specific humidity. Obviously, (p - e) is the partial pressure of dry air.

g. Dewpoint temperature (T_d) is the temperature at which the air begins to be saturated, i.e., the relative humidity reaches 100%.

h. Wet-bulb temperature (T_w) is the temperature indicated by the wet-bulb thermometer, where the source of water is unlimited.

i. The virtual temperature (T_v) is the temperature at which dry air would have the same pressure and density as air with the present humidity and temperature. It may be found by the approximate equation

$$T_v = T(1 + 0.61\ q) \qquad (2\text{-}9)$$

where T is the absolute temperature of the moist air and q is the specific humidity.

Of the above expressions, those which indicate the degree of saturation (namely, relative humidity and vapor pressure deficit) are the best parameters of air humidity for the study of plant and animal responses. In other words, the absolute value, such as specific humidity or mixing ratio, is less important than the relative value, but is useful for synoptic and dynamic meteorology. Unfortunately, this idea has been neglected and misused.

2.2.3 *Mass exchanges*

Mass exchange may be defined as the movement of air, water, or soil from one place to another by means of driving forces such as gravitational, frictional, Coriolis, and molecular forces. Mass ex-

[30]It shows the variation of saturation vapor pressure with temperature over either water or ice.

change may occur in air, water, or soil. Some mass exchange processes require a period of several hundred years to achieve completion, while others need only a few seconds. For example, transfer of a large amount of air by mass exchange in the upper atmosphere might proceed at a rate of 50 miles per hour or even much faster, but to achieve a noticeable accumulation of loess[31] might require thousands of years. Wind is apparently responsible for the transfer of air, dust, and moisture in the atmosphere. In the soil, mass movements of water, air, and soil occur. Runoff and subsurface runoff are phenomena of mass movement of water in a horizontal direction; percolation and infiltration are phenomena of vertical mass movement. The upward movement of water in the soil is known as capillary action. The flow of water in a water table represents mass transfer of water in a water medium. The movement of ions by flocculation and dispersion involves mass transfer of ions as well as soil particles in the soil medium. Soil erosion is the movement of soil particles along the soil surface. The exchange of oxygen and carbon dioxide at the air-soil interface is another example of mass exchange. A detailed explanation of mass exchanges will be given in Chapter 4.

[31]Wind-blown dust in large quantity blown from the Great Plains and Alluvial Flood-Plains largely to the North Central regions of the United States. Originated from a German word, "der Loss," a deposit of fine yellowish-gray silty loam found in the Rhine and other river valleys.

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CHAPTER 3

Fundamental Considerations in the Biological Processes

3.1 GROWTH AND DEVELOPMENT IN PLANTS

It is necessary to differentiate the word "growth" from "development," for the two differ basically. Growth refers to an increase in weight or volume of a certain organ of a plant, or a plant as a whole, within the time interval of a certain phase or an entire life span. Development is the appearance of a phase or series of phases during a plant's life cycle. For example, the flowering of a plant is "development," while the elongation of a stem is "growth." In considering the plant growing season, one can recognize that growth is a continuous function and that development is a discontinuous one.[1] Regarding the changes of chemical and physical plant composition, growth gives quantitative changes but not profound qualitative changes. Development, on the other hand, indicates the progress of a series of qualitative changes (with or without external changes) throughout all different stages until death. Thus, it follows that the growth of a plant can be measured by the elongation of stem and shoot, the increase of dry and fresh weight, and so forth. However, development is usually observed by the date of germination, the date of initiation of floral primordia, the date of inflorescence, and that of fruiting. In other words, a study of the development of a plant is a more or less morphological and phenological approach, but that of growth is generally physiological and ecological. Plant physiologists may consider growth a complex phenomenon and a process hard to define. For growth connotes all and any of these aspects: reproduction, increase in dimensions, gain in weight and cell multiplication, and others. It depends upon the kind of individual organ taken

[1]Strictly speaking, development may also be recognized as a continuous function provided both the visible and the invisible phenological phases are considered. It should be taken as a discontinuous function for most agricultural practices because the invisible phases are difficult to detect.

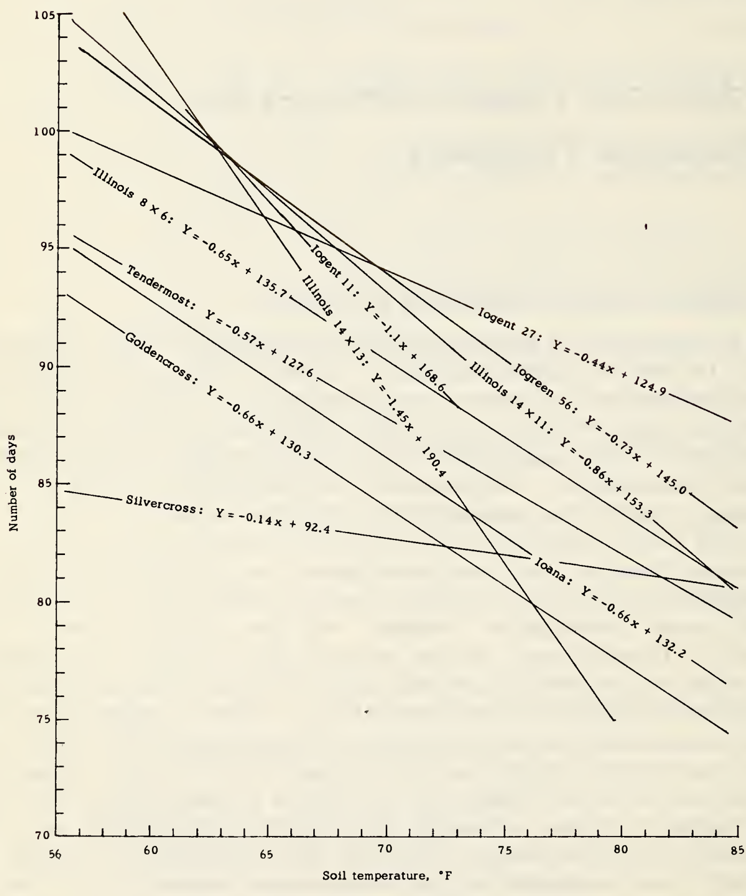

Fig. 3-1. Soil temperature as a factor for the determination of corn maturity date — a linear relationship.

as a measure of growth. In the case of germinating seeds and sprouting tubers, the total dry weight of the young seedling and seed combined, or of the sprout and tubers, is less for a period than the weight of the original seed or tuber, due to respiration. However, Miller (1938) has defined growth as a permanent increase in weight, attended by a permanent change in form, induced primarily by an increase in the quantity of protoplasm. In agrometeorology the best definition of growth is: the increase in weight or dimension of an organ which is most sensitive to environmental changes. In common agricultural practice, vernalization, winter chilling, and the breaking of dormant seeds or buds are problems of development and not growth. Since these are essential problems in agriculture, an investigation of the development-environment relationship would be an important research project.

The following illustration serves the purpose: Wang (1958, 1960) has studied the morphological development of the subterranean ears of sweet corn at the early vegetative stage in connection with their maturity date. Emphasis was placed on the choice of a significant element out of a group of environmental factors as well as that of a significant period around the seedling stage of sweet corn. A test was set up for ten different sweet corn varieties for a period of 13 years (1938-50) in Ames, Iowa. It was found that the subterranean ears initiated underground on the stem became functioning ears if environmental conditions were favorable. Thus, (a) the time interval for the first 12 days after planting would be the significant period;[2] (b) the soil temperature should be one of the significant elements; and (c) a family of curves, obtained by plotting the mean soil temperature during the significant period against the number of days of growth for each year and for each individual variety, serves as the predictor. This is shown in Fig. 3-1. In fact, each curve characterizes the varietal differentiation. In short, this method attempts to predict the maturity date of sweet corn about two months or more ahead of time by virtue of the concept of the physiological predetermination through the developmental process. A comparison of this method with that of the heat unit approach has been worked out by Wang (1958), who pointed out that the former is superior to the latter in its accuracy, earliness, and simplicity.

3.2 PHASIC DIVISIONS AND THE PLANT LIFE CYCLE

Some fundamental concepts of biological processes other than growth and development of a plant are also important in agrometeor-

[2]This 12-day period is arbitrarily taken for the best result of the present experiment. This period includes the date of planting. As to the number of days necessary for any other experiment, further investigation is needed.

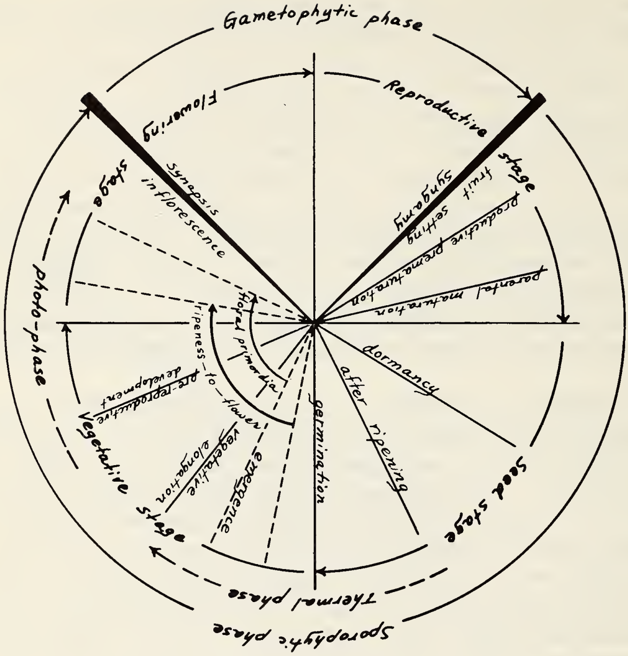

Fig. 3-2. Life cycle of an annual plant.

ological research and will be discussed in the last section of the present chapter. This section deals with the classification and significance of the phases and stages in a plant life cycle. In general, the life cycle of an annual plant as interpreted by various authors (Azzi, 1956, Whyte, 1960, and others) can be divided into four stages as shown in Fig. 3-2.

The four quadrants of Fig. 3-2 merely indicate the sequences of the life cycle of an annual plant and do not represent the duration of each sequence. Terms used for various stages such as seed, vegetative, flowering, and reproductive, are similar for all annuals. However, the phasic division, as well as the responses to environmental effects, will be quite different from one plant to another. Also, there are controversies regarding the responses of thermal phases and photo-phases related to various ages of a plant. These phases appearing in Fig. 3-2 are arranged to represent the general opinion of most authors. Whyte (1960), for example, gave some detailed discussions of these controversies.

The following are essentials for the understanding of plant phasic divisions:

3.2.1 *Basic assumptions and evidence*

Lysenko (1935) postulated the theory of phasic development of plants according to the assumptions that (a) growth and development are not identical phenomena, (b) the entire process of the development of an annual seed plant consists of individual stages, or phases, (c) these stages always proceed in a strict time sequence so that a stage, or a phase, cannot set in until the preceding stage has been completed, and (d) different stages of development of the same plant require different environmental conditions for their completion. Klebs (1918), Kidd & West (1918-1919), and Tincker (1924) proposed and supported the theory of physiological predetermination of plants. This theory emphasizes that environmental effects in the seed stage as well as in the seedling stage determine the growth and development of the vegetative and the reproductive stages. Valuable results from this theory for modern agricultural practices are vernalization, winter chilling, and various treatments of seeds. Various field and greenhouse experiments performed by many modern workers have proved that phasic division is a necessary step in the study of plant responses. For example, moisture is an extremely important factor for the growth of sweet corn at and just prior to the reproductive stage (somewhere around tasseling and silking). It is not so important at other stages, but when too much moisture is applied at the early stage it may have a negative effect.

Fig. 3-3 is used to illustrate the responses of vegetable crops to environmental factors at different phases. The crops are classified according to the economic importance and uses of vegetable parts: earth vegetables (roots and underground stems), herbage vegetables (the green foliage or the flowers, buds, petioles, and stems), and fruit vegetables (fruits and seeds). The responses of crops to environments are listed according to this classification as "significant periods," "significant elements," and "types of effects." "Significant period," used here, refers to a certain period of the life of a plant in which the effects of environmental factors are especially crucial for such phenological events as yield, quality, flowering, and growth. "Significant elements" refers to certain environmental factors which dominate that period concerned. The symbols M, T, S, L, W, and D represent moisture, air temperature, soil temperature, light, wind, and daylength; e and d stand for excess and deficiency. Hence, "Me" reads "moisture excess," and "Td," "temperature deficiency." "Significant effects" refers to total effects of favorable and unfavorable conditions of the environment on the growth and development of plants. Y, Q, G, and F stand for yield, quality, growth, and flowering. Here no quantitative values can be given to the symbols, nor do these symbols convey all environmental requirements, because they are subject to change with species, varieties,

	Events of Crops			Environmental Factors
CLASS OF VEGETABLE	PHASE	SIGNIFICANT PERIOD (or stage)	TYPE OF EFFECTS	SIGNIFICANT ELEMENTS[3]
(1) EARTH VEGETABLE:	i - Planting	I	G	Me, Md, Sd
	ii - Germination			
	iii - Underground Part Initiation	II	G	Me, Md, Td, Ld
	iv - Flowering	III	G, F, Q	Me, Md, Te, Td, Le, Ld, De, Dd, We
	v - Maturity	IV	Y, Q	Me, Md, Ld, De, Dd
(2) HERBAGE VEGETABLE:	i - Sowing	I	G	Me, Md, Sd
	ii - Germination	II	G	Me, Md, Td, Ld
	iii - Grand Rapid Growth	III	G, F, Q	Me, Md, Ld, De, Dd, We
	iv - Flowering	IV	Y, Q	Me, We, De, Dd, Ld
	v - Seed Production			
(3) FRUIT VEGETABLE:	i - Sowing			
	ii - Germination	I	G	Me, Md, Sd
	iii - Lateral Branching	II	G	Md, Ld, Td
	iv - Fructification			
	v - Initial Stage of Maturity	III	Q, F	Md, Le, Ld, De, Dd, We, Td
	vi - Full Maturity	IV	Y, Q	Me, Td, Le, Ld, We

[3] M, T, S, L, W, and D represent Moisture, Air Temperature, Soil Temperature, Light, Wind, and Day Length; e and d stand for excess and deficiency.

Fig. 3-3. An illustration on division of phases for vegetable crops.

and interrelationships between environmental factors. Also, symbols, such as M, T, S, L, W, and D, should be further specified. In other words, Fig. 3-3 shows only the relative significance in phasic environmental requirements in a generalized manner. In regard to applications, which will be discussed in Part II, there are many controversies. For example, in coffee plantations, abundant rainfall during the stage prior to flowering is advantageous, while high wind and temperature are detrimental. But rainfall will be harmful to premature flowering. During the reproductive stage (flowering to fruit setting), rainfall is also harmful and a dry clear sky is highly favorable; yet clear days accompanied by high wind will seriously interfere with fruit setting. After setting to maturity, abundant rainfall is an important factor; however, humid rainy days will encourage the development of *Stilbum Flavidum* (a disease very harmful to coffee). Therefore, specification is absolutely necessary. Studies on phasic division of plants with specification will be employed throughout this book.

3.2.2 *Visible and invisible phases*

Most phases and subphases[4] of a plant are recognizable morphologically, but some are not apt to be seen by the naked eye. Among those which can be seen are emergence, tasseling, and silking of corn, and emergence, flowering, and fruiting of peas. They are examples of visible phases. Those which cannot be seen by the naked eye are vascular bundles, tip covers,[5] and the formative stage of corn, as well as the grand-rapid-growth stage and the maturity of peas. They are examples of invisible phases. Of these, some can be measured with an instrument — the maturity of peas can be measured by a tenderometer — while the formative stage of corn must be measured indirectly by counting the number of leaves and the height of the plant, etc. In some cases, invisible phases are more important than visible phases and they should be carefully measured or determined by indirect means, such as the date of first leafing and number of leaves present. For further discussion, the reader may refer to Chapter 6, on detectable and undetectable events.

Obviously, success in dividing the phases of a plant relies upon the exactness of phase determination, or "sharpness of phases."

3.2.3 *Sharpness of phases*

The choice of suitable techniques for determination of phasic development should be further investigated; for example, the measure-

[4] A phase refers to any conspicuous phenological event, such as tasseling or silking of corn. A subphase is the further division of a phase, e.g., the tasseling phase can be subdivided as tassel emergence and tassel pollen shed. A stage, on the other hand, refers to the time-interval between two successive phases, for example, from seed to germination is seed stage. Usually, the words "significant period" refer to "significant stage."

[5] The distance from the end of the corn cob to the tip of the husks.

ment for maturity of peas by means of alcoholic insoluble products (AIS) would be far more accurate than a tenderometer reading (T. R.); however, the former is not practical because it is a time-consuming process. In the visible phase, blossoming in a field of crops could occur at different time intervals varying from one day to two weeks. Thus, observation must be expressed in percentage of occurrence of a certain phase in the field. To obtain the correct percentage without sacrificing the sharpness of phases, the results of field observations should be plotted against time, and the portion of the curve with the greatest slope is usually the region representing the correct percentage, as illustrated schematically in Fig. 3-4. The ordinate of Fig. 3-4 indicates the accumulated percentage frequency of occurrence of a certain phase, e.g., flowering, while the abscissa represents the calendar date of the occurrence in a specific year (from the beginning to the end of a phase). This is simply because the change of percentile with time increases rapidly there. Unfortunately, the measurable changes of both visible and invisible phases are usually determined by rather primitive and subjective means. For instance, the ripeness of green peppers can be tested by pressing with the fingers, while the maturity of most small grains can be tested either by rubbing between the fingers or biting with the teeth. These measurements are not sharp. The criteria for sharpness of phases are:

(a) Determinations must be objective.
(b) Determinations must be accurate.
(c) The beginning and ending of a phase for the same variety in the same field should occur in a short interval of time, not more than a day or two.
(d) The method for phase determination should be as simple as possible.

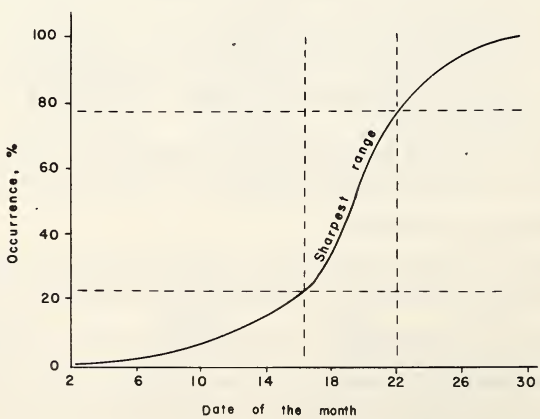

Fig. 3-4. Schematic diagram illustrating the sharpness of phase.
After Wang, 1958

To be objective, again using peas as an example, both the tenderometer (a mechanical means) and alcoholic insoluble products (a chemical means) should be used to measure the maturity of canning peas. However, the tenderometer reading for phase determination is much simpler than alcoholic insoluble products procedures, although the latter method is much more accurate than the former. Half silking date of sweet corn is also quite accurate and fairly objective, even though it is observed by the eye. The occurrence of half silking is usually observed within one day in a whole cornfield. The customary farm practices on the maturity of small grains and the like (namely, biting with the teeth, rubbing between the fingers, etc.) are definitely subjective.

Thus, various techniques should be developed to determine the sharpness of phases and subphases accurately so far as environmental factors are concerned. Clements (1943) in Hawaii found that the sugar content on the sheath of sugar cane was a better indicator of environmental effects than any other organ of the plant. Clues for detecting a special organ can be obtained by chemical, physical, physiological, and morphological techniques. For instance, physical techniques involve mechanical measurements of the tensile, compressive and shearing stresses of certain plant parts, e.g., the tenderometer reading of canning peas is the result of a test on the shearing stress of the seeds. Other physical properties can also be used — thermal capacity and electrical conductivity, optical polarity and spectral analysis, etc. A color scale display would be an appropriate indicator for the degree of maturity of most fruits, i.e., the optical properties on the spectral analysis. Furthermore, the accustic measurement of the pitch as well as the impedance measurement of a certain organ of a plant, e.g., tapping a watermelon for maturity, would be another angle for the application of physical techniques in determining the sharpness of phases. Physiological and morphological techniques can also be very useful in some respects. As was mentioned in the beginning of this chapter, the development of morphological techniques in the study of the relationship between the subterranean ear-shoot and the functioning ear would be important toward the forecasting of sweet corn maturity.

Finally, classical indicators for determining the sharpness of phases sometimes are good enough to meet the requirements of the above-mentioned criteria. They are usually set up for the best quality and maturity. In the case of cauliflower, for example, the classical criterion used is when the heads attain the proper size and before they begin to "rice" or become discolored. For Snowball No. 16 (cauliflower variety), this would be about a 2 lb. head, $6\frac{1}{2}$" in diameter; for Snowdrift, a 2 lb. head, 7" in diameter; for Super-Snowball, a $1\frac{3}{4}$ lb. head, $6\frac{1}{2}$" in diameter, for the best quality of maturity. In order to indicate all phenological events instead of simply maturity and quality, an improved indicator is needed for each phase and each kind of crop.

3.3 PHYSIOLOGICAL RESPONSES IN ANIMALS

The word "animal" in its broadest sense used here includes livestock, domestic fowl, pests, and their relatives.

In this section we will discuss first the differentiation of animals from plants in their responses to environment, and types of research on animal-environment relationship; secondly, the radiation and temperature regulation processes concerning internal and external heat transfer, and thermal control; and finally, considerations of factors other than temperature and radiation affecting the physiological functions of animals. Specific discussions related to the methodology and applications for individual livestock, domestic fowl, and their pests are dealt with in later chapters.

3.3.1 *General considerations*

(a) Animal versus plants. With respect to environmental studies, the differences between animals and plants, which are numerous and sometimes obvious, may be summarized as follows:

(1) By and large, animals in their natural environment associate with a larger variety of climatic conditions, while plants are rather restricted to local, microclimatic conditions. In other words, the study of micro-, meso-, and macro-climate will be all-important to animals, due to their high mobility. To plants, only the microclimate of the air and the soils are considered to be important.[6]

(2) Therefore, animals are susceptible to the adaptation of the optimal climatic conditions in which they seek comfort.

(3) The sensitivity and the type of the responses of the animal to the environment are greater than those responses of plants. Also, there is a wide range of responses in animals. For example, sexual differentiation in environmental responses is highly significant in animals, but not in plants.

(4) Most animals have nervous systems and sensory organs of hearing and seeing; therefore, the acoustic and optical properties of the environment are important to animals.

(5) The physiological functioning of animals is much more complicated, e.g., most of them except the cold-blooded animals are capable of regulating the temperature and radiation. Further complications are due to the fact that there are many more topics to be studied in animals than in plants. In plants we have only yield,

[6]Strictly speaking, according to the broad definition of animal in this section, some animals also are confined to a small environment (microclimate), such as earthworms in the soil and domestic fowl in the poultry house.

quality, blossoming, growth, and the like, but in animals there are very many items to be studied.

(b) Animal-environment response studies. The literature on animal-environment response studies in agricultural meteorology, which are confined mostly to research under controlled environmental conditions, is more voluminous than that of plant studies. In general, body temperature, respiration rate, reproductive efficiency, blood composition, and endocrine activities of the physiological responses of domestic species are the most common subjects. Other studies discuss adaptability of various breeds of animals to climatic extremes, and ameliorating thermal stress on animals by such physiological means as shading, sprinkling, and mechanical air circulation.

In cattle, studies have been directed primarily at the relative tolerance tests of individuals or groups, the characteristics responsible for differences observed between individuals and groups, and the distribution of adaptability within existing breeds and groups. Since cattle are relatively cold-tolerant but respond to temperatures of 80°F and above, most attention has been focused on conditions in this upper range. The varietal differentiation in cattle is important.

For swine, which lack sweat glands, studies on the effects of temperature, humidity, and solar radiation on physiological processes have been directed toward controlling extremes of these factors by proper housing, wallows, etc. Diseases and parasites of swine which are influenced by meteorological factors have been more thoroughly studied than similar diseases and parasites in other animals.

In sheep and goats, reproductive activity and fertility have been the factors most intensively studied in relation to the physical environment, particularly temperature. Wool production and wool quality are other common topics. Still other studies deal with the comparative responses of sheared and unsheared sheep to temperature effects. A lesser amount of research has been devoted to horses, rabbits, etc.

In poultry, studies on the effect of temperature, light quality, day length, humidity, thermal radiation, and many other environmental factors are the main features. The physiology of poultry involves metabolism, fertility and hatchability, egg production, brooding, growth and feed consumption, feathering, molting, respiration, sexual development, breeding, disease and parasites, and mortality. Domestic fowl includes chickens, turkeys, ducks, geese, pigeons, guineas, and others. Among them, of course, chickens are of major importance. Considerable research has been devoted to defining the optimum range of conditions for poultry production. Attempts have been made to adapt indigenous and imported poultry, especially chickens, to conditions prevailing in a particular area of the world by modifying housing and equipment.

Pests, which may include fungi, bacteria, viruses, insects, arachnids, nematodes, and similar organisms, attack plants and animals. Those invertebrates and microscopic organisms beneficial to man, which may be termed as "relatives of the pests," are bees, earthworms, flower-pollinating insects, mushrooms, and antibiotic-producing fungi. Studies of fungi, viruses, and bacteria as related to environmental factors are numerous. Control programs of spraying, avoiding favorable (disease) areas, and testing for disease resistance are the major topics of research. Diptera (flies and mosquitoes) respond to light, for example, with wavelength of 3200 to 4000 Ångströms (Å). With some species the highest catch is at about 3650 Å, for this near-ultraviolet region of the spectrum is the most sensitive region for insect eyes. Synoptic weather patterns, such as cyclonic and anticyclonic actions associated with air pressure change, air movement, and frontal systems are significant to insects (Wellington, 1954) and diseases (Bourke, 1957), but of only secondary importance to farm animals. Furthermore, Wellington (1954b), in his study of forest entomology found great diversity in environmental requirements among insects. He used the forest tent caterpillar, *Malacosoma disstria*, Hbn., and spruce budworm, *Choristoneura fumiferana* (Clem.), as illustrations. The outbreak of the former follows southern and southwestern air and moderately warm, humid, partly cloudy and prolonged rainy weather; that of the latter follows northern and western air with dry, sunny weather.

(c) Some significant physical aspects. It is well known that warm blooded animals (homoiothermous animals) keep a constant body temperature until death, with slight variations at various times of the day and occasional high temperature upon illness. In some homoiothermous animals, such as the cat, dog, rabbit, and bird, the heat-regulating mechanism is not operative at birth. The young animals are somewhat cold-blooded (poikilothermic) at birth and continue to be so for some days (Rogers, 1938). However, for most of the homoiothermous animals a constant body temperature represents a balance between heat production and heat loss. This may be termed "heat balance." In general, it may be stated that the physiological operations leading to heat production are chemical; those leading to heat dissipation are physical. The major chemical process taking place in all parts of the animal body for heat production is oxidation, known as the metabolic process. Metabolic heat is produced more rapidly in younger than in older animals, in smaller than in larger, and in females than in males. Under normal conditions, when body temperature is not changing, "heat gain" occurs by receiving short and long wave radiation and by metabolic processes, while "heat loss" occurs by evaporation and infrared radiation. On the other hand, when the body temperature is changing, the surface-weight ratio is of great importance in determining the rate of change. Thus conduction, convection, and the albedo of the surface (depending upon the skin color and the coat characteristics, such as woolly-coated versus curly-coated animals) should also be considered.

For cold-blooded animals, the changes in body temperature depend upon the environment, the metabolic heat, and the mobility of the animal. In some cases the skin structure protects the deeper layers of the body (for example, the reptile's skin is opaque to radiation). No generalization can be made for all animals as far as heat balance is concerned. Nevertheless, cold-blooded animals are definitely poor in control of body temperature, which tends to approach the environmental temperature. Change of body temperature of bees ranging from 57° to 69°F has been reported by thermoelectric measurement. Likewise, when lizards bask in the sun the body may be warmed to as much as 68°F higher than the initial body temperature.

In studying physiological responses of warm-blooded animals, the establishment of a single heat budget equation is helpful in two ways: (1) it will facilitate research in making the first approximation of metabolic heat computation, and (2) it will be of importance as a guide for engineering design. A heat budget equation is a process of equating "heat gain" to "heat loss." Since the change of body temperature[7] ($\dot{B}$) with time is small (because of the thermoregulatory ability of warm-blooded animals), and since both the mean specific heat ($\bar{c}$) of the body and the mass (m) of the body is large, the product of the three, or $m\bar{c}\dot{B}$, is near to a constant value. The metabolic heat (M) produced is equal to the difference of ($m\bar{c}\dot{B}$) and heat transfer (T) which is a process to propagate heat to (or from) the body of an animal. The value T is positive when heat is moved *away* from the body (or the skin of an animal). This is a cooling process. When the heat is transferred *toward* the body, T is negative, hence

$$M = m\bar{c}\dot{B} - T. \tag{3-1}$$

In the following equations, T may be considered as the algebraic sum of the radiating heat R, the convecting heat C, the evaporating heat E, and the conducting heat K:

$$T = R + C + E + K. \tag{3-2}$$

Terms to the right of equation (3-2) can be expanded as:

$$R = f_1 f_2 \sigma (T_s^4 - T_a^4) S_1 \tag{3-3}$$

$$C = C' V^n (T_s - T_a) S_2 \tag{3-4}$$

$$E = E' V^n (v_s - v_a) S_3 \tag{3-5}$$

[7]The normal body temperature of all breeds of cattle is generally accepted as 101°F, according to Brody. See S. Brody. 1945. ***Bioenergetics and Growth***. Reinhold Publishing Co., New York. 972 pp.

$$K = K'(T_b - T_s)S_4 \qquad (3\text{-}6)$$

Each of the above equations can be expressed by cal per sq cm per minute in terms of the metric system (C. G. S.). The reader may transfer to the British thermal unit (Btu ft^{-2} hr^{-1}) for convenience of engineering use. The sign notation is the same as that of the T value stated above, since the algebraic sum of equations (3-3) to (3-6) is equal to T. Symbols used in these equations are:

f_1 = shape factor, or the percent of the surface exposure of the animal for radiation, in %;

f_2 = emissive power (radiant emittance) of the animal, in watt cm^{-2};

σ = Stefan-Boltzmann constant = 8.17×10^{-11} cal cm^{-2} $°K^{-4}$ min^{-1};

T_s = animal surface temperature (or skin temperature), in °K;

T_a = ambient air temperature (or temperature of the surroundings in the case of the radiation heat transfer), in °K;

T_b = internal body temperature of the animal, in °K;

S_i = the effective surface for R is S_1 and for C is S_2 and the like (thus, the size of the surface is conditioned by the type of heat transfer), and is expressed in square centimeters. In general, the body surfaces can be calculated from the formula used by Meeh, $S_i = KW^{2/3}$, where S_i is in sq cm, W is the weight in kilograms, and K is a constant and is expressed in $cm^2 kg^{-2/3}$. The values of K are 10.5 for calf, 12.1 for sheep, 8.7 for pig, 8.5 for Guinea pig, 10.4 for fowl, 12.0 to 12.9 for rabbit, and so forth.

C' = convection coefficient (which is a function of the surface characteristics and the shape of the animal), in cal $cm^{-(n+4)}$ min^{n-1} $°K^{-1}$;

V^n = air velocity passing by the skin of the animal, cm min^{-1}, with nth exponent;[8]

E' = evaporation constant, in cal $cm^{-(n+4)}$ min^{n-1} mb^{-1};

K' = over-all coefficient of heat transmission of the animal body, in cal cm^{-4} min^{-1} $°K^{-1}$;

v_s = partial vapor pressure of water at the skin surface of the animal, in mb;[9]

v_a = partial vapor pressure of water in the air, in mb.

[8] The exponential n should be determined by the species of animal.

[9] 1 mb = 3/4 mm of mercury.

In equation (3-1) above, when the heat transfer term (T) is positive, more metabolic heat[10] per square centimeter per minute should be produced in order to maintain the constant body temperature (B). When (T) is negative, less metabolic heat[11] will produce or increase respiratory activity and other heat consumption processes in order to release the excessive heat. Terms used in the above equations obey strictly physical laws; however, their physiological significance should be further investigated. Equation (3-1) is valid only within the upper and lower lethal temperatures for survival. Equations (3-1) to (3-6) are basic equations though all the terms have not yet been determined. For example, experimentally the term $m\bar{c}B$ can be determined without measuring each individual factor, namely m, $\bar{c}$, and B; however, the accuracy of measurement depends upon the observational techniques. Sometimes, during the observation, animals become excited, which results in a "higher" temperature.

3.3.2 *Differentiation in physiological responses*

Different species of animals respond differently to the same type of environment. Heat and radiation are the two primary factors in animal response studies, while other factors such as rainfall, relative humidity, and wind are secondary.

(a) Heat and radiation. As has been stated in the early part of Chapter 2, it is temperature instead of heat and it is light instead of radiation that have been employed in plant response studies. This is true, too, with animals. Also in Chapter 2 it has been pointed out that heat is always associated with radiation and the two cannot be separated; therefore, these two will be discussed jointly in the present section on the response of several domestic animals.

Technological advances offer the possibility of creating microenvironments which approach optimal conditions of light and temperature for maximum production, reproductive efficiency, and health in domestic animals. These factors have been studied mostly under controlled conditions.

According to the experience of many researchers in natural field conditions, the body temperature of European dairy cattle breeds increases with increasing ambient air temperature above 70°F. When the ambient temperature reaches 80°F and above, a marked effect would be a depression of appetite and, in turn, reduction of milk production. High light intensity might be the major cause of decreased appetite, and therefore suggestions have been made to pasture cows

[10]The amount of metabolic heat produced should be at least $m\bar{c}B - T$ calories per sq cm per minute in order to secure the heat balance.

[11]According to theoretical considerations, T less metabolic heat probably will be produced.

during darkness in tropical weather. Of course, high temperature will cause a depression of thyroid secretion rate and lower the metabolic rate. Within the temperature ranges studied, however, heat does not have a significant effect on milk composition when digestible nutrient intake is maintained. It appears that the fat percentage is slightly lowered. Furthermore, the effect of hot weather on the dairy cow may be either immediate or delayed, depending on prior adaptation of the animals and severity of the heat stress. The most striking contrasts in response to high temperature are between European and Zebu breeds. The latter, which possess the ability to utilize various means of heat dissipation, probably due to their body form, have greater heat tolerance. The physiological characteristics related to heat tolerance are respiratory rate, body temperature, surface evaporation, surface area, coat characteristics, body form, blood composition, thyroid secretion rate, heat production, skin, and hair temperature. In hot weather an increase in respiration rate is the primary mechanism for the maintenance of heat balance in most animals. Barrada (1957) concluded that the respiratory reaction of Jersey cows in a controlled chamber with 104°F temperature and 80% relative humidity for 170 minutes, and Holstein cows for 150 minutes, will reach the peak (i.e., the limit of the physical capacity of the respiratory system), after which the respiratory reaction declines. The sweat glands[12] are responsible for the supply of available moisture for surface evaporation. Temperature and light stimulating the sweating rate should be investigated. This is another mechanism of heat dissipation. The surface area[13] together with coat characteristics and body form will be still another consideration of heat dissipation. Physiological functioning with respect to heat tolerance is too complicated to be considered individually, and therefore the integrated effects should be investigated. The heat balance idea, as illustrated in equations (3-1) to (3-6), will be one example of integrated studies, if all terms have been properly determined. This is one of the basic considerations in agrometeorological approaches.

Other fundamental considerations are the climatic effects as a whole on the animal, and not just temperature alone. In other words, studies in conjunction with certain climatic types would be far more important than that of a single-factor approach. Moreover, objective measurements of animal performance with respect to breed, age, stage of lactation, and level of nutrition are necessary. The en-

[12]The major portion of moisture available for evaporation is secreted by the sweat glands, even though controversies still exist. The ability of cattle to sweat, for example, is by no means as well developed as in the horse. Sweating rate in cattle, which is the basic consideration with respect to heat tolerance, varies between species and individuals.

[13]Brahman cattle, for example, which have about 12% greater surface area than average cattle, are high heat tolerant cattle.

vironmental requirements of the phasic development of plants are analogous to those of animals. Both the young animals and the seedlings of a plant are susceptible to the cold and require high enough temperatures for survival. Hibernation is analogous to winter dormancy; estivation to summer dormancy; conception to fertilization; and lactation stage to reproductive period. These analogies emphasize the annual periodicity and sexual cycle of animals in association with their environment.

In addition to accuracy and simplicity of measurement, the choice of the right organ or parts of an animal which would serve as the best indicator of its environment is fundamental to studies in animal-environment relationships. Ideas given in the early part of the present chapter regarding "sharpness of phases" and criteria associated with them should be considered here in animals.

For most farm animals, particularly rams and ewes, the influence of high temperature, intense light, and long day duration[14] on reproduction, such as a decrease in fertility, semen quality, and sperm production, have been investigated by a number of researchers. Light has been shown to be effective by acting on the anterior pituitary gland through neural pathways from the eyes. Some researchers believe that light may act indirectly through increased wakefulness, metabolic activity and feed intake. Studies on daylength effects on animals, known as "photoperiodicity," are numerous in poultry but not other farm animals. Light stimulates egg production in fowls and the onset of sexual activity in many wild birds. Studies of light quality effects on livestock are rare, though much work has been done on plants.

Dutt & Simpson (1957), in their study of the influence of ambient temperature on the fertility of Southdown rams early in the breeding season, pointed out that high summer temperatures are responsible for the poor conception rate of ewes bred to Southdown rams. They also indicated the possibility of improving conception rate early in the breeding season by keeping rams at lower temperatures, 45° to 48°F, and high humidity, 70-80%. On the contrary, Dutt & Hamm (1957) found that the motile cells of unsheared rams after the fifth week's treatment of high temperature (90°F) and low humidity (60 to 65%) had dropped to less than 10% while the average percentage of motile cells of sheared rams ranged between 80 and 85. At the same time, the sperm cell concentration decreased more appreciably in the unsheared than in the sheared rams, but the semen quality was not

[14]Of course, in mammals, short day breeders respond to decreasing light and long day breeders to increasing light. This apparent inconsistent reaction has been reconciled by results suggesting an imbalance between the follicle-stimulating and the luteinizing hormones in the short day breeders, and not a decrease in pituitary activity while under light stimulus.

affected after eight weeks of treatment. The heat treatment resulted in an increase in the percentage of abnormal ova.

In the case of beef cattle, the most important effect of high temperature is a reduction of growth rate, presumably resulting in a lower rate of fattening (Warwick, 1958). This applies to swine and probably to sheep. Heitman et al. (1958), in their study of the influence of air temperature on weight gain in swine, stated that significant correlation coefficients between average daily gain and body weight for air temperature at 10° intervals were positive at 50° and 60° F and negative at 80° through 110° F. At 70° F, correlation at weight less than 180 lbs. was positive and significant, while at higher weights it was negative and lacked statistical significance. The relationships of their study are shown in Fig. 3-5. Data were obtained from 24 experiments in the California Psychrometric Chamber at Davis, California, involving 94 hogs and 367 hog-periods. Air temperatures ranging from 40° to 110°F were used as the abscissa and average daily gain in pounds per pig as the ordinate. Body weight ranging from 100 to 350 lbs. also entered in the diagram, as shown in Fig. 3-5.

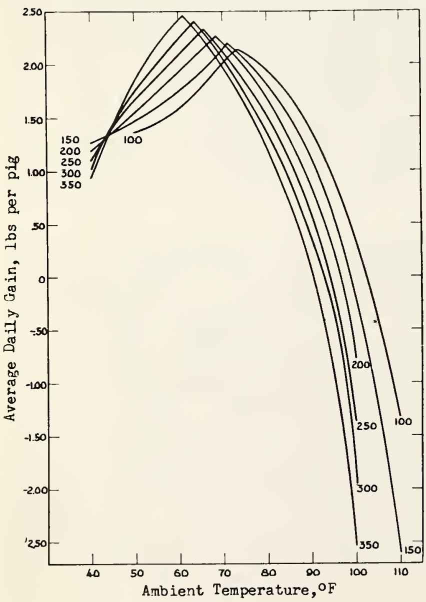

Fig. 3-5. Air temperature and body weight gain of hogs.
After Heitman, Kelly & Bond, 1958

During the past 25 years, a great many studies of physiological responses of animals to heat and radiation have been reported.[15] No attempt is made here to review all the important contributions to knowledge on this subject. However, the results on climatic physiology by Brody and his associates at the Climatic Laboratory, University of Missouri (Kibler & Brody, 1954, and Brody, 1956) will be used as illustration of the differentiation in physiological response among dairy cows. Three breeds of cattle, the European, Indian, and Santa Gertrudis, housed in climatic chambers of constant day and night temperature, air humidity, and air movement, with

[15]Wang has made a collection of over 1000 references relating to the climatic physiology of livestock, included in his ***Bibliography of Agricultural Meterology*** (1962), published by the University of Wisconsin Press.

the same wall and ceiling, were observed for differentiation in their temperature responses. The findings are that the "comfort zone" of European cows is about 30° to 60°F. An environmental temperature of 105°F increased rectal temperature to 105°F in Indian cattle, 106°F in Jerseys, and to a near-lethal 108°F in Holsteins. At environmental temperatures of 105° to 107°F, the European cows were near collapse after seven hours' exposure. The relative cold tolerance of Holsteins is indicated by a 10% increase of heat production on lowering of temperature below their comfort zone, down to 9°F. Acclimatized European cattle are cold tolerant and are not in need of protection against cold as such, but only against adverse weather, e.g., wind, snow, and rain. They do need protection against heat. For Indian cattle, the comfort zone was found to be between 50° and 80°F. The higher heat tolerance of Indian cattle seemed to be due to low heat production, greater surface area per unit weight, shorter hair, and other body temperature regulating mechanisms not visually apparent. The relative cold tolerance of Zebu cattle is indicated by a 60% increase on lowering the environmental temperature from 50° to 9°F. The Santa Gertrudis were found to be near the Brahman in heat tolerance; they grew equally well and maintained a rectal temperature only 0.4°F higher at 80° F than at 50° F environmental temperature. The Santa Gertrudis were more cold tolerant than the Indian heifers. These findings are very practical in raising cattle in the loose-housing barn.

(b) Other environmental elements. Meteorological factors other than temperature and light which have been used for physiological response studies will be reviewed in this section.

Under field conditions, humidity has little or no effect on body temperature of cattle,[16] whereas a marked effect has been found by a number of researchers in controlled chambers. The combined effect of relative humidity, air speed, and temperature on the rectal temperature of dairy cows under controlled conditions has been investigated by Kibler & Brody (1954). The air speed was regulated between 0.5 and 10 miles per hour, temperature ranged from 0 to 110°F, and vapor pressure ranged from 0 to 65 mm of mercury. Results are shown in Fig. 3-6.

In Fig. 3 - 6 the shaded area represents the "Zone of Normal Rectal Temperature." In this area, the air speed is kept at 0.5 miles per hour for 24 hours a day for a period of two weeks. Also, the air temperatures were kept between 5 and 80°F and vapor pressures between 0 and 16 mm mercury. This zone of normal rectal temperature can be extended up to a high temperature and humidity region if the

[16]The contradictory statement is that when air is humid during the night, the infrared reradiation from the ground is retarded. It follows that night temperature is high and thus soil temperature rises. In such a condition, high body temperature of cattle results, with consequent reduction of food consumption and decrease in beef and milk production.

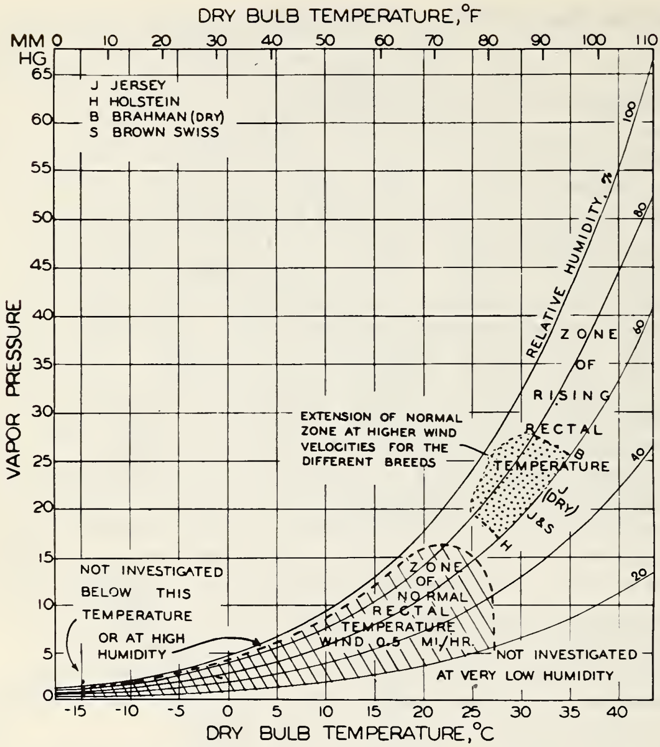

Fig. 3-6. Air movement and comfort zone of dairy cattle.
After Kibler & Brody, 1954

air speed is increased up to 6 and 10 miles per hour. This is given in the dotted area, where high air speed increases the heat dissipation. When the combination of temperature and humidity is still higher, it will reach the "Zone of Rising Rectal Temperature" indicated by the unshaded area. As far as body temperature is concerned, solar radiation is a far more important factor than wind speed and humidity.

In natural field conditions, rainfall is another factor to be considered. Rhoad (1941) pointed out that rainfall is an important factor in the case of sheep. British mutton breeds thrive in a moist, cool climate. In England the denser sheep populations are found in areas with 20 to 40 inches of annual rainfall.[17] On the contrary, in

[17]The argument to Rhoad's statements is that the high population of sheep in England may be due to better management, because the Merino breed is also popularly raised in England.

South Africa it has been found that the best wool-growing areas have less than 20 inches of rainfall and that the production of cross-breeding Merino sheep for fat lambs is possible only in areas with more than 30. It is generally recognized that the Merino breed is not adaptable to a humid environment.

Soil moisture, which is mainly a hydrologic balance of rainfall and evapotranspiration, is still another factor to be considered. The survival of eggs of worm parasites (Lucker, 1941, and Spedding, 1957), for example, depends upon a number of factors, with soil moisture of major importance. It is a well-known fact that the eggs of the round worm, in order to undergo development on pastures before they become infective to their intermediate or definitive hosts, need adequate moisture to complete the life cycle. On the other hand, if the environment is exceedingly dry, the round worm population will be definitely reduced. The reader may refer to the references given in the bibliography for further research in this area.

As was mentioned in Chapter 1, one of the purposes of agrometeorology is to transfer greenhouse techniques to the natural field. This is true in animals. However, due to complications, the controlled chamber experiments have not successfully duplicated field conditions. Therefore, the construction of a controlled chamber which will be able to reproduce a near-natural rhythm of diurnal and seasonal weather changes, such as a biotron, is necessary.

3.4 OTHER PLANT PHYSIOLOGICAL CONCEPTS

Some fundamental considerations in biological processes for both animals and plants which are basically important to agrometeorological research have been discussed in the above sections. In this section, emphasis will be placed upon the study of physical processes versus biological sequences. For example, the change of a plant medium follows mainly physical processes, while the growth and development of a plant follows physiological processes. Seeking methods to coordinate these two processes is the main purpose of the agrometeorologist. The following are some fundamental concepts used as guides for the coordination of these two processes.

3.4.1 *Constancy of biotic factors*

The assumption of the constancy of biotic factors mentioned in Chapter 2 has been proved to be most useful in the study of agrometeorology. This is one of the most important concepts in plant response studies. Some methods recommended are:

(a) Method of discarding discrete data. Some individual data which lack consistency with the rest of the data in a sample due to biotic effects should be discarded prior to statistical manipulation.

This inconsistent data must be carefully investigated and distinguished from valid data. For example, when insect, disease, and weed damages become so serious in a certain year as to cause a *significant reduction* of crop production, these years are considered as discrete bad cases and are discarded. In the case of crop yield, a significant reduction in yield might be designated arbitrarily as a yield which is one standard deviation less than the average of all years.

(b) Method of trend computation. Due to the yearly improvement of cultural practices in farm operation, crop yield is increased from time to time. It is obvious that the weather does not improve from year to year to suit the growth and development of a crop. Therefore, factors contributing to this high yield involve a number of biotic factors resulting from the improvement of various cultural practices, such as weed, insect, and disease control. In order to eliminate these factors, a linear trend line can be used as the mean yield line, as shown in Figs. 3-7 to 3-9. Fig. 3-7 shows the modification of crop data for cucumbers in Alma, Michigan, and Neshkoro, Wisconsin, for the period 1945-1959. The modified mean yield instead of the actual mean yield is used to compute the departure of yield. The modified mean yield in this case is obtained by lowering the actual mean yield a half standard deviation value of the yield to the left end of Fig. 3-7 and raising it the same amount to the right. Thus line "A" (or 25 bu/Ac)

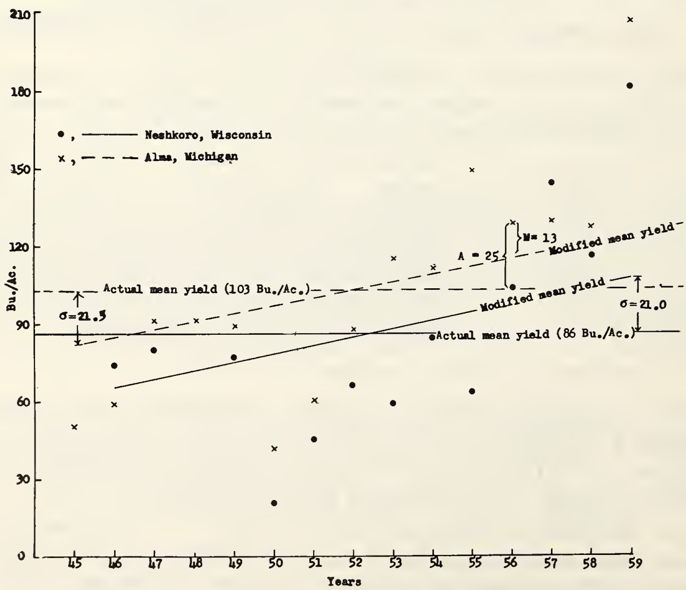

Fig. 3-7. Modification of crop data at two localities.

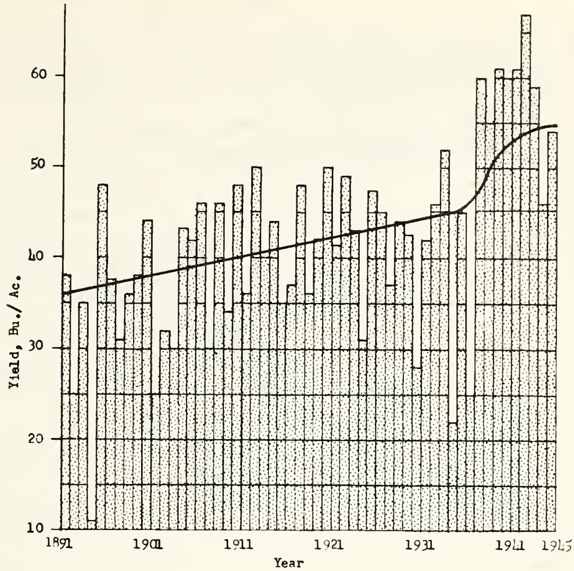

Fig. 3-8. Trend line fitted to average annual county corn yields for Ames, Iowa, showing individual years as above or below normal.
After Barger & Thom

shows the actual departure, and line "M" (or 13 bu/Ac) shows the modified departure of yield in the case of Alma, Michigan, for the year 1956. In other words, for the years 1945-1952 the departures of the yield have been increased by using the trend line. On the other hand, departures have been reduced for the years 1952-1959. Actual mean yield line and the modified mean yield line coincide at the year 1952. This means that in the year 1952 they are identical in the computation of departure of yield.

The important considerations in the modification of crop yield data depend upon a number of factors. They are introduction of new varieties, the use of new fertilizer, and the like. An excellent example of this has been published by Barger (1949) for the study of corn grown in Iowa. His diagram is reproduced in Fig. 3-8. The trend line—the heavy solid curve — has a small positive slope extending from 1891 through 1935, a parallel line at a high yield level for the period 1941 through 1944, and a curve spanning the transition era. The transition era, as called by Barger, covered the period 1936 through 1940. This is simply because prior to 1936 less than 10% of Iowa corn acreage was planted with hybrid seed, while after 1940 more than 90% was hybrid. The trend line was prepared by the least squares method, and

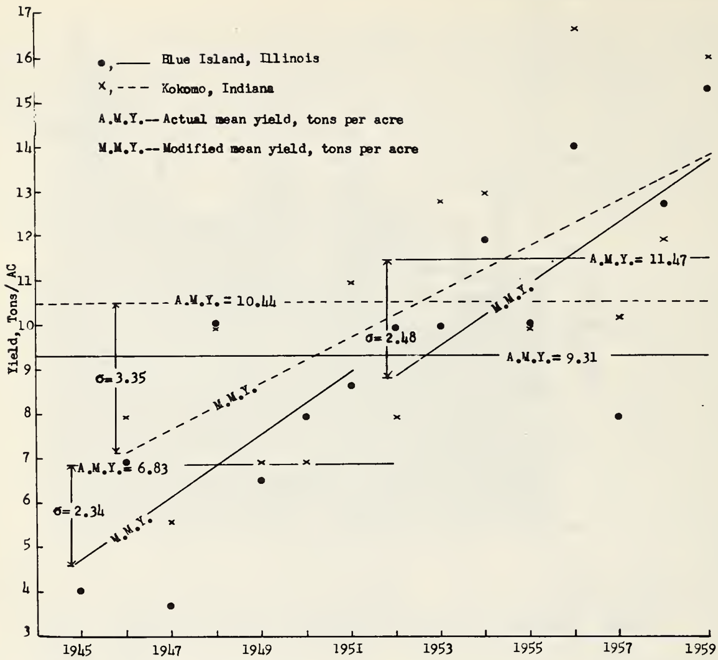

Fig. 3-9. Trend line fitted to average annual tomato yields for Blue Island, Illinois, and Kokomo, Indiana.

was fitted to the yield data for the period 1891-1933. The yields below this line have been designated as below normal, those above the line as above normal.

Fig. 3-9 shows the trend line of tomato yields for Blue Island, Illinois, and Kokomo, Indiana. The notation used is the same as in Fig. 3-7, except that one standard deviation, instead of half a standard deviation is employed. This is because there is more variability of yield in tomatoes than in cucumbers. In other words, the number of standard deviations used for making the trend line is decided by the fluctuation of yield from year to year so that the number of cases above the trend line will equal or nearly equal that below. In the case of Kokomo, we have a single trend line, while for Blue Island the double lines work best. In the latter case, no single trend line will be able to divide cases equally.

It seems improbable that a constant rate of increase in yield will occur over a number of years as illustrated in the above examples. However, due to the constant demand for increase of yield by farmers and growers, a constant rate of increase in yield would be a logical assumption to follow, if no other information is available. This procedure is certainly better than ignoring the trend. In fact, many crops have been tested by this constant trend method and the results were definitely improved, even though not all unwanted biotic factors have been eliminated.

Aside from the application of the constancy of biotic factors concept in historical data analyses, it is advisable to establish a constant biotic environment. A near constant environment can be achieved by using the same variety of crop with the same genetic seed from year to year, by keeping seeds in control chambers to assure constant physical environment in storage, by applying identical cultural practices, and by maintaining the same rotational system in the same type of soil from year to year.

3.4.2 *Physiological constants and variables*

In order to analyze these complicated processes, it is necessary to reduce variables and establish constants. Some of the physical variables such as relative length of day and night, quality of light, presence of oxygen and carbon dioxide in the air, and soil temperature at a depth of 20 inches or more (for most regions in Wisconsin), can be considered nonvariable, if a five-day or one-week range of time is used. Even if they vary, the variations are probably too small to be of significance to crop growth and development. These are examples of constants in the environment. On the other hand, Veihmeyer (1950) claims that the ratio of the monthly use of water by crops, in inches, and the monthly evaporation for each group of crops is constant, being independent of the total leaf area and also of crop height. Azzi (1956) has announced that the product of the interval of time (in hours) between "the germination to the beginning of leafing" and "the beginning of leafing to the phase of maximum weight" for a certain variety of corn is constant. Van't Hoff & Arrhenius found that for each temperature rise of 18°F, the rate of the reaction involved increases by a multiple of two. These are examples of physiological constants. Workers using the heat unit system claim the existence of a varietal constant of heat sum in several crops. Plant physiologists consider that limiting as well as retarding factors are constants with respect to a certain variety of plants and a certain set of environmental conditions. Nevertheless, the author regards all of the above relationships as quasi-constant. In fact, none of the above "constants" has ever been proved to be constant under all conditions.

On the other hand, examples of physical and physiological variables are much greater in number than constants. All of the constants for physical and physiological factors have been mentioned above. Remaining variables include temperature and moisture of the physical parameters, and transpiration and photosynthesis-respiration relationships of the physiological parameters. They are not only multiple in number but are also subject to change, for diurnal, interdiurnal, and seasonal variations exist within them. Thus, variables are even harder to treat than the relationships mentioned in the previous paragraph; however, it is still possible to simplify them into two large categories: "continuous values" and "discontinuous values."

3.4.3 *Continuous and discontinuous functions*

Those environmental and biological factors or variables which change continuously with time are continuous in number, while those which change abruptly with time are discontinuous, or discrete, in number. Examples for the classification of physical and physiological variables in this manner are tabulated as follows:

Table 3-1. Examples of the Continuous and Discontinuous Functions of Physical and Physiological Variables

Physical Variables	Physiological Variables
Continuous	
i. Air and soil temperature.	i. Growth (mean growth for the whole growing season).
ii. Air and soil moisture.	ii. Metabolism (anabolism and catabolism).
iii. Wind (intensity and direction).	
Discrete	
i. Frost.	i. Growth (diurnal and between phase)
ii. Fog and smog.	ii. Development.
iii. Precipitation (intensity and frequency).	iii. Transpiration.
iv. Cloudiness.	iv. Photosynthesis and respiration
v. Dew.	v. Translocation.
	vi. Absorption, etc.

3.4.4 *Functional relationships*

The functional relationships and interrelationships between physical and physiological processes should be known in order to link the two processes. Photosynthesis, which is a physiological process, can be used as an illustration. The essential conditions of this process are functionally related to the physical elements. The following tabular form is so numbered that each physiological condition, as a function of one or more physical elements, is clearly shown.

It can be expressed as P is a function of (E, O_2, CO_2, H_2O, T, S, Ch, etc., . . .). In the case of photosynthesis it reads that the photosynthesis process is a function of radiation energy, oxygen and carbon dioxide content, water presence, air temperature conditions, soil temperature situation, chlorophyll amount, and many others. It is advisable to make certain that these conditions are also function-

Table 3-2. Examples of Physiological versus Physical Processes

Physiological conditions (P)	Physical elements, or processes
i. Radiation energy, restricted to visible light, (E).	i. Cloudiness; air pollution.
ii. Oxygen, (O_2).	ii. Diffusion; wind direction; soil temperature and moisture.
iii. Carbon dioxide, (CO_2).	iii. Same as ii, above.
iv. Water, (H_2O).	iv. Precipitation; evapotranspiration.
v. Temperature, (T).	v. Wind; solar intensity.
vi. Soil temperature, (S).	vi. Air temperature; solar intensity; soil moisture.
vii. Chlorophyll, (Ch).	vii. Quality of light, temperature, and water.
viii. Others.	viii. Others.

ally related to several essential physical elements, as indicated in Table 3-2.

In order to solve this type of complex, an agrometeorological treatment involving single factors, multiple factors, and combinations of factors is suggested. These will be studied in Part II of this book.

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CHAPTER 4

Microenvironments and Crop Production

4.1 RADIATION

As has been described in Chapter 2, the intensity, duration, and quality of light are the three major factors of radiation which control the growth and development of plants. More work has been done on the duration of light, or photoperiodism, than on intensity and quality of light.

The difference between the incoming radiation from the sun and the outgoing radiation from the earth has been termed the ***net radiation***. Therefore, the duration, quality and intensity of the net radiation should be considered. When the incoming radiation surpasses the outgoing, a positive net radiation results; and vice versa, a negative. The equilibrium which exists between the radiation received by a surface and that emitted by the same surface is called the ***heat balance*** of the surface. For the earth's surface, the heat balance is the major factor which dominates the microclimate, such as heating and cooling of the air, and the process of dew formation in the microlayer. It follows then that solar radiation is the prime source of energy which determines the weather of the earth and, in turn, the plant response.

Problems of energy transfer in the atmosphere by conduction and convection processes are a concern of ***dynamic meteorology;*** those of radiation, ***physical meteorology***. Studies of heat and moisture in the air and soil are the major topics of ***thermodynamics*** and ***hydrology*** respectively; plant response studies, as related to all physical environmental factors, are subjects of ***agrometeorology***. ***Synoptic meteorology*** , on the other hand, deals with the application of physical laws of the air to weather forecasting. Studies of all meteorological factors next to the ground or at the air-soil interface are subjects of ***micrometeorology***. Microclimatic study is the fundamental approach to agrometeorology, because most crops are in the realm of the microenvironment. A comprehensive study in microclimatology is that of

Geiger (1959), *The Climate Near the Ground.* A special study of microclimate and plant relationship is that of Slatyer & McIlroy (1961), *Practical Microclimatology.* A more theoretical treatment of the subject has been written by Sutton (1953), *Micrometeorology, A Study of Physical Processes in the Lowest Layers of the Earth's Atmosphere.* A wide collection of microclimatic measurements and studies has been edited by Lettau & Davidson (1957), entitled *Exploring the Atmosphere's First Mile,* in which instrumentation and data evaluation are treated in Volume 1, while site description and data are tabulated in Volume 2. A knowledge of these areas would contribute to the better understanding of plant response studies.

Plant responses to the intensity, duration, and quality of net radiation, and the heat balance of the microlayer will be discussed here; the influence of heat and moisture on plants will be dealt with in the remaining sections.

4.1.1 *Intensity of light*

Photosynthesis, which has long been recognized as the major physiological process of plant growth, is governed principally by the intensity of light. When light intensity is low, respiration dominates; when high, photosynthesis dominates. In the process of chlorosis, plants etiolate at an extremely low light intensity. On the other hand, floral initiation is inhibited by an excess of light. Extremely high light intensities exert an inhibitory effect on photosynthesis. This is known as solarization, which is principally governed by photo-oxidation processes. When the rate of photosynthesis balances that of respiration, the evolution of carbon dioxide and the absorption of oxygen by plants reaches equilibrium. This equilibrium is known as the compensation point. Two compensation points (e. g., the lower and the upper) should be determined for each individual plant. To determine these limits in terms of light intensity is a complicated problem. Furthermore, the rate of photosynthesis under natural field conditions as related to light intensity is difficult to determine. The relationships are overshadowed by a number of environmental and physiological factors:

(1) Solar radiation includes the ultraviolet spectrum which is harmful to most plants, as well as the visible spectrum which is useful. As the intensity increases, both the harmful and the useful spectrum will be increased. Their joint effects have to be determined according to the phase of development of plants.

(2) Solar radiation also includes the infrared spectrum, which gives practically no photosynthetic effect, but which does give a thermal effect. In fact, all solar radiation contributes thermal effects to plants at various degrees. To differentiate the light intensity effect from the thermal effect of solar radiation is almost impossible. It can

be partially achieved through laboratory techniques, such as with a phytotron. Complete separation of light and temperature is not yet possible, for cold light sources are not available at present.

(3) More research should be directed toward the study of photosynthesis-respiration relationships of crops in association with solar intensity. In this connection, instrument design is extremely important. An ideal instrument would be able to cover an area-wide record of at least a few hundred acres of land, to integrate these records into one figure for a period of time (e.g., one or two days), to specify types of radiation (e.g., direct and sky-radiation), and to differentiate the quality of radiation (e.g., infrared, ultraviolet, and visible radiation). Ångström (1951), in his study of actinometric measurements, stated,

> The radiation which we are able to measure is very seldom the radiation that is effective in the biological processes. Neither the radiation on a horizontal surface, recorded for instance by a pyranometer, nor on a spherical surface, nor on a surface perpendicular to the solar beam as in pyrheliometers is equally proportional to the radiation falling on a given plant. The effectiveness of the radiation is, in general, quite different at different parts of the plant's surface. . . . Instruments should be characterized by a certain simplicity and stability and their results should be easily comparable with those from other stations. . . . Instruments which measure or record the radiation from the sun and sky on a horizontal surface and on a surface perpendicular to the solar beam, would satisfy more general needs. An accuracy of 5 percent seems sufficient provided that the instruments are not subject to systematic errors or changes.

Finally, he suggested the establishment of an actinometric network for the improvement of biological radiation studies.

(4) In determining the rate of photosynthesis, it is necessary to consider the interrelationships of complex environmental factors, in conjunction with solar intensity on the growth and development of a plant. Through research, some available methods have been established with agrometeorological techniques. These methods will be described in Chapter 7.

The foregoing complications can be simplified, if the ***physical mechanism*** of solar radiation from the sun to the plant and from the crown of the plants to the ground below is better understood. Let us consider first how solar energy is transmitted through the atmosphere from the sun to the plants. The thermal effects of solar energy propagation from the sun to the crown of the plant involve many factors such as the intensity of light, heat, and moisture in the air and soil. The amount of incoming solar radiation received on any date by a crop is conditioned by the solar elevation, the transparency of the atmosphere, the length of sunlight period, the sunniness (if any), and the interception of the sun's rays by the crown of the crop. These factors should be studied and consequently the interpretation of crop response to solar intensity will be possible.

The sun has a mean surface temperature of about 5700°K,[1] with about 99 percent of its energy output falling within wavelength intervals of 0.15 to 4.00 microns, which includes the entire visible radiation (0.40 to 0.74 microns), and a portion of infrared[2] and ultraviolet radiation.[3] Of the total solar radiant energy, 9 percent occurs in the ultraviolet, and 46 percent in the infrared spectra. About 45 percent of the total energy of solar radiation is in the visible spectrum with a peak intensity near 0.474 microns. In agrometeorology, the spectral ranges which we are concerned with here are the portion which reaches the earth's surface, i.e., 0.29 to about 3 microns. The rate at which the total amount of heat is received from the sun at a unit surface area of the outer atmosphere, normal to the incoming radiation, and at the earth's mean distance from the sun, is known as the solar constant. The value of the solar constant has been measured and calculated by many investigators since 1902, and has resulted in an average figure of 1.94 gram calories per square centimeter per minute (or 1.94 ly min^{-1}). This amount of heat represents more than $4\frac{1}{2}$ million horsepower of energy per square mile! Recently, a value of 2.00 has been suggested for the solar constant (Johnson, 1954); however, the extreme change varies from 1.88 to 2.01. The variation is presumably caused by changes in radioactive processes on the sun and the annual changes in distance from earth to sun. No evidence has been found so far for plant response to variation of the solar constant. Perhaps the study of the annual ring of a tree will reveal some such relationship.

When a huge amount of solar radiation passes through the atmosphere, it is subject to enormous changes. The atmospheric processes governing the changes are transmission, reflection, and absorption. The composition of the air — water vapor, ozone, carbon dioxide, and aerosol — also plays an important role in changes of solar radiation. Assume a total of 2.00 ly min^{-1} (or solar constant) of heat as 100 percent coming through the atmosphere; 0.68 (or 34 percent) of the total is lost, and 1.32 (or 66 percent) of the total is gained by the atmosphere and the earth's surface. This total loss of radiation, or 34 per

[1]For all measurable spectra, the surface temperature of the sun is about 5700° to 6000° K, of which the infrared temperature is 7000°K, while the ultraviolet temperature is less than 5700°K.

[2]The lower limit of the infrared spectrum is bounded by visible radiation and is extended to an infinite upper boundary. However, the upper limit has often been considered as the microwave and radiowave regions, and has been designated arbitrarily as 0.74 to 1000 microns. Infrared is the major constituent of terrestrial radiation, with wavelengths between 4.0 and 80 microns.

[3]The upper limit of the ultraviolet radiation is bounded by visible radiation. It ranges from 0.001 to 0.4 microns. The ultraviolet radiation of the sun has marked actinic and bacteriacidal action.

cent, is the mean albedo of the earth's surface for all wavelengths.[4] An over-all picture of the heating of the earth and its atmosphere by solar radiation during the day, expressed in percentages, is listed below:

Total heat received from sun at the outer limit of the atmosphere is assumed to be 100%; then

Heat loss into space:	
(a) reflected from clouds	23%
(b) scattered by aerosols, air molecules, etc. .	9%
(c) reflected by earth's surface . . .	2%
	34%
Heat gained by earth and its atmosphere:	
(a) absorbed directly by earth . . .	24%
(b) sky-radiation absorbed by earth . . .	23%
(c) absorbed H_2O, O_3, CO_2, N_2, etc. . .	19%
	66%

Thus, heat returned to space (34%) plus heat absorbed by the earth and its atmosphere (66%) equals 100%. In short, about two-thirds of the incoming solar radiation is effective in heating the earth and its atmosphere. The above estimates cannot be taken as they are, but for what they stand for. In other words, a comparative study of factors involved would serve the purpose. Therefore, in the study of plant response to incoming solar intensity, it is necessary to notice the important factors, such as cloudiness, aerosols, and water vapor. The reflection of clouds will reduce solar intensity greatly; absorption of water vapor, carbon dioxide, ozone, and aerosol will further weaken the intensity. The presence of aerosol, such as dust and haze, has been observed collectively by the eye.

Since cloudiness and visibility have been observed, should the correlation between solar intensity and the combination of cloudiness and visibility be established, it would be expedient to evaluate the solar intensity for regions lacking observation. This kind of research should be encouraged. In 1928, Ångström established an equation of the form

$$Q/Q_0 = a + b(n/N),$$

where Q is the average solar radiation; Q_0, the radiation during cloudless days; a and b are constants of the value of 0.235 and 0.765 respectively; and n/N is expressed as a fraction of the possible number of hours of sunshine. This classical formulation will be one way of approach and has been widely used since then.

During the night the long wave (infrared) outgoing radiation from the earth's surface dominates. According to the Stefan-Boltzmann

[4]The mean albedo of the earth's surface has not been determined with finality, and calculations have ranged from 34 to 43 percent.

law of radiation, the amount of heat radiated from a black body (R_b) is proportional to the fourth power of its temperature (T), or

$$R_b = \sigma T^4, \tag{4-1}$$

where σ is the Stefan-Boltzmann constant and has a value of about 8.17×10^{-11} cal cm^{-2} °K^{-4} min^{-1} (or ly °K^{-4} min^{-1}) for the metric system, and T is the temperature expressed in absolute units. The earth has been considered a black body, and therefore the R_b can be computed if the earth's surface temperature is given. However, there exists a counter radiation (L_D) from the air to the ground. Thus, the "effective outgoing radiation" or R_e will be the difference of R_b and L_D, that is

$$R_e = R_b - L_D. \tag{4-2}$$

Ångström, in 1929, formulated R_e as

$$R_e = R_b[a + b \cdot 10^{-ce}] \tag{4-3}$$

where a, b, and c are constants, and e is the vapor pressure in millimeters. These constants were given by Raman in 1935 as a = 0.23, b = 0.28, and c = 0.074. Thus, from equations (4-1) and (4-3),

$$R_e = \sigma T^4 [0.23 + 0.28 \cdot 10^{-0.074 e}] \tag{4-4}$$

Phillips, in a theoretical study in 1940, assigned a new set of values for these constants as a = 0.220, b = 0.148, and c = 0.068.

According to the Wien Law, the product of the absolute temperature (T) of a radiating body and the wavelength of maximum radiation (λ_m) is a constant (k), thus,

$$k = \lambda_m T. \tag{4-5}$$

Assume that the sun's surface temperature is 6000°K and the maximum wavelength, 0.474 micron; the average earth's surface temperature, 285°K (or 53.6°F) and its maximum wavelength, 10 microns; then apply these values to equation (4-5). The result is that the constant k is equal to 2844 and 2850 micron degrees for the sun and the earth, respectively.[5]

When the above values are applied to equation (4-1), we have the heat radiation at the surface of the sun as 10.54×10^4 ly min^{-1}, while the back radiation from the earth's surface is 0.54 ly min^{-1}. This shows how weak the outgoing long wave radiation from the earth is compared to the incoming short wave radiation from the sun.

[5]The constant (k) is usually assigned as 2897 micron degrees or 0.2897 cm °K. When the maximum intensity of the sun is taken as 0.474 microns, then the surface temperature of the sun would be 6112°K, which is known as the color temperature of the sun. When the maximum intensity of the earth's radiation is taken as 10 microns, the surface temperature of the earth is 289.7°K. Conversely, for a body near room temperature at 300°K, $\lambda m = 9.6\mu$; for a temperature at 2000°K, $\lambda = 1.4\mu$.

The diminishing of solar radiation from the sun to the earth may be summarized in the following figures.[6] It is 10.54×10^4 ly min^{-1} at the sun's surface, and 2.00 ly min^{-1} at the surface of the outer atmosphere. When this enters into the atmosphere, it is 1.32 ly min^{-1}, of which 0.94 ly min^{-1} is absorbed by the earth's surface from both direct solar radiation and sky-radiation. However, the long wave back radiation as computed by equation (4-1) is 0.54 ly min^{-1}. Thus, the difference, or 0.40 ly min^{-1}, is used for evaporation as latent heat, and for heating the air as sensible heat. This is a rough generalized picture of the intensity of solar radiation in the macro- and mesoclimate.[7] When the microclimate is considered, this is much more complicated. Further complications come from the variation in solar altitude, solar declination, and the transmission power of the atmosphere. For example, the highest solar intensity over the top of the atmosphere is 1059 ly per day at latitude 40° South on December 22 as has been computed, whereas the theoretical value is 2 ly per minute, or 2880 ly per day. When this amount of solar intensity reaches the ground, it is 898 ly per day at a transmission coefficient of 0.9. The corresponding northern latitude receives much less solar radiation, due to the fact that the earth is farther away from the sun in the northern summer. For details, the reader may refer to the Smithsonian Meteorological Tables.

The incoming radiation (I_0) from the sun which falls on the crown of a plant is partially reflected (R) by the leaf surfaces, and a small fraction emerges (T). The rest of the radiation is absorbed (A). If the crown of the plant is not thick enough, a portion of the radiation will reach the ground. Presumably, the total solar and sky-radiation reaching the crown of the plants is 100 units, by assuming that no direct radiation reaches the ground; then,

$$I_0 = R + A + T = 100, \qquad (4\text{-}6)$$

[6]The diminishing of solar intensity as the light is transmitted through the entire atmosphere may be expressed very nearly by the Rayleigh scattering law for parallel light as

$$\gamma = e^{\frac{-8.56 \times 10^{-3} m}{\lambda^4}}$$

where λ is the transmissivity (i.e., the ratio of the flux density of the light at the surface of the earth to the flux density at the top of the atmosphere), m is the optical air mass, and γ is the wavelength expressed in microns. The values of m vary with the secant of the sun's zenith angle when the zenith angle is less than 80. The air mass for the sun's zenith angle of 0-80 is shown below:

Sun's zenith angle	0	10	20	30	40	50	60	70	80
Optical air mass	1.00	1.02	1.06	1.15	1.30	1.55	2.00	2.90	5.60

Therefore the attenuation of extinction of the atmosphere as a whole depends upon the change of the zenith angle of the sun.

[7]Mesoclimate is a small area climate of distinguished climatic regions, including topographic or landscape features, from a few acres to a few square miles, such as a small

where R is the reflection of the plant leaves, A is the absorption, and T is the transmission. Equation (4-6) may be rewritten as

$$A = 100 - R - T. \qquad (4\text{-}7)$$

The leaf temperature of the plants depends upon short wave absorption from the sun during the day with some modifications of long wave emission, transpiration, and others. But short wave absorption is the controlling factor. During the night, long wave emission is the major process by which the leaf temperature is reduced. In other words, the energy absorbed by the leaves raises the leaf temperature during the day, and the energy released by the leaves lowers this leaf temperature by night. This furnishes us with a fairly good idea of plant response to light intensity, because the photosynthesis-respiration relationships of plants depend upon the change of plant temperature. The parts of radiation absorbed and reflected cover a very large percentage of the total incoming radiation reaching the crown, and therefore these two portions need to be studied more carefully.

The absorption of sunlight by the leaves of a plant is a function of the density and thickness of the leaves if the crown of the plant covers the ground completely, in all directions. Considering the thickness of a single leaf, $d\ell$, and its density, ρ, we have

$$dI_a = -\alpha \rho I_a \, d\ell. \qquad (4\text{-}8)$$

The proportionality constant α is the absorption coefficient of the leaf for all wavelengths and I_a is the total amount of radiation passing through the crown of leaves, including both absorbed and transmitted radiation. If I_0 is the total solar and sky-radiation before reaching the crown and the total reflection of all wavelengths by leaves is R, then I_a can be defined as $I_0 - R$. Integration of equation (4-8) gives

$$I_a = I_0 \exp\left[-\alpha \int_0^\ell \rho \, d\ell\right]. \qquad (4\text{-}9)$$

The integral $\int_0^\ell \rho \, d\ell$ represents the mass of leaves in a column of unit cross section extending the distance ℓ. It is known as the optical path length and is denoted by m. Substituting this symbol for $\int_0^\ell \rho \, d\ell$ in equation (4-9), we obtain the well-known Beer's law of absorption:[8]

$$I_a = I_0 e^{-\alpha m}. \qquad (4\text{-}10)$$

valley, a forest clearing, a beach, or a field site. The mesoclimate is intermediate in scale between the macroclimate and the microclimate.

[8]This law, known as Bouguer's Law, was first established experimentally by Bouguer in 1760. At a later date, Beer applied it to transmission of light through a turbid liquid. The law was rediscovered by Lambert, and known as Lambert's law of absorption.

Equation (4-10) was originally used by Beer for a turbid liquid in a beam of monochromatic wavelength. When applied to a layer of unit cross section of mass of leaves, the αm term can be approximated by measuring solar intensity above the crown, I_0, that below the crown, I_b, and that reflected, R. Thus, $\alpha m = \ln I_0/(I_b - R)$. It follows, then, that I_a, which is the solar energy both absorbed and transmitted by the unit cross section mass of leaves, can be obtained from equation (4-10).

When a beam of monochromatic wavelength λ is considered, equation (4-10) becomes

$$I_{a_\lambda} = I_{0\lambda} e^{-\alpha_\lambda m}, \tag{4-11}$$

where α_λ is the absorption coefficient for wavelength λ. This absorption coefficient α_λ should be distinguished from the absorptivity $a_\lambda(\ell)$. Dividing equation (4-6), or $I_0 = R + A + T$, through by I_0 to obtain ratios, we have

$$1 = r + a + \gamma \tag{4-12}$$

where r is the reflectivity or R/I_0, a is the absorptivity or A/I_0, and γ is the transmissivity or T/I_0. By Kirchoff's law, at the same temperature and wavelength the emissivity ε of a body is equal to the absorptivity of the same body. For a true black body, $r = 0$, and $\gamma = 0$; thus $\varepsilon = a = 1$, and when wavelength and thickness of the body are specified we have $\varepsilon = a_\gamma(\ell)$. From equation (4-11) the difference between absorptivity and the absorption coefficient is

$$a_\gamma(\ell) = 1 - e^{-\alpha_\gamma \ell}. \tag{4-13}$$

Hypothetically, the absorptivity a of all opaque bodies is constant for all wavelengths and it serves for definition and classification of opaque bodies as

$a = 1$, for ideal black body;
$a = 0$, for ideal white body;
$0 < a < 1$, for gray body.

More details will be given shortly upon the dependence of absorption, reflection, and net radiation on wavelength.

In the event of a reflection of the monochromatic light or reflectivity for all wavelengths, it is commonly referred to as the albedo (R) or reflectance, which is the ratio of the amount of radiation by a body to the amount incident upon it, and is usually expressed in percentages. Absorptivity (or absorption power) is 1.00 - R. The absorptivity and reflectivity for all wavelengths of various farming areas are listed in Table 4-1.

As mentioned before, the albedo of radiation from leaves is a function of wavelength. The albedo of green leaves lies between 8 and 20% for visible light, less than 10% for ultraviolet, and approximately 44% for infrared. Geiger (1959) has summarized the spectral distribution of albedo as shown in Table 4-2.

In a study of the heat economy of plants, a knowledge of the net radiation near the ground is necessary. During the day in wet farming areas, the energy of the net radiation is transformed into latent heat by evaporation from the soil and transpiration from plants. In fact, in the British Isles, the annual net radiation is equal to the annual latent heat of evaporation from short grass (Penman, 1948, and Pasquill, 1950). Over bare, dry lands, on the other hand, the net radiation energy is used mostly as sensible heat to raise the air temperature and to heat the soil as storage heat.

In the evaluation of net radiation in a microlayer, an energy balance research should be employed. There have been many studies along this line during the past decade in micro-, meso-, and macroclimate, and some studies even extend over the entire surface of the earth. These studies of concern to agrometeorology pertain to microenvironment. The energy balance for a thin surface layer of the soil was first given by Albrecht (1943). The idea was originated by Schmidt (1915) for determining evaporation. There are many factors and methods employed in each individual study; however, the energy balance concept is the same. Their purposes aim at the evaluation of evaporation, evapotranspiration, soil moisture, and even the surface soil temperature. Factors related to radiation balance of a microlayer are:

I_0 — the incoming short wave radiation from sun and sky

L_D — the downward long wave radiation from the atmosphere (or counter radiation)

L_U — the upward long wave radiation from the ground or crown of vegetation

R_L — the net long wave radiation, $L_D - L_U$

R_n — the net radiation for all wavelengths

α — the coefficient of absorption

T_S — the surface temperature of the radiative body

β — the heating coefficient, or $-dR_L/dR_n$

From the above definitions, we have

$$R_L = L_D - L_U, \tag{4-14}$$

$$R_n = I_0 - \alpha I_0 + R_L = I_0(1-\alpha) + R_L \tag{4-15}$$

where I_0, αI_0, and R_n can be measured and thus, R_L can be obtained from equation (4-15) as

Table 4-1. Absorption and Reflection of Various Surfaces in Farming Areas*

Type of Surface	Percent Reflected	Percent Absorbed	Type of Observation	Observer and Remarks
Alfalfa, dark green	3	97	by estimation	Ashburn & Weldon (1956)
Aluminum foil	85	15	photometers	Moon (1936)
Bare ground, some trees	7	93	aircraft photometers	Kimball & Hand (1930)
Black body	0	100	theoretical consideration	by definition
Concrete	40	60	----------------	Hottel (1954)
Fields, dry plowed	20-25	75-80	aircraft photometers	Tousey & Hulburt (1947)
Forest, green	4-10	90-96	aircraft photometers	Tousey & Hulburt (1947)
Galvanized iron, clean, new	35	65	-----------------	Dunkle & Gier, et al. (1953)
Glass pane (incident angle 35°)	10	90	-----------------	Hottel (1954)
Grass, high fresh	26	74	total albedo measured by pyrheliometers and pyranometers	Ångström (1925)
Oak woodland	18	82	total albedo measured by pyrheliometers and pyranometers	Ångström (1925)
Pine forest	14	86	total albedo measured by pyrheliometers and pyranometers	Ångström (1925)
Plaster, white	93	7	-----------------	Coblentz (1913)
Snow, fresh	81	19	total albedo measured by pyrheliometers and pyranometers	Ångström (1925)
Spinach	24-28	72-76	no specification	Thornthwaite (1954)
Sugar cane	6-18	82-94	pyrheliometers	Chang (1961)
Water (normal incidence)	2	98	by computation	by using Fresnel formula for fresh deep water
Water				
at 30° incidence	2.1	97.9	by computation	by using Fresnel formula for fresh deep water
at 60° incidence	6.0	94.0		
at 90° incidence	100.0	0		
White body	100	0	theoretical consideration	by definition
Wheat	7	93	aircraft photometers	Kimball & Hand (1930)

*Refers to 0.3 to 2.5 microns.

Table 4-2. The Spectral Distribution of Albedo of Leaves and Plants

Spectral Range	Wavelength, in Microns	Albedo
Ultraviolet	below 0.36	below 10%
Visible light	0.36-0.76	8-20%, with maximum at 0.51 micron
Infrared	0.80	45% (maximum)
	1.0	42%
	2.4	9%
	10.0	5%

After Geiger, 1959

$$R_L = R_n - (1 - \alpha) I_0$$

Solve equations (4-14) and (4-15) simultaneously, then

$$L_U = L_D + (1 - \alpha) I_0 - R_n , \qquad (4\text{-}16)$$

where L_D can be obtained from any formal radiation chart (e.g., Kew Radiation Chart, Robinson, 1950; and Elsasser Radiation Chart, Elsasser, 1940 and 1942). Thus, the effective radiative temperature of the surface can be determined by

$$L_U = \varepsilon \sigma T_S^4 + (1 - \alpha) L_D , \qquad (4\text{-}17)$$

where ε is the emissivity and has been compiled by Brooks (1959) as shown in Table 4-3, and

$$\sigma = 8.17 \times 10^{-11} \text{ cal cm}^{-2} \, {}^\circ\text{K}^{-4} \text{ min}^{-1} .$$

In 1961, Monteith & Szeicz published results of a three-year study on the radiation balance of bare soil and vegetation at Rothamsted Experimental Station, Harpenden, Herts, England. The vegetation used for this study was grass (40% S.51 Timothy and 60% S.214 Meadow Fescue), spring wheat (Koga II), and sugar beets (Klein E). Their study was restricted to cloudless days for the radiation balance of the diurnal variation, long wave exchange, and reflection coefficient.

The correlation between solar and net radiation for 532 cloudless hours in the summers of 1957 to 1959 has been studied by Monteith & Szeicz, as shown in Fig. 4-1. A regression line has been prepared for the variation of hourly totals of net radiation, R_n, with net short wave radiation, $(1 - \alpha) I_0$. The regression formula used was

$$R_n = a (1 - \alpha) I_0 + b , \qquad (4\text{-}18)$$

where a and b are constants. The linear correlation runs as high as .95 to .99. From equations (4-14) and (4-16), a linearity between R_L and R_n exists. The mean wind speed in meters per second at 2 meters above short grass is indicated by U_2, and the correlation coefficients r^2 have been summarized by Monteith & Szeicz in Table 4-4.

Table 4-3. The Emission of Various Surfaces in Farming Areas *

Type of Surface	Longwave Emissivity, ε	Type of Surface	Longwave Emissivity, ε
Black body	.99	Plaster, white	.91
Water (at 60° incidence)	.95-.96	Bricks, red	.92
Snow	.89	Concrete	.88
Frozen soil	.93-.94	Glass pane (at 35° incidence	.94
Sand, dry and wet	.90-.95		
Grass	.90	Wood, planed oak	.90
Alfalfa, dark green	.95	Aluminum foil	.01-.05
Oak woodland	.90	Galvanized iron, clean, new	.13
Pine forest	.90		

* Refers to 2.5 microns and up. After Brooks, 1959

Table 4-4. Correlation of Short Wave Net Radiation and Total Net Radiation at the Rothamsted Experimental Station

Crop	Period	Year	U_2*	a	b	β	r^2
Spring wheat	25 May to 27 July	1957	3.2	0.87	-7.9	0.15	0.98
Sugar beet	3 July to 27 Sept.	1958	1.3	0.83	-5.8	0.21	0.94
Grass	23 July to 27 Aug.	1959	1.4	0.82	-5.9	0.22	0.97
Bare soil	14 April to 30 April	1957	2.4	0.74	-4.5	0.35	0.97
Bare soil	1 May to 18 June	1958	1.1	0.72	-5.2	0.39	0.90
Bare soil	13 June to 20 June	1959	2.8	0.71	-6.8	0.41	0.97
Bare soil	7 Sept. to 20 Sept.	1959	1.2	0.73	-5.9	0.37	0.93

* U_2 is the mean wind speed in m sec^{-1} on relevant days, at 2 m over short grass in the meteorological enclosure. After Monteith & Szeicz, 1961

The coefficient of reflection of Monteith & Szeicz's findings for grass increased from 23% at solar elevation 60° to 28% at 20°, with a daily mean of 26%. For kale, they increased from 19% at solar elevation exceeding 30° to 20% below 30°, with a daily mean of 24%. For long grass and short grass, they were almost identical when the leaves were dry; when wet, there was considerably more reflection from short grass. There was more reflection from wet kale than from either of the grasses. For bare soil, the corresponding increase was from 16% to 19%, with daily mean 17%. These reflection coefficients refer to clear day conditions. This finding agrees very well with Table 4-1 for high grass observed by Ångström in 1925. In mid-June,

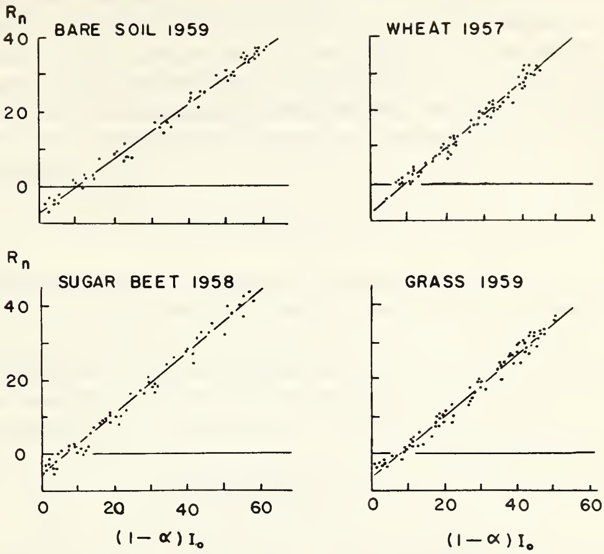

Fig. 4-1. Variation of hourly totals of net radiation, R_n, with net short wave radiation, $(1 - \alpha)I_0$, on cloudless days.

After Monteith & Szeicz, 1961

the net incoming long wave radiation for bare soil decreased from -10% during the night to -40% in the early afternoon. Under clear skies, the incoming long wave component varied much less than the outgoing component, and the net flux, R_L, was closely related to the surface temperature. This will enable us to evaluate the soil surface temperature from the net incoming long wave radiation. The heating coefficient, β, for grass, sugar beets, and potatoes lies between 0.15 and 0.22, with a variation which may depend on wind speed rather than on the crop. The value for dry bare soil was high because there was greater surface heating. This is in agreement with Pasquill's findings in 1950 at Cambridge, and with Rider & Robinson's findings in 1951 at Kew, England.

So far we have discussed the radiation budget of long and short wave spectra at the surface of the radiating body, namely the earth's surface. We have studied the total radiant energy balance in terms of the net radiation for all wavelengths R_n, the net incoming long wave radiation R_L, and the net incoming short wave radiation, $(I - \alpha I)$. When this energy is applied in the study of the heating and cooling of a thin surface layer of the earth, it may be called the heat balance of that layer. This thin layer can be a layer of the top soil, as in the case of bare soil. It can be a layer of a few inches composed of short lawn grass. It can also be a layer of corn field with a depth of several feet. The stress is upon the surface characteristics that are exposed to the air. Nevertheless, the heat balance concept is the same as that of the energy balance. Heat that flows *away* from this layer in any direction is called the "heat loss," which is considered "negative," while heat that flows *toward* the layer from any source is "heat gain," considered "positive." The heat balance equation, expressed in terms of the total net radiation R_n, may be written as

$$R_n = Q + L + G + e, \tag{4-19}$$

where Q is the flux of sensible heat, L the flux of latent heat, G the ground heat storage (or heat conduction into the soil), and e the error term. The latter, which can be either a positive or a negative term, comes from the deficiencies in the measurement technique itself.

The two terms in equation (4-19) that can be measured directly, and more or less satisfactorily, are G and R_n. This heat conduction may be expressed as

$$G = \int_0^z \rho_s c_s \frac{dT}{dt} dz, \tag{4-20}$$

where ρ_s is the bulk density of the soil, c_s the specific heat per unit mass of soil, dT the temperature change of each layer for the period dt, and dz the thickness of the layer.

R_n can be measured at a distance some five to six feet above the soil surface in order to avoid the shadow of the instrument. Q and L can be determined jointly by means of the Bowen ratio, which has been widely adopted by many researchers. In his study of the ratio of heat losses by conduction and evaporation from any water surface, Bowen (1926) concluded that the ratio of sensible to latent heat exchange at the water surface is constant. This constancy, known as Bowen's ratio, is B, or

$$B = Q/L = 0.46\,(t_s - t_a)/(e_s - e), \tag{4-21}$$

where t_s and t_a are the surface and the air temperatures above the water in degrees centigrade, and e_s and e are the surface and the air vapor pressures in millimeters of mercury.

In the case of farming lands, substituting equation (4-21) in equation (4-19) and ignoring the error term, we have

$$\begin{aligned} Q &= (R_n - G)/(1 + \tfrac{1}{B}); \\ L &= (R_n - G)/(1 + B); \\ R_n &= Q(1 + \tfrac{1}{B}) + G. \end{aligned} \tag{4-22}$$

The above equations would enable the computation of latent heat, the direct measurement of which involves the determination of evaporation from free water surface and transpiration from plants, and which is often inaccurate. However, in certain environmental conditions, the Bowen ratio fails to be constant, and these conditions should be carefully handled, particularly in the selection of a surface, because:

(a) the ratio is not very reliable near sunrise and sunset, since the temperature and moisture gradients from which it is calculated are generally small;

(b) the ratio will not hold constant on dry bare soil, particularly sandy soil, where local heating initiates the upward steady current;

(c) the ratio will give a negative value when there is a strong warm air advection, and when this ratio is near zero, it is not useful; and

(d) the ratio varies with the height above the ground. The departure of the ratio increases with height; however, the ratio for the lower level is greater than that for the upper level.

Even with all these discrepancies, the Bowen ratio still serves as a convenient means for the first approximation for the evaluation of heat balance. When transfer of the sensible heat from the air to the ground (Q) and the latent heat from soil and plant (L) are treated separately, it is necessary to measure the wind velocity at two levels — temperature and vapor pressure gradient, and the evapotranspiration. Thus, for the sensible heat flow, we have

$$Q = \rho c_p \overline{\omega (T_s - T_z)}\, dz \,, \qquad (4\text{-}23)$$

where c_p is the specific heat of the air, ρ, the density of the air, T_s and T_z, the air temperature at two levels, z, the height, ω, the vertical wind, and the bar above the terms indicates the mean value of the product. For the latent heat flow, we have

$$L = m L_v \,, \qquad (4\text{-}24)$$

where m is the mass of water evaporated, L_v is the latent heat of vaporization of water, expressed in cal gm^{-1}, which varies with the air temperature as given below:

Temp, °F	32	41	50	59	68	77	86	95	104	113
L_v	597.3	594.5	591.7	588.9	586.0	583.2	580.4	577.6	574.7	571.9

In short, the Bowen ratio is highly variable and sometimes negative. It has been estimated that an average value for the ocean surface is about +0.1. The U. S. Geological Survey (1954) conducted the Lake Hefner Studies and found that with a mean of 5, 10, and 20 day periods from May to December, the values range from -0.5 to +0.5 and are predominantly positive. The measurements used for this study were temperature, wind, and humidity gradient of the air over the lake. This range of values is very close to the average value for the ocean; however, the daily values were quite different, ranging from -20.20 to +31.50. Therefore, in order to get a more accurate value for the Bowen ratio, or to have a good result in heat balance studies, it is necessary to improve the technique of measurement. A network should be established for this purpose — for example, a network of wide geographical distribution of net radiation measurement.

During the past decade the measurement of net radiation was rather rare in the sense of time and space. However, some regular observations of solar intensity, such as the Eppley Pyrheliometer observation, have been maintained for a long period and over a widespread area. The estimation of net radiation from direct solar intensity data is useful. Shaw (1956) has made such an estimate for both cloudy and cloudless days as shown in Fig. 4-2. The daily values of total solar radiation and total net radiation at Ames, Iowa, were observed for the period late June through November, 1954. The correlation for a clear day is 0.98, and for a cloudy day, 0.97. In the clear day cases, Monteith & Szeicz's data, indicated in Table 4-4, also give high correlations.

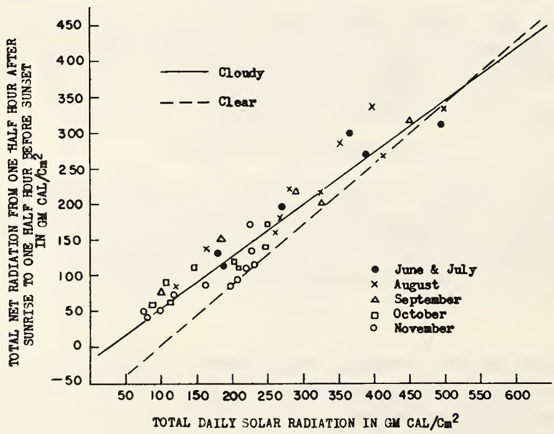

Fig. 4-2. Relationships of solar radiation and net radiation at Ames, Iowa, 1954. After R. H. Shaw

The regression equations for clear days and cloudy days by Shaw are given in equation (4-25):

$$\bar{Y} = 0.87x - 82.0 \text{ (clear days)};$$
$$\bar{Y} = 0.75x - 21.4 \text{ (cloudy days)}, \qquad (4\text{-}25)$$

where $\bar{Y}$ is the total net radiation from $\frac{1}{2}$ hour after sunrise to $\frac{1}{2}$ hour before sunset, and x is the total daily radiation. Both x and $\bar{Y}$ are expressed in ly day^{-1}. Chang (1961) has made a similar study in Makiki, Oahu, Hawaii, for the period August, 1959, to July, 1960. He found the correlation coefficient to be 0.95; his regression equation is given in equation (4-26):

$$Y = 0.72x - 27.6, \qquad (4\text{-}26)$$

where Y is the daily net radiation and x the daily incoming radiation in ly day^{-1}.

Findings on plant response to light intensity vary with a number of factors such as the kinds of instrument used, the type of environment chosen (artificial or natural), and the plant material selected (including species and varieties of plants as well as phases of development). Owing to these complications, there is no way to evaluate the importance of the findings. For example, light intensity under controlled conditions is much weaker than solar light. Nevertheless, past studies on light intensity and plant responses are illustrated below.

Popp (1926) studied the effect of light intensity on the growth of soybeans and its relation to the autocatalyst theory of growth. He found that soybeans receiving the greatest amount of light are the most vigorous and produce the best leaves and fruit. But those grown in the shade have longer stems. Jacobi (1914) found that the presence of moisture decreases the effect of light intensity on seedling elongation for a number of plants. Li (1928) observed the effects of air temperature, relative humidity, sunlight intensity, and evaporation on the suction force of the leaf of lilac seedlings. Livingston (1911) attempted to find some simple means of physically determining the intensity of solar radiation with reference to its effects on plant transpiration. Martin (1935) studied the effect of solar radiation on the transpiration of sunflowers. Brouwer (1956) correlated the rate of transpiration and the radiation intensity in the Netherlands. Auchter et al. (1926) studied the influence of shade on the behavior of Stayman Winesap apple trees in regard to growth, fruit bud formation, and chemical composition. Kramer & Decker (1944) found that the rate of photosynthesis in loblolly pine and certain hardwoods is closely related to light intensity. Kozlowski (1957) also studied the effect of high light intensity on photosynthesis of loblolly pine, red oak, and dogwood seedlings. The photosynthetic efficiency of tomatoes as related to light intensity has been studied by Porter (1937). Abd el Rahman et al. (1959) have observed the effect of light intensity and photoperiod on transpiration and growth of young tomato plants under controlled conditions in Holland. McCool (1935) studied the effect of light intensity on the manganese content in plants. This is one of the contributions of the Boyce Thompson Institute for Plant Research. In fact, an enormous amount of research has been conducted by the

Institute for many years, particularly on the dormancy of seeds and the germination of many plants. Blackman et al. (1949-1955) studied the interrelationship between light intensity and the mineral nutrient supply on the vegetable growth of sunflower, bluebell, and *Lemna minor*. He also studied light intensity and the net assimilation, leaf area ratios, and relative growth rates of different species of plants. The utilization of nitrates by coffee plants under different sunlight intensities has been observed by Tanada (1946).

The study of light intensity effect on the flowering of vegetables and ornamentals has been done by many investigators. Scully & Domingo (1947) studied the effect of duration and intensity of light upon flowering in several varieties and hybrids of castor bean. The effect of light intensity on the initiation and development of flower buds in *Saintpaulia ionantha* has been investigated by Stinson & Laurie (1954). Chrysanthemums have been studied by Watson & Andrews (1953). The influence of nitrate level and light intensity on the production of greenhouse roses has been studied by Post & Howland (1946). Chandler & Watson (1954) also studied the growth and yield of greenhouse roses as affected by light intensity. Tukey et al. (1957) applied radioactive tracers to the study of leaching of carbohydrates from plant foliage. They found that light intensity is one of the important factors to be considered. The influence of moonlight on movement of leguminous leaflets has been studied by Gates (1923). The low light intensity and cotton boll-shedding has been investigated by Dunlap (1943). The effect of light intensity on tissue fluids in wheat has been found by Loehwing (1930). On the other hand, Mason (1925) studied the inhibitive effect of direct sunlight on the growth of the date palm. The growth of alfalfa and brome-grass was related to light intensity by Pritchett & Nelson (1951). The joint effects of light intensity, temperature, and soil moisture on the growth of alfalfa, red clover, and birdsfoot trefoil seedlings have been studied by Gist & Mott (1957).

Investigations on light intensity, duration, and quality on plant growth will be discussed in the following sections.

4.1.2 *Duration of light*

The length of daylight is usually considered as the time interval between sunrise and sunset. The daily additional daylight time will be the twilight time before sunrise and after sunset. The duration of twilight as well as sunlight varies with latitude and season, due to the fact that the sun's daily path across a certain latitude meets at different angles for the time of day and different declinations for the season of year. Sunrise and sunset may be defined as the instant of time when the upper edge of the sun appears or disappears on the horizon.[9] Several definitions for twilight have been commonly used according to the angle subtended between the sea level horizon and the position of the sun. These angles are 6°, 12°, and 18° for civil twilight, nautical twilight, and astronomical twilight, respectively. For most plant response studies, the civil twilight will be meaningful. For the study of solar intensity, twilight time has some bearing, even though the intensity is small. For the study of energy balance, a separation of duration according to net radiation types is necessary. In other words, this is to differentiate the positive type of net radiation from the negative type for their duration. Obviously, the longer the period of sunlight, the greater will be the total insolation.[10] In the polar regions, the sunlight together with the twilight period reaches a maximum of 24 hours in the summer and a minimum of zero hours in the winter. At the equator, day and night are almost equal. This holds true in higher latitudes for the vernal equinox (March 21) and the autumnal equinox (September 21). The longest and shortest duration of sunshine and twilight at different latitudes is shown in Table 4-5. The annual course of sunrise, sunset, morning twilight, and evening twilight hour for latitude 45° is shown in Fig. 4-3 for illustration. In this figure, the x-axis indicates the local Greenwich time, expressed in hours. The solid line is the sunrise and sunset hour, and the dash lines, the morning and evening twilight times. The shaded and unshaded areas show the night and day periods, respectively, according to the definition of the Civil Twilight Time. In order to convert the Greenwich time to the local time desired, some computation should be made — the difference in longitude for the desired locality from Greenwich is divided by 15° longitude to obtain the difference in hours from the Greenwich time. The local time will be earlier than the Greenwich time if the station is east of Greenwich and vice versa for the west. The slope of the ground in one locality would modify the duration and amount of sunlight greatly. This is a study of the sunniness. It is so important that it will be discussed more fully.

The sunniness, which may be defined here as the duration and amount of sunshine as affected by the slope of the ground, is another aspect of insolation. In general, sunniness is less on a slope than on a horizontal surface. This depends upon the steepness (or inclination[11]) and the direction (or orientation) of the slope at the different times of the day and year. However, in some specific cases,

[9] In Great Britain, the center of the sun's disk is used instead of its upper edge, for the definition of sunrise and sunset.

[10] Insolation in general may be defined as solar radiation received at the earth's surface. More specifically, it may be defined as the rate at which direct solar radiation is incident upon a unit horizontal surface at any point on or above the surface of the earth.

[11] Slope inclination may be defined as the angle between the slope surface and the horizontal surface at the foot of the slope.

Table 4-5. The Longest and Shortest Duration of Daylight and Twilight

Lat.		January	February	March	April	May	June
0	D	12:07-12:08*	12:06-12:07	12:06-12:07	12:06-12:07	12:07-12:07	12:07-12:08
	d'	00:44-00:46	00:42-00:44	00:42-00:42	00:42-00:42	00:44-00:44	00:44-00:46
10	D	11:33-11:41	11:44-11:53	11:56-12:13	12:16-12:28	12:31-12:39	12:41-12:42
	d'	00:44-00:46	00:42-00:44	00:42-00:42	00:42-00:44	00:44-00:46	00:46-00:46
20	D	10:56-11:15	11:18-11:39	11:45-12:19	12:24-12:51	12:56-13:15	13:17-13:20
	d'	00:46-00:48	00:44-00:46	00:44-00:44	00:44-00:46	00:46-00:48	00:48-00:50
30	D	10:14-10:43	10:50-11:23	11:32-12:27	12:36-13:17	13:26-13:55	13:59-14:05
	d'	00:50-00:52	00:48-00:50	00:48-00:48	00:48-00:50	00:50-00:54	00:54-00:56
40	D	09:22-10:05	10:16-11:04	11:17-12:36	12:49-13:51	14:02-14:47	14:52-15:01
	d'	00:58-01:00	00:54-00:58	00:54-00:54	00:54-00:58	00:58-01:04	01:04-01:06
50	D	08:09-09:13	09:29-10:38	10:56-12:50	13:08-14:37	14:54-16:00	16:04-16:22
	d'	01:12-01:16	01:06-01:10	01:04-01:06	01:06-01:12	01:14-01:24	01:26-01:30
60	D	06:00-07:48	08:13-09:59	10:26-13:10	13:37-15:52	16:18-18:10	18:26-18:52
	d'	01:40-01:54	01:24-01:36	01:24-01:24	01:26-01:40	01:48-02:30	02:50-03:32
70	D	00:00-04:40	04:40-09:20	09:20-13:50	13:50-18:50	18:50-24:00	24:00-24:00
	d'	03:00-04:28	02:10-03:10	02:00-02:16	02:16-24:00	24:00-24:00	24:00-24:00
80	D	00:00-00:00	00:00-06:00	06:00-16:00	16:00-24:00	24:00-24:00	24:00-24:00
	d'	00:00-00:00	00:00-08:00	02:00-16:00	16:00-24:00	24:00-24:00	24:00-24:00
90	D	00:00-00:00	00:00-00:00	00:00-24:00	24:00-24:00	24:00-24:00	24:00-24:00
	d'	00:00-00:00	00:00-00:00	00:00-24:00	24:00-24:00	24:00-24:00	24:00-24:00

*Read as: 12 hours and 7 minutes for the shortest duration of daylight in the month of January at the equator. The longest duration is 12 hours and 8 minutes. The shortest twilight time before sunrise and after sunset is 22 minutes, and the day total is 44 minutes. The longest twilight is 46 minutes.

N. B.—D stands for the daylight duration from sunrise to sunset; d' stands for the total civil twilight time per day, or the morning twilight duration plus the evening twilight duration. When the total of D plus d' exceeds 24 hours, it indicates an overlapping of both. For example, at Lat. 70° and during the month of June, both sunlight and twilight last 24 hours.

This table may apply to the southern hemisphere when the data are arranged by approximately six months intervals. For detail, see Table 174, "Daylight and Twilight for Southern Hemisphere," in Smithsonian Meteorological Tables.

by Month at Various Latitudes in the Northern Hemisphere

July	August	September	October	November	December
12:07-12:08 00:44-00:46	12:06-12:07 00:42-00:44	12:06-12:07 00:42-00:42	12:06-12:07 00:42-00:42	12:07-12:08 00:42-00:44	12:07-12:08 00:44-00:46
12:35-12:42 00:44-00:46	12:21-12:32 00:42-00:44	12:04-12:18 00:42-00:42	11:49-12:01 00:42-00:44	11:36-11:47 00:44-00:44	11:32-11:35 00:46-00:46
13:05-13:19 00:48-00:50	12:36-13:00 00:46-00:48	12:02-12:31 00:44-00:44	11:30-11:57 00:44-00:44	11:04-11:25 00:46-00:48	10:55-11:01 00:48-00:48
13:39-14:02 00:52-00:54	12:54-13:32 00:50-00:52	12:00-12:45 00:48-00:48	11:08-11:51 00:48-00:48	10:26-11:00 00:50-00:52	10:13-10:22 00:52-00:52
14:22-14:56 01:02-01:06	13:16-14:13 00:56-01:00	11:58-13:03 00:54-00:56	10:42-11:45 00:54-00:56	09:40-10:30 00:56-01:00	09:20-09:33 01:00-01:02
15:24-16:15 01:20-01:28	13:45-15:09 01:08-01:18	11:55-13:27 01:04-01:08	10:06-11:36 01:04-01:06	08:36-09:49 01:08-01:14	08:04-08:25 01:14-01:18
17:07-18:38 02:12-03:16	14:33-16:43 01:34-02:00	11:51-14:06 01:22-01:30	09:11-11:24 01:22-01:28	06:48-08:44 01:30-01:44	05:52-06:29 01:48-01:56
22:00-24:00 24:00-24:00	15:40-22:00 02:36-24:00	11:15-15:40 02:00-02:36	06:30-11:15 02:00-02:30	00:00-06:30 02:30-05:40	00:00-00:00 04:10-05:20
24:00-24:00 24:00-24:00	22:00-24:00 24:00-24:00	10:20-22:00 04:00-24:00	00:00-10:20 04:00-08:00	00:00-00:00 00:00-04:00	00:00-00:00 00:00-00:00
24:00-24:00 24:00-24:00	24:00-24:00 24:00-24:00	00:00-24:00 24:00-24:00	00:00-00:00 00:00-24:00	00:00-00:00 00:00-00:00	00:00-00:00 00:00-00:00

Source of data:

For Lat. 0° to 60°: computations made from U. S. Naval Observatory, Nautical Almanac Office, 1959, The American ephemeris and nautical almanac (for the year 1961). U. S. Government Printing Office; Washington, D. C., pp. 386-393.

For Lat. 65° to 90°: estimation made from graphs prepared by R. J. List, ed., 1951, Smithsonian Meteorological Tables, 6th Rev. Ed., The Smithsonian Institution, Washington, D. C., pp. 515-516.

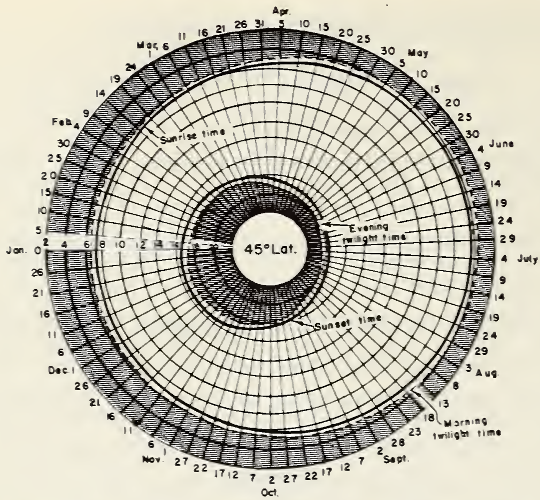

Fig. 4-3. The annual course of sunlight and twilight duration at 45° latitude.

sunniness is independent of the steepness of the slope, and thus the differentiation between the slope and horizontal surface does not exist. In 1959, Fuh studied the influence of the slope on sunniness in greater detail. He specified the sunniness in eight directions of the slope and considered both their influence on the hours of sunshine and the amount of insolation for different latitudes. His diagrammatic presentation for the hours of sunshine versus different times of the year is very informative. He also studied the annual courses of daily amount of astronomical solar radiation on the slope. The major factors which he used in his study are slope inclination β, latitude Φ, and declination δ.[12] He concluded that

(a) The duration of sunshine on the south slope in the winter half year is identical with that on a horizontal surface; but in the summer half year, it decreases with increase of slope inclination and, when the inclination is larger than latitude, it even diminishes with increase of solar declination (approaching the summer solstice).

(b) In low latitudes, the daily duration of sunshine on the southeast and southwest slope, when the inclination is rather large, decreases with the increase of solar declination in the summer half year, but increases with the decreasing solar declination in the winter half year — the more so, the larger the slope inclination.

(c) In the summer half year, on the north slope, when the inclination is $\beta \leq 90° - \Phi + \delta$, the duration of sunshine is identical with that

[12]Solar declination may be defined as the angular distance between the position of the sun and the equator of the earth.

on a horizontal surface; but when it is $\beta > 90° - \Phi + \delta$, sunshine can exist for an amount of time, longer or shorter, only in the forenoon after sunrise and in the afternoon before sunset, respectively, while around the middle of the day the north slope is situated rather in the shade. In the winter half year, the duration of sunshine on the north slope decreases very rapidly with the increase of inclination as well as latitude; and when the inclination is $\beta > 90° - \Phi + \delta$, sunshine cannot exist on the slope throughout the day.

(d) In low and high latitudes when the inclination is rather large, the daily amount of solar radiation which the south and the southeast (southwest) slopes receive decreases with the increase of solar declination in the summer half year, while in the winter half year there is a period, longer or shorter, in which such daily amounts of solar radiation increase with the decrease in solar declination. Thus, the maximum daily amounts of solar radiation occur at winter solstice or around the equinoxes, while at the summer solstice the primary or secondary minimum of solar radiation occurs.

(e) In the summer half year, the daily duration of sunshine and the daily amount of solar radiation on the south slope of inclination β at latitude Φ are just equal to those on a horizontal surface at latitude $\Phi - \beta$, while those on the north slope of inclination β at latitude Φ are just equal to those on a horizontal surface, at $\Phi + \beta$ in the winter half year. Hence, as to the influence on the duration of sunshine and on the solar radiation, all increase of inclination of the south slope corresponds to all decrease of latitude in the summer half year, while the opposite is true for the north slope in the winter half year.

In short, the duration and intensity of light will be greatly modified on the slope, and therefore the microclimate will be affected by different orientations and steepnesses of the slope. Let us denote the intensity of radiation emitted from a unit surface of a body in a direction making an angle θ with the normal to the surface, by I_θ. Lambert's law states that I_θ is proportional to $\cos\theta$, or

$$I_\theta = I_0 \cos\theta , \tag{4-27}$$

where I_0 is the value of I_θ at normal emergence. A schematic diagram as shown in Fig. 4-4 illustrates the effect of a slope upon the amount of solar energy received per unit area. Fig. 4-4, which is self-explanatory, is so designed that angle θ is 60° and the south-facing slope B has an inclination of β also equal to 60°. Thus, in this case the solar intensity that reaches the south slope is the maximum possible intensity available for the season concerned. Assume I_0 has a unit intensity of 60 cal $cm^{-2} hr^{-1}$. Then area B receives 60, area C receives 30, and area A receives 0. It has been observed from time to time that crops grown at various slopes behave differently. The study of slope in relation to climate has been known as slope-climate.

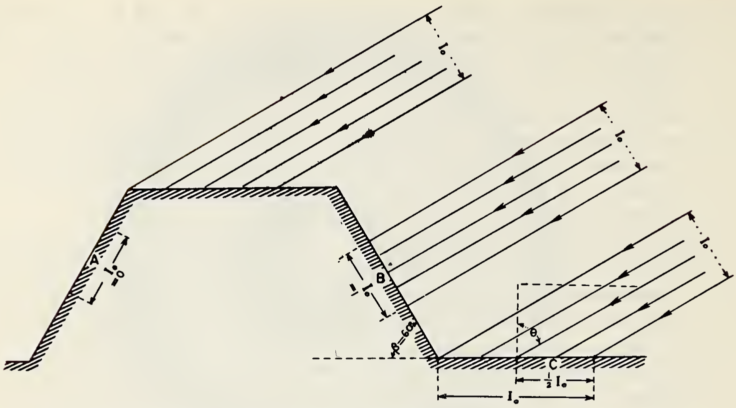

Fig. 4-4. Schematic diagram of sunniness.

So far, we have focused our attention, more or less, on the physical aspects of the intensity, duration, and quality of light. The biological aspect, such as plant response, will also be discussed.

Plant response to the duration of light, known as "photoperiodism," was discovered and defined by Garner & Allard (1920). As far back as 1852, Henfrey, in his book *The Vegetation of Europe*, had considered the length of the day as a factor in the natural distribution of plants. In 1913, Klebs induced hen-and-chickens, *Sempervivum Funckii*, to flower by exposing them for a few days to continuous electric illumination. Many researchers (Schübeler, 1880; Kjellman, 1885; Bonnier, 1895; Turnois, 1912) observed the effects of daily exposure to natural or artificial light on plant growth and development prior to the discovery of "photoperiodism." It has been known that the initiation of flowering depends upon the duration of daylight. The flowers of some plants are induced under a longer daylength of 14 to 16 hours. Others need a short daylength of 8 to 10 hours. Still others require somewhere between 12 and 14 hours. Those which take a longer photoperiod for floral initiation are known as "long-day plants," while those requiring a short photoperiod are called "short-day plants." Examples of the former are spinach, lettuce, radish, and potato; of the latter, some tobaccos and soybeans, chrysanthemum, salvia, poinsettia, and cosmos. Climbing hemp-weed, wild beans, and spurge, *Eupatorium torrayanum*, demand an intermediate duration of 12 to 14 hours. Either above or below this length, flowers are inhibited. These are designated by Allard (1938) as the "intermediates." Some plants flower at any photoperiod and are known as "day-neutral plants." These do not possess photoperiodic responses. Some day-neutral plants are dandelion, buckwheat, cotton, some squashes, and cucumbers.

Plants can be classified as long-day, short-day, day-intermediate,

Table 4-6. Classification of Photoperiodism According to Stages of Development

Representative Species	For Flowering	For Fruiting
Strawberry, *Cineraria*	Short-day	Long-day
Oxeye daisy, Spring barley	Long-day	Long-day
Physostegia virginiana, Boltonia latisquama	Long-day	Short-day
Soybeans, *Cosmos bipinnatus*	Short-day	Short-day
Phlox paniculata	Long-day	Day-neutral
Late rice varieties	Short-day	Day-neutral
Chrysanthemum osticum	Day-neutral	Short-day
Spinach, wheat	Day-neutral	Long-day
Pepper, early rice, buckwheat	Day-neutral	Day-neutral

After Eguchi, 1937

and day-neutral plants, according to the initiation of flowers, seed germination, stem elongation, leaf enlargement, tillering, leaf abscission, and fruit-setting. However, a long-day plant for floral initiation can be a short-day plant for fruiting, and vice versa. Strawberry, spinach, and wheat are of this type. Eguchi (1937) has made a classification of flowering and fruiting as shown in Table 4 - 6. Specifications of growth and development are needed in the classification of the photoperiodic nature of plants.

Studies on the duration of night have gained the attention of many researchers. Experiments conducted under controlled conditions have shown that the duration of night, or dark period, in some cases is much more important than the duration of the day. In the consideration of the duration of night, it is the complete darkness which is important. Assume that a specific long-day plant during its vegetative stage requires an 8-day treatment with a *minimum* of 14 hours of natural light during the day and a three-hour extension of low artificial light at night for the stimulation of flowering. A total of 17 hours of both natural and artificial light is needed. To achieve the same result, a 50-minute illumination in the middle of the dark period is sufficient instead of the three-hour extension of artificial light at the beginning and the end of the dark period. It seems that the plant can be "cheated" by thus altering the division of day and night! Hamner (1940) found that cocklebur, *Xanthium pennsylvanicum*, a short-day plant, must have a photoperiod of approximately 30 minutes or more (the time required is dependent on light intensity) followed by a minimum of eight-and-one-half hours of continuous darkness for floral initiation. If the darkness is interrupted by a short period of illumination, or if the time sequence of the 30 - minute photoperiod and the eight-and-one-half-hour dark period is reversed, the treatment is found to be ineffective. It is interesting to note that intermittent supplementary flash lighting for one - half to one minute, followed by a dark period, is as satisfactory as continuous illumination. Also, a few minutes illumination in the middle of the dark period is as effective as the intermittent flash lighting. Although these treatments are more economical, the kind of plant should be considered first, in application of this type of treatment.

It appears certain that green leaves are the organs which perceive the photoperiodic stimulus for both long- and short-day plants. This stimulus is transmitted slowly through the leaves to the stems. The photoperiodic sensitivity of a single leaf depends upon its age. The youngest mature leaf is most sensitive. When old, it becomes relatively insensitive. For a plant as a whole, the number of sensitive leaves increases with age. It follows that the older a plant is, the higher its sensitivity will be.

Research on plant responses is conducted more in relation to the duration of light than to the intensity and quality of light. Nevertheless, both intensity and quality are always associated with the duration of light. When the intensity of light alone is considered, photosynthesis requires intense light such as natural light, but for photoperiodic experiments a low supplementary light will be sufficient. For long-day plants, a supplemental light of less than five f.c. is sufficient. Withrow & Benedict in 1936 found that the light intensity can be as low as 0.1 f.c. for the China aster. The requirement of the dark period varies with the intensity of light received during the day.

Since light and heat cannot be separated, studies of temperature effects on photoperiodism have long been reported. In this connection, several terms have been defined: Thermophotoperiodic induction is the same as photothermal induction and is the effect of temperature on photoperiodism. Flowering and fruiting of late maturing soybeans such as Biloxi are favored by a combination of a short day and a warm temperature, that of *Rudbeckia bicolor* by a long day and a warm temperature, and that of sugar beets by a long day and a low temperature. Roberts & Struckmeyer in 1938 - 39 demonstrated the night temperature effect on photoperiodism in a great variety of plants. Poinsettia, a short-day plant, for example, failed to bloom when the night temperature was 55°F, while *Rudbeckia laciniata* , a long-day plant, responded to a night temperature of 55°F and short-day exposure. But at a night temperature of 60-65°F and with the same photoperiod, it remained in a rosette stage of growth. Went (1944) conducted experiments in the phytotron in California for the study of plant response with varying day and night temperatures. He named this light-temperature interaction thermoperiodicity. His work on the relationship between temperature and the rate of stem growth on tomato plants is shown in Fig. 4-5. The optimal growth was achieved by the combination of 79.7° F day temperature and a night temperature of 63.5°F. Went called the night temperature the nyctotemperature, and the day temperature the phototemperature. Likewise, the dark period was named nyctoperiod. In his later research he found that the optimal growth was also influenced by light intensity during the photoperiod. Usually lower temperature is associated with lower light intensities. The conditions that were optimal for stem elongation were also found to be optimal for the fruit set and growth. The adaptation of plants in their native or artificial habitat to specific temperature and photoperiod requirements has been known as thermoperiodic adaptation.

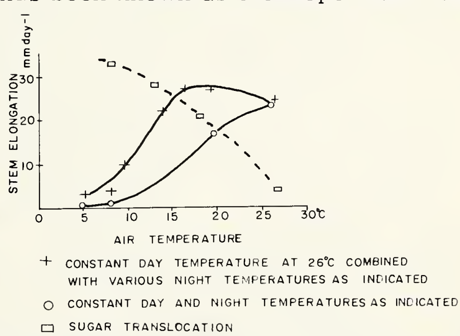

Fig. 4-5. Relationships of temperatures and tomato stem growth. After Went, 1944

Light quality is expressed in terms of various spectra, and has been studied extensively in association with photoperiodism. The blue and red spectra of the visible light range, as well as the infrared, far red, and long wave spectra, are most useful in the study of photoperiodism. Detailed descriptions of photoperiodic wavelength relationships will be explained shortly.

In agricultural application, in both fields and greenhouses, the influence of photoperiodism on the formation of flowers and development of fruit and seeds is of primary concern for successful crop production. The choice of the variety of crop and the selection of the farming area are closely related to thermoperiodic adaptation. In the natural field, commercial crops of the short-day type have commonly been covered with frames of black paper or curtains of black cloth during a part of the day. To lengthen the photoperiod for long-day plants, electric illumination of a comparatively low intensity can be used for crops that will justify high costs. In recent years, considerable research has been conducted under controlled photoreaction. Two approaches which have proved useful are the qualitative aspect of the photoperiodic response for a specific light spectrum, and the response to chemical controls such as coumarin, nitrate, indole-3-acetic acid, gibberellic acid, and several other compounds. For a more detailed discussion of literature on photoperiodism in plants and animals, the reader may consult Wang & Barger's (1962) ***Bibliography of Agricultural Meteorology,*** published by the University of Wisconsin Press, Murneek & Whyte's (1948) ***Vernalization and Photoperiodism***, published by the Chronica Botanica Company, Massachusetts, USA, Rottier et al.'s ***Proceedings of the International Photobiological Congress***, published by Veenan and Zonen in the Netherlands.

4.1.3 *Quality of light*

The physiological response of plants to various wavelengths differs with species, varieties, and strains. The effect of spectral energy distribution on the biochemical reaction of plants has been investigated intensively during the past 20 years; however, we are still restricted to the controlled environmental study. For the sake of agricultural practices, it is necessary to study the quality of light in the natural setting. The quality of light at sunrise and sunset, at twilight, on a clear or cloudy day, in foggy weather, and over high plateaus should be differentiated. The change of the air composition, such as the high concentration of ozone in the upper atmosphere, the presence of aerosol, as well as the changes in the solar declination associated with the seasonal variation, also have bearings on the light quality. Moreover, companion crops, under partially shaded conditions and under artificial cloth or polyethylene cover, will give some modifications. These are factors or conditions to be considered in research in the natural field. For successful research, instrumentation for crop and spectrum observations is of paramount importance.

As far as the light spectrum is concerned, there are numerous papers relating the effects of ultraviolet and visible light to such plant responses as seed dormancy, germination, photosynthesis, and metabolism. Other investigations are concerned primarily with the transmission and absorption of ultraviolet and visible light and portions of the infrared energy in the atmosphere; some describe their injurious effects on living organisms. Some special studies are concerned with X-rays and cosmic rays, particularly with respect to their possible application in genetics and plant breeding.

In short, plant response to spectral effects may be generalized as follows: Radiation up to 0.25 μ has a lethal effect, and near 0.30 μ, a therapeutic effect. In fact, wavelengths less than 0.29 μ have not been observed on the surface of the earth. From 0.30 to 0.55 μ and from 0.70 to 10 μ it has a photoperiodic effect; from 0.40 to 0.69 μ it is most active in photosynthesis. Between 0.40 and 0.74 μ it is mostly absorbed by chlorophyll. Above 0.74 μ it is in the infrared spectrum regime, where respiration is encouraged and thermal effects dominate.

Since most of the past work on plant response to the quality of light is restricted to controlled conditions, it is subject to certain limitations. First, there is a problem involving the choice of light, for different artificial lights produce different effects. Incandescent light, such as a tungsten filament lamp, provides a continuous spectrum. Its emission increases toward the longer wavelength with a peak in the infrared. The heating effect is serious. However, it would be useful for the extension of daylight. The gas discharge lamps, such as the mercury vapor, neon, and sodium lamps, are characterized by line spectra. The white fluorescent lamp, for example, can be designed with a peak emission at almost any point in the visible spectrum. Lamps of this type are most suitable, since they have little infrared radiation, and consequently have a less direct effect on the plant tissue. They also offer a much wider choice of spectral composition than any other type. For work with a narrow wavelength, it is necessary to use some kind of filter to absorb the unwanted wavelengths. This limitation causes difficulties in comparisons of data resulting from the application of the various light sources.

Secondly, there is a problem in the choice of plants. The large plants such as trees, except seedlings, are very difficult to perform an experiment upon. So far, the most successful studies of wavelength effect on plant growth and development are restricted to algae rather than higher plants. Further complications may arise due to the impossibility of producing light intensity comparable to the sun. It is interesting to note the effectiveness of low intensity which has been employed in such a study. Despite the above discrepancies, experiments have been made on some vegetable crops. In the study of light quality problems, both light intensity and photoperiod are usually specified. Vince & Stoughton (1957), in their study of tomatoes, found that a crop grown for a 16-hour period in a red light or in a combination of red and infrared light showed an abnormal internode extension. When grown in an eight-hour natural daylight and given radiation at different wavelength regions for another period of eight hours, abnormal internode extension also occurred. But when plants have first received infrared radiation, followed by red light radiation, this procedure has no effect. Table 4-7 shows the effect of a wavelength of

Table 4-7. Tomato Response to Quality of Light

	Type of Light					Significant Difference
	Blue	Green	Red	Infra-red	White	at P = 0.05
Height of plants (cm)	29.3	30.6	31.6	41.4	29.0	2.51

After Vince & Stoughton, 1957

a low intensity light, given as a supplement to daylight, on stem length of tomatoes. The experiment was conducted in April 1953, with the treatment of eight hours daylight plus eight hours of supplementary light at 2.09 cal cm^{-2} min^{-1} for a period of eight weeks.

Dunn & Went (1959) measured the photosynthetic effectiveness of tomatoes at the Earhart Laboratory, by correlation of dry weight of the plants and wavelengths in the visible spectrum at different intensities. Their findings are shown in Fig. 4-6. This shows that green light has the least photosynthetic efficiency. Neither the blue nor the red is as effective as the "warm white" light from fluorescent lamps. But their combination has the greatest effect. It was proved that the green wavelengths produce inhibiting effects on the growth of tomato plants. Neutral gray filters were chosen to reduce the green spectrum from full daylight, which resulted in the growth of larger and more healthy leaves, but a lighter green colored plant was produced after ten days of treatment.

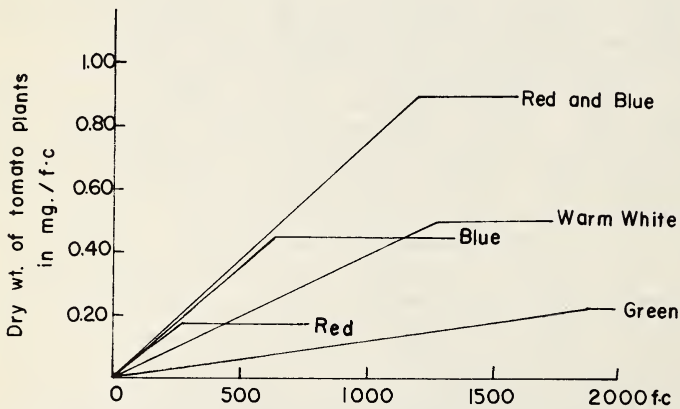

Fig. 4-6. The photosynthetic effectiveness of tomatoes and the visible spectrum. After Dunn & Went, 1959

Hendricks & Borthwick (1954), in their study of a reversible photoreaction controlling seed germination of lettuce, *Lactuca sativa,* and cocklebur, *Xanthium saccharatum,* found that a joint effect of light intensity and spectrum distribution contributes to the promotion of floral initiation at various energy levels. This is shown in Fig. 4-7. Other crops, such as barley, soybeans, and tomatoes have also been studied by them.

Much work can be done in this field, particularly experiments on plant response to light intensity, quality, and duration in a natural field condition. Further discussion on this subject will be given in Chapter 11, under "control of artificial environment."

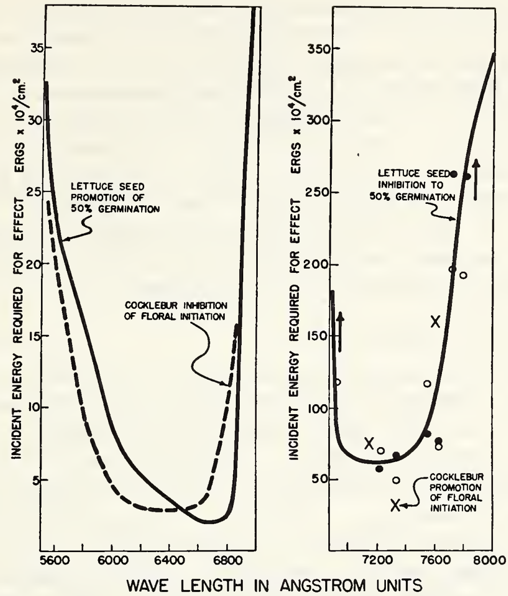

Fig. 4-7. Reversible photoreaction on seed germination of lettuce and cocklebur. After Hendricks & Borthwick, 1954

4.2 HEAT AND TEMPERATURE

Temperatures, which have long been known as an essential element for the growth and development of plants, are considered here as a means of representing the available energy which plants may need for growth as well as a parameter for measuring the survival and injury of plants. The measurement of air temperature is relatively easy, although the true temperature (or the representative temperature surrounding a plant) is hard to determine. The soil and plant temperatures are more difficult to measure. Using temperature as an environmental factor for plant response studies, the following aspects should be considered: (a) the extremes and variations of temperature with respect to lethal and threshold temperature limits, optimal temperature ranges, and hardiness, dormancy, and vernalization problems; (b) the duration of temperature levels and their significance in plant response; (c) the space temperature variations and their vertical and horizontal gradients; and (d) the heat unit system — i.e., the daily accumulation of temperature above a certain threshold value for a specific phase or stage of plant development.

As has been explained in Section 2.2.1, the available energy in the air, soil, and plant for the growth and development of a crop can be represented by heat. At the present stage, no instrumentation is available for the direct measurement of heat from the plant in the field condition without causing damage to the plant. Unless the density and the specific heat for the heterogeneous material of the soil and plant are known,[13] the effective measurement of heat is not possible. For convenience, temperature has often been employed as a substitute for heat. The term "heat unit system" implies an assumption that the temperature is a measure of heat, but it has certain shortcomings. The evaluation of the "heat unit system" will be presented later. In this section, we are interested in obtaining more representative temperatures for the description of the thermal response of a plant. Various methods will be suggested.

4.2.1 *The cardinal temperature*

The effects of extreme temperatures on the survival or injury of plants vary with species, varieties, age, stage of growth, weather condition, and even with the pre-treatment of plants.[14] During the dormant stage, plants can survive at much lower — and sometimes higher – temperatures than otherwise. Some plants need extreme temperatures to break dormancy. The word "hardiness" is generally accepted for the degree of resistance of a plant to low temperatures. Warm-season crops, such as tomatoes, sweet potatoes, okra, and watermelon, are tender; cold-season crops such as peas, cabbages, beets, alfalfa, and wheat are hardy. There are also crops which lie between these two categories.

Vernalization, on the other hand, usually designates a phenomenon of cold treatment (temperature at about 32°F) of the germinated seeds before sowing, or of seedlings before transplanting, for the hastening of the time of flowering, which in turn results in an early harvest. Vernalization of seeds sometimes occurs while they are still attached to the parent plant. A warm spell followed by a cold spell may offset any vernalization which has already been achieved during the cold period. This phenomenon is termed "devernalization." The vernalization of winter cereals has been studied intensively for more than 30 years. Vernalization is an example of physiological preconditioning or predetermination. Other examples that have already been discussed are photoperiodic induction, photothermal reaction, etc.

[13]Due to handicaps in the technique of measurement, and to heterogeneity of the soil and plant material, density and specific heat cannot be measured accurately. Even when temperature is used, instead of heat, the determination of exact plant temperature is still a problem.

[14]The weather conditions designated here as environmental factors other than temperature are associated with temperature and determine survival and injury of plants. Examples of the combined factors are temperature-light interaction and temperature-humidity relationship. As to the treatment of plants, some are artificial (e.g., hardening the tissue plants), and others natural. Alfalfa in the natural field, for example, suffers less injury if the time schedule of the cuttings is arranged so as to reserve enough carbohydrates and sugar for these plants to resist cold temperatures.

Further study of physiological predetermination in the event of crop forecasting will be given in Chapter 8.

The study of the intensity (absolute) and the variation (relative) of temperature in terms of the plant's optimal, lethal, and threshold temperature requirements are listed below.

(a) Temperature limits. The uppermost and lowest temperatures which are detrimental to a plant's growth are the lethal temperatures of that plant. For most higher plants, the upper lethal limits are around the daily maximum of 125°F, and the lower at about the daily minimum of 32°F. Some plants can survive at exceedingly high temperatures, and others, exceedingly low. It is commonly known that perennials exist over winter in the coldest regions of the world, and through the summer in the very hottest areas. The highest and lowest temperatures recorded anywhere on the earth except at the polar regions are 136°F at El Azizia, Libya, North Africa, on September 13, 1922, and -90° F at Verkhoyansk, Siberia, February 5 and 7, 1892. In the winter of 1938, the lowest unofficial temperature at Oimekon, Siberia, was -108°F.

Oakley & Garver (1917) reported that the species *Mediago falcata*, a yellow-flowered alfalfa, was grown in Siberia where temperatures went as low as -84°F. Aamodt (1941) stated that certain varieties of alfalfa have been grown successfully where maximum summer temperatures exceed 120°F. The most striking fact is that pigweed seeds break their dormancy at a temperature above 104°F for germination. Harrington (1923) treated Johnson grass seeds, *Holcus halepensis* , by alternating temperatures at 86°F for 18 to 22 hours and 113°F for two to eight hours, for the improvement of germination. Overwinter alfalfa is not killed by the frozen ground, but by the ice-sheet cover which stops respiration. Evergreens are often killed by the so-called physiological drought which is caused by low temperature and high solar intensity. In this case, there can be an abundance of water present in the soil.

It has been reported by Brown & Hutchison (1949) that the lethal temperature for sweet corn at the milking stage is 28.9°F. The lethal temperatures of the soil for the germination of various vegetable crops are listed in Table 4-8. When the plant ceases to grow below or above the lower or upper threshold temperatures, respectively, a temperature limit is defined.

The differentiation of the lethal and threshold temperatures is not always clear. Some investigators do not believe that this distinction can be made. Thus, the lower limit of the two may be treated as the "minimum temperature requirement," or the "freezing temperature" of the crop. Likewise, the upper limit is termed the "maximum temperature requirement." Should there be no differentiation between the

Table 4-8. Soil Temperatures for Vegetable Seed Germination*

Crop	Lower Lethal	Lower Threshold	Optimal Range	Upper Threshold	Upper Lethal
Asparagus	32	50	77-86	95	105
Bean, Lima	38	60	65-80	85	100
Beet	30	40	50-85	95	---
Cabbage	32	40	45-95	100	---
Carrot	30	40	45-85	95	---
Corn	33	50	60-95	105	107
Cucumber	38	60	60-95	105	---
Lettuce	32	35	40-80	85	100
Onion	32	35	50-95	95	100
Pea	30	40	40-75	85	95
Radish	30	40	45-90	95	100
Squash	38	60	70-95	100	---
Tomato	36	50	60-85	95	---
Watermelon	38	60	70-95	105	---

*This was compiled from the results of several authors' investigations. Temperatures are in degrees Fahrenheit.

lethal and threshold temperatures, the "range" rather than the specific value becomes of major concern.

(b) Optimal temperature ranges. The optimal temperature for plant response is also difficult to define. It cannot be determined as sharply as the lethal and the threshold temperatures, but an optimal range can always be established for one locality and for a specific crop. In the case of crop yield, there is no absolute standard set up for the optimum. And the average high yield of all geographical regions cannot serve as a standard, either. Strictly speaking, neither can we use the greenhouse production as our standard. This applies to all other events concerning growth and development of a crop.

The optimal soil temperature ranges for the germination of various vegetable crops are listed in Table 4-8; the type of cultural practice, the instruments used, and the kinds of crop chosen, are by no means absolute. Cultural practices for germination are many. Materials used for germination tests are cultural solutions, vermiculite, sand-peat-leafmold mixture, and even cotton. Three environmental conditions other than temperature are required for germination: light, water, and oxygen. Thus, different cultural practices will provide different oxygen and water contents of the soil, which affect the soil temperature. In the case of hydroponics, it is the water temperature that is measured. Moreover, the optimal temperature range varies with intensity, duration, and quality of light. Seed storage and seed treatment are other factors that need consideration. The difference in the type of instruments employed may also bring about different results. Therefore, experimental results on optimal temperatures should always be evaluated in the light of the above conditions.

In the study of cardinal temperature, temperatures of plant organ or organs are essential information. The leaf temperature is a better indicator of temperature limits than is the air temperature. The root temperature is superior to the soil temperature. When the upper lethal temperature is considered, a crop may be killed because its temperature is too high, which is influenced only indirectly by the ambient air temperature. Thus, the air temperature in the greenhouse can be high enough to cause damage, but with the same air temperature in the natural field, the leaf temperature will remain low enough to avoid injurious effects. The wind velocity, the water vapor pressure gradient, and the transpiration rate reduce the temperature of a leaf, while the solar radiation and the air temperature increase its temperature. On days with low sunlight intensity, leaves transpire rapidly, and their temperatures are much lower than the surrounding air. This holds true for leaves in the shade. When the leaf is exposed to sunlight, on the other hand, the leaf temperature can be 25°F higher than the enveloping air. Therefore, the upper lethal temperature is best determined by the leaf temperature during the day, especially during clear days. The difficulties encountered are the inadequacy of instrumentation and the constant fluctuation of leaf temperatures due to momentary weather changes. A single wind eddy will turn leaves from an unshaded to a shaded position in minutes. The intermittent sunshine results in frequent shifts in the leaf temperature. Therefore, it is necessary to design a new instrument, which will be able to measure the entire integrated temperature of all leaves instantaneously.

During the night, the leaf temperature is about the same as the air temperature, if there is a wind turbulence. On calm, clear nights, the leaf temperatures can be considerably lower than the air temperatures. Shaw (1954) found that the night air temperature at 1 cm above tomato leaves is 1.8°F higher than the leaf temperature. In the meantime, the temperature registered at the weather shelter (about $4\frac{1}{2}$ feet above the ground) indicates 5.4°F to 8.1°F warmer for a calm, clear night, but it is only 3.6°F warmer for an overcast night. When some tomato leaves start to freeze, the temperature of the leaves rises from 24.4°F to 28.0°F. The source of heat may be the heat of fusion, as indicated by Shaw. But he has not found all leaves to have such properties. Noffsinger (1961) also indicated that the shelter air temperature at plant level does not provide a good measure of plant temperature. Papaya, with a respiration and transpiration pattern characteristic of the mesophytes, shows a leaf temperature which remains relatively near the air temperature, but may be higher or lower than the air temperature, depending upon the condition of radiation, cloud cover, and wind. During the daylight hours, the leaf temperature of pineapple, a xerophyte, shows an average of 1.5 to 3.5°C above the ambient air temperature. For short periods of high solar radiation a leaf temperature of 7.6°C above the air temperature was recorded for pineapples. Both papaya and pineapple leaf temperatures are below the air temperature during the night. His observation records on April 12, 1960, in Hawaii are listed below. The temperatures are expressed in degrees Centigrade.

Local time:	0400	Sunrise	0800	1200	1600	2000	2400
Air temp.	21.9	22.0	22.0	25.7	26.7	22.3	22.2
Leaf temp. (avg.)							
Pineapple:	22.1?	21.7	23.5	29.5	27.1	21.7	21.5
Papaya:	21.0	21.7	21.3	25.1	24.8	21.2	20.5

When the lower lethal temperature limit is considered, the night leaf temperature is important, particularly during calm clear nights. In short, both upper and lower limits of the lethal temperatures are best determined by the leaf temperature. This holds true for the upper and lower threshold temperatures and the optimal temperature ranges, as well.

When the subterranean environment is considered, the root temperature is superior to the soil temperature. Studies of soil and root temperatures will be further elaborated later in this section. The water temperature is well represented by the root and underground stem temperatures in cultural solution. The water temperature is about the same as the root temperature if the solution is well stirred. It is obvious that the water temperature is much easier to measure than the soil and root temperatures.

(c) Physiological aspects of temperature influences. The lower threshold temperatures vary with species and varieties of plants. Hardy plants can take subfreezing temperature at a certain phase of their life cycle without injury, while tender, warm-season crops cease to grow even at a temperature of 50°F. This inherited nature of plants can be explained in two ways: the change of the environment to suit the plant, and the change of the plant to fit the environment. The first category will be discussed fully in Chapter 11. In the second category, geneticists and plant breeders have developed cold-resistant hybrids. This has been done successfully, but with the expense of time. An even longer time would be taken for a certain species of plant to survive in a new environment without the aid of a breeder. Acclimatization is the process by which a living organism or plant becomes adapted to a change of the climatic environment, and is sometimes called "acclimation." The latter, which refers to a pure natural process (or state) developed by living organisms themselves, is a better term than the former, which denotes a process evoked by human agents. However, in Great Britain, the term "acclimation" has never been accepted, while in the United States both "acclimation" and "acclimatization" are used. Adaptation may be defined as the modification of an animal or plant (or of its parts or organs) fitting it more perfectly for existence under the conditions of its environment. In relation to plant studies, the word "adaptation" has been loosely used with "acclimatization." It is interesting to notice the change in the morphological development of a crop for adaptation to a new environment. Some hybrids will survive in a cold climate, but become dwarfed, reduce yields, and shorten the growth period. Other plants will best adjust themselves for heat economy. In other words, plants will accept the wanted and reject the unwanted heat and radiation. This is an inherited nature of plants to apply the process of energy balance (or heat balance) for their benefit by changing the position of leaves or even the structure of the plant. Kessler & Schanderl (1931) published photographs of the white melilot, *Melilotus albus* , with its leaves in different positions. The leaves of certain plants, after 15 minutes of irradiation by an electric heater, will change to their daytime position and crease their surfaces so as to reduce the heat absorbing area. During the night, the leaves stand up almost vertical to reduce the long-wave radiation losses. In the severe radiation and heat of the tropical desert, cactus plants can survive by tufts of thorns and pubescence, which cover the leaf surface so as to break the irradiation. Sunflowers turn around in order to receive the maximum solar radiation. They follow the sun's diurnal position. The seasonal variation in the color of leaves, the hourly change in the appearance of the landscape, and many other examples reveal the heat economy of plants.

So far there has been much discussion concerning the relationship of plants to their thermal environment. Mention should also be made concerning dormancy and vernalization. These have been two major topics for biologists, and belong in the province of botany.

The state of the inhibited growth of seeds, buds, and other plant organs as a result of internal causes is usually called dormancy, but is sometimes referred to as the "rest period." The external influences, such as temperature, light, and humidity, tend either to break or to prolong dormancy. Research on seed dormancy was done by Crocker et al. over a 30-year period, at the Boyce and Thompson Institute for Plant Research at Yonkers, New York. Most of the work was done under controlled conditions, but many observations have been made under natural field conditions. It was reported that the external influences on the dormancy of seeds started as early as the premature seeds attached themselves to the parent plant. The intensity of light, temperature, relative humidity, and rainfall are the factors considered. These factors are also a control on the dormancy of buds and other organs of plants.

A plant displays the capacity to respond to low temperature when dormancy of the ripe seed is broken and germination begins. Winter cereals proceed most rapidly to reproduction if they are first chilled, followed by an exposure to a number of days with an optimal temperature. In the research on developmental physiology, Gassner (1918) was one of the early chillers of grains. In 1928, Lysenko published his first article on "Effect of the thermal factor on length of phases in development of plants" in the USSR. He set up the foundation of vernalization known as "Lysenko's Method for the Pretreatment of Seed." Since then, techniques have been well developed on other phases of plant development and a large number of crops has been tested. It has achieved world-wide acceptance, extending to the tropical crops (Sircar, 1948). As has been pointed out previously, vernalization is one of the physiological phenomena of predetermination.

Another aspect that needs consideration is the *change of temperature* with time and space. The space variation of temperature in a large area will appropriately be introduced as the "growing season."

4.2.2 *The growing season*

A true growing season may be defined as the number of days in a year in which a crop can grow. Usually the definition of a normal growing season is understood as the time that elapses between the mean date of the last occurrence of killing frost in the spring and that of the first in the fall of the same year. This, of course, will not apply to all crops in one region, for each one of them responds to a different threshold temperature.

Recently, workers of the agricultural experiment stations in the United States have computed the growing season according to certain *specific minimum temperatures*, namely 16, 24, 28, 32° F, etc. (Decker, 1951; Pengra & Magnuson, 1954; Shaw, Thom & Barger, 1954). The last occurrence of these temperatures in the spring and the first occurrence in autumn determines the growing season for native and cultivated plants. Nevertheless, discrepancies are still not completely eliminated. On the one hand, only the normal dates of a few specific minimum temperatures have been selected and computed. Therefore, minimum temperatures other than those selected must be interpolated but not extrapolated. Thus, only a limited number of selected temperatures can be estimated. Too much labor has to be put into the process of computation for one single region and hence it will be difficult to secure data for all regions. Temperatures in the microlayer more closely represent the ambient air of a crop than do temperatures taken in the weather shelter. Therefore, the specific

Table 4-9. A Comparison of the Last and First Occurrence of Killing Frost, with Freezing Temperatures in Spring and Autumn, for 10 Selected Stations in Wisconsin, 1930-1954

Station	Date of occurrence of killing frost		Date of occurrence of freezing temp., 32°F		Difference in days, between killing frost and freezing temp.	
	Spring	Autumn	Spring	Autumn	Spring	Autumn
Beloit	4-26	10-16	4-26	10-12	0	4
Green Bay	5-4	10-9	5-6	10-9	2	0
La Crosse	4-28	10-11	5-1	10-11	3	0
Madison	4-23	10-19	4-25	10-19	2	0
Medford	5-17	9-24	5-20	9-24	3	0
Milwaukee	4-26	10-21	4-30	10-19	4	2
Oconto	5-13	10-1	5-18	9-24	5	7
Oshkosh	5-6	10-6	5-6	10-6	0	0
Shawano	5-7	10-8	5-5	9-26	2	12
Waupaca	5-14	9-30	5-10	10-6	4	6

minimum temperatures being observed in the weather shelter are not appropriate (Shaw, 1954). They must be interpreted in terms of associated temperatures in the microlayer. This can be seen readily in Table 4-9, which illustrates the difference in days between killing frost and freezing temperature of the weather shelter.

In this connection, a simple scheme must be established so that the normal date of occurrence of *any* minimum temperature in the microlayer in the spring, as well as in the fall, can readily be obtained in a region without much computation. This method has been developed by Wang & Suomi (1957).

Both physical and physiological principles are involved in the evaluation of a true growing season. The changes of the thermal state of the lower atmosphere are physical processes, while the responses of crops to these changes are physiological sequences.

The main assumption involved in this method is that when the freezing temperature of the air in the microlayer near the ground reaches 32°F, the killing frost will occur. A killing frost is designated here as one which is destructive to vegetation and staple products. This applies to both "black" and "white" frost, which has been explained in Section 2.2.1. Table 4-9 shows that the dates of occurrence of the freezing 32°F do not agree completely with the dates of occurrence of killing frost. Nevertheless, when both frost date and freezing temperature are considered simultaneously, the above assumption holds true.

Since types of soil are the main controlling factor in the formation of killing frost, they can be used as a test of the validity of the above assumption. For each type of soil, at the date of occurrence of the killing frost, the thermal diffusivity of soil will vary with the difference between 32°F and the monthly mean daily minimum temperature in Fahrenheit. The latter property is a measure of the difference between the freezing temperature at the ground and the mean monthly daily minimum temperature at the weather shelter. This difference may be called "K".

Thus, if the monthly mean of the daily minimum temperature ($\bar{T}_m$) is used, "K" is defined as

$$K = \bar{T}_m - 32. \tag{4-28}$$

If the monthly mean daily temperature ($\bar{T}$) is adopted instead of the monthly mean daily minimum temperature, then a different value is obtained:

$$K = \bar{T} - 32. \tag{4-29}$$

Since $\bar{T} = \frac{1}{2}(T_M + \bar{T}_m)$, where $\bar{T}_M$ is the monthly mean daily maximum temperature and $\bar{T}_m$ the monthly mean daily minimum temperature,

$$K = \frac{1}{2}(\bar{T}_M + \bar{T}_m - 64). \tag{4-30}$$

Of the two definitions of K, equation (4-28) is preferable.

In an area the size of the state of Wisconsin, K may be a quasi-constant with respect to a definite type of soil (e.g., Miami Silt loam) at a specific season of the year (spring or autumn). The complex relationships between mean K values, season, and the types of soil or the thermal diffusivity of soil are displayed in Table 4-10, which is self-explanatory.

Table 4-10. Temperature Constant "K" According to Type of Soil and Thermal Diffusivity

	No. of Cases	Seasonal mean K* Spring	Fall	Annual mean K	Ratio of K	h
Peat Soil (in the vicinity of)	9	25.0	25.6	$K_p = 25.3$	$K_p/K_p = 1.0$	$h_p/h_c = 0.5$
Sandy Soil	41	23.0	23.6	$K_s = 23.3$	$K_s/K_p = 0.9$	$h_s/h_c = 0.6$
Loamy Soil (silt)	41	20.9	21.6	$K_\ell = 21.3$	$K_\ell/K_p = 0.8$	$h_\ell/h_c = 0.8$
Clay Soil	15	16.5	18.9	$K_c = 17.7$	$K_c/K_p = 0.7$	$h_c/h_c = 1.0$

*As defined in equation (4-28).

Types of soil in Wisconsin have been arranged into four main groups as indicated. They consist of:

(i) Peat Soil --peat and associated poorly drained sand "islands;"
(ii) Sandy Soil --sandy soils, rough land, and wet land;

(iii) Loamy Soil --Miami Silt loam, Knox silt loam, Prairie soil, Boone fine sandy loam, and Kennan loams;

(iv) Clay Soil --red clays with and without sandy loam cover.

With the aid of the above soil groups, mean K values for 106 stations in Wisconsin were prepared. This is shown in Table 4-10, where K_p, K_s, K_ℓ, and K_c stand for the temperature constant "K" of peat, sandy, loamy, and clay soils; h_p, h_s, h_ℓ, and h_c stand for the heat diffusivity of the respective soils.

A simple graphical method for the estimation of the true growing season is as follows: Plot either the monthly mean minimum temperatures or the monthly mean daily temperatures as ordinate against the day of the month as abscissa. Plot each monthly mean temperature at the middle of that month as is illustrated in the solid line of Fig. 4-8. The temperature here refers to the temperature recorded in the weather shelter. Enter the normal frost date on the temperature curve at a point labelled "F." Extend this point downward until it reaches a point where the temperature reads 32°F. The occurrence of the freezing temperature 32°F is used here as the date of formation of either white or black frost. Obviously this refers to temperature at the microlayer. The vertical distance between the point F and 32°F, expressed in degrees Fahrenheit, is K, defined in terms of the monthly mean daily temperature. With this K value, a temperature curve for the microlayer can be prepared. This is illustrated as the dash line of Fig. 4-8. If any temperature (T) is of interest, the normal date of the last oc-

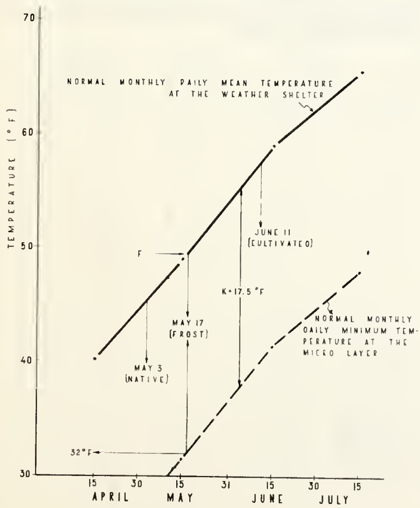

Fig. 4-8. Evaluation of "K" value for Port Wing in spring.

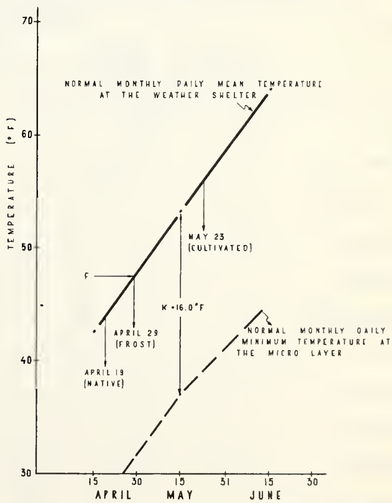

Fig. 4-9. Evaluation of "K" value for Sheboygan in spring.

currence of that temperature corresponds to a temperature reading on the graph of T + K.

Figs. 4 - 8 and 4 - 9 are used as an illustration of the method described above. In Fig. 4-8, the normal killing frost date of Port Wing, Wisconsin, is May 17. After plotting the monthly daily mean temperature of the weather shelter, and entering the frost date, the value of K is 17.5°F. With this K value, a parallel line can be drawn. This dashed line is the normal monthly daily minimum temperature in the microlayer. If one assumes 40°F as a threshold temperature for the growth of a group of cultivated plants, then 40 + K or 40 + 17.5 = 57.5°F. This temperature intersects the solid line at the date of June 11. This is the date of the last occurrence of 40°F at Port Wing in the spring. Similarly, if 28°F is chosen as the threshold temperature for a group of native plants, then the normal date of occurrence of 28°F would be May 3.

A comparison of Port Wing (46° 46' N; 91° 24' W) and Sheboygan (43°45' N; 87°43' W) in Figs. 4-8 and 4-9, respectively, shows that both temperature curves and frost dates are quite different from one another. Nevertheless, the K values are quite close to each other. Port Wing K is 17.5°F, while Sheboygan K is 16.0°F. This may be due to the fact that both of these stations have nearly the same type of soil, namely a red clay.

Table 4-11. Verification of Actual and Estimated Date of Occurrence of Various Minimum Temperatures

Station	Minimum Temperature Scale											
	16		24		28		30		32		34	
	S*	A*	S	A	S	A	S	A	S	A	S	A
Beloit	-3	0	3	2	0	1	0	1	0	-4	0	2
Green Bay	2	0	6	-1	2	0	3	-1	2	0	0	0
La Crosse	2	-1	2	0	2	1	-1	-2	-4	0	-2	0
Madison	-2	2	2	-2	0	1	-2	3	-2	0	-5	3
Medford	4	-1	-2	4	-3	3	-3	2	0	2	-1	0
Milwaukee	-8	7	2	1	-3	1	-5	0	-4	3	0	-1
Oconto	1	1	0	-4	2	3	-3	5	-4	6	-3	3
Oshkosh	6	-2	0	1	1	0	1	1	-1	1	-1	-1
Shawano	6	-5	6	0	-1	1	0	0	-1	2	3	0
Waupaca	6	-3	5	0	0	3	-3	2	-3	3	-2	3
Absolute value of mean departure	4	3	3	2	1	1	2	2	2	2	2	1

*S = spring; A = autumn.

The difference in days between the estimated values and the actual values of six minimum temperature scales (16°, 24°, 28°, 30°, 32°, and 34°F) are given in Table 4-11. The positive value in the table shows the actual date occurring later than the estimated date in spring or autumn, respectively, and vice versa for the negative value.

The departures existing between the actual and the estimated dates — though they are small — may be due to:

(i) the difference between the actual temperature in the weather shelter and the assumed temperature in the microlayer;

(ii) the frost data not being completely accurate, and being subjective in observation; or

(iii) the fact that there is always a greater lapse rate of temperature between the surface and the weather shelter than from there on up.

Therefore, the estimated data representing the micro-air-layer will definitely be different from the observed data of the weather shelter air. Further elaboration on the accuracy of the present method is given below.

The bending of the normal monthly daily temperature curve from month to month will cause the difference in data evaluation. This is the only possible error besides that induced from the above assumption in data evaluation. This abrupt change of temperature curve will shorten the growing season, if bent inward, and vice versa, if outward. Thus error is introduced by the deviation of the monthly daily temperature from a straight line.

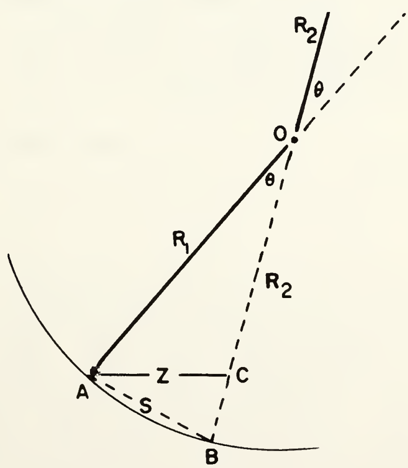

Fig. 4-10. Accuracy for the illustration of growing season evaluation.

In Fig. 4-10, let $\overline{OA}$ or R_1 be the straight line extending from the temperature curve of the later month in the spring. $\overline{OC}$ or R_2 will be the temperature curve of the present month. Thus, the deviation of R_2 from R_1 is θ. With O as the center of a circle and $\overline{OA}$ the radius, then S is the chord. Z is parallel with the abscissa, and represents time, i.e., the date.

From the Law of Cosine, $S = 2R_1 \sin \theta/2$, hence

$$Z^2 = S^2 + (R_1 - R_2)^2 - 2S(R_1 - R_2)\cos\left(\frac{\pi}{2} - \frac{\theta}{2}\right)$$

$$Z^2 = (R_1 - R_2)^2 + 4R_1R_2 \sin^2 \theta/2. \qquad (4\text{-}31)$$

Consider R_1 constant; then differentiate equation (4-31)with respect to time and simplify.

$$Z\,dZ = (R_2 - R_1)\,dR_2 + 2R_1 \sin^2\frac{\theta}{2}\,dR_2 + 2R_1R_2 \sin\frac{\theta}{2}\cos\frac{\theta}{2}\,d\theta. \qquad (4\text{-}32)$$

But $2\sin^2\frac{\theta}{2} = 1 - \cos\theta$ and $2\sin\frac{\theta}{2}\cos\frac{\theta}{2} = \sin\theta$. Substituting these in equation (4-32), thus,

$$Z\,dZ = (R_2 - R_1\cos\theta)\,dR_2 + R_1R_2\sin\theta\,d\theta, \text{ or}$$

$$Z\,dZ = C_1dR_2 + C_2d\theta,$$

where $C_1 = R_2 - R_1\cos\theta$. If θ is small[15] and less than 10°, C_1 approaches 0, $C_2 = R_1R_2\sin\theta\,d\theta$, hence,

$$Z\,dZ \approx C_2\,d\theta. \qquad (4\text{-}33)$$

Applying the Green Bay data in equation (4-33) for illustration, the values R_1, R_2, and Z can be measured in the graph; they are 4.1 cm, 3.6 cm, and 0.5 cm, respectively. Take finite values for dZ and $d\theta$ as ΔZ and $\Delta\theta$, thus $0.5\Delta Z = 4.1 \times 3.6 \sin\theta\Delta\theta$, where ΔZ is the departure in days due to the deviation of $\Delta\theta$. The result is tabulated in Table 4-12.

Table 4-12. Verification of the Accuracy of the Growing Season Estimates, in Days

$\Delta\theta$ (in degrees)	0	1	2	3	4	5	10
ΔZ (in days)	0	0	0	0	0.2	0.2	1

Area distribution of the growing season may be presented by the following growing season maps: (1) normal data of the last freezing temperature in the spring; (2) normal date of the first freezing temperature in autumn; (3) average length of the growing season; (4) normal growing season for native and cultivated plants; (5) the variation of the growing season for the 60 and 80 percent probabilities; (6) growing season of any specific crop concerned; and (7) classification and distribution of frost zones. Items (3), (4), and (7) for

[15]As θ rarely exceeds 10°, the error due to the departure from a straight line is negligible.

Wisconsin are shown in Figs. 4-11 through 4-14. The methods of analysis are explained below.

The climatological stations which provide the basic data for analyses are not ideally distributed. Some stations are located in places which do not represent the agricultural area of their immediate vicinity, such as in urban areas or in river valleys. In addition, there are not enough stations for a detailed analysis, so one must interpolate between stations. The differences in the climate within an area the size of a county are caused by local influences on the general weather pattern. If one takes into account local effects, he obtains a more realistic interpolation of the climate between stations. It is qualitative, but the results are much more representative than would be obtained with a simple linear interpolation.

In the analysis, four local effects were considered — topography, type of soil, vegetative cover, and proximity to cities, lakes, or rivers.

Topography is important because the steepness of a slope, as well as its orientation, has a marked control over the temperature.

Soil type is important since each may have different thermal properties, as explained before. The 12 main soil types for Wisconsin were qualitatively classified into four groups according to their heat diffusivities (see Table 4-10). On the one hand, peat soils have a markedly lower heat diffusivity than other soils, allowing the temperature of the microlayer to drop very rapidly at night. On large marshy areas, frost may form even in summer. On the other hand, loamy and clay soils, which have greater heat diffusivity, tend to restrict the diurnal temperature range. For example, Coddington, a station within marshy areas, has a normal growing season of 100 days. But the surrounding stations, such as Stevens Point, Wisconsin Rapids, Hancock, and Waupaca, have 145, 141, 131, and 147 days, respectively (see Fig. 4-11). In a case like this, the isolines are drawn to fit the data and the shape of the marshy area.

A vegetation map was classified into three types of coverage: the virgin timber area, the pastureland area (including the general farm land), and the second growth timber area (including cutover and waste land). The virgin timber areas are especially important because when they are located on the upper portions of a slope they tend to reduce the flood of cool air running down the slope to the valley floor. Consequently, spring usually comes early in these regions. On the other hand, pastureland tends to be cooler, through processes of evaporation and back radiation, thus facilitating frost formation.

For example, in Fig. 4-11, the 130-day isoline of the normal growing season has bulged northward as far as the Tomahawk Spirit Reservoir stations, while Shawano, located further south, has only a 125-day growing season. This is true even though the elevation of Tomahawk is 1435 feet and Shawano only 796 feet.

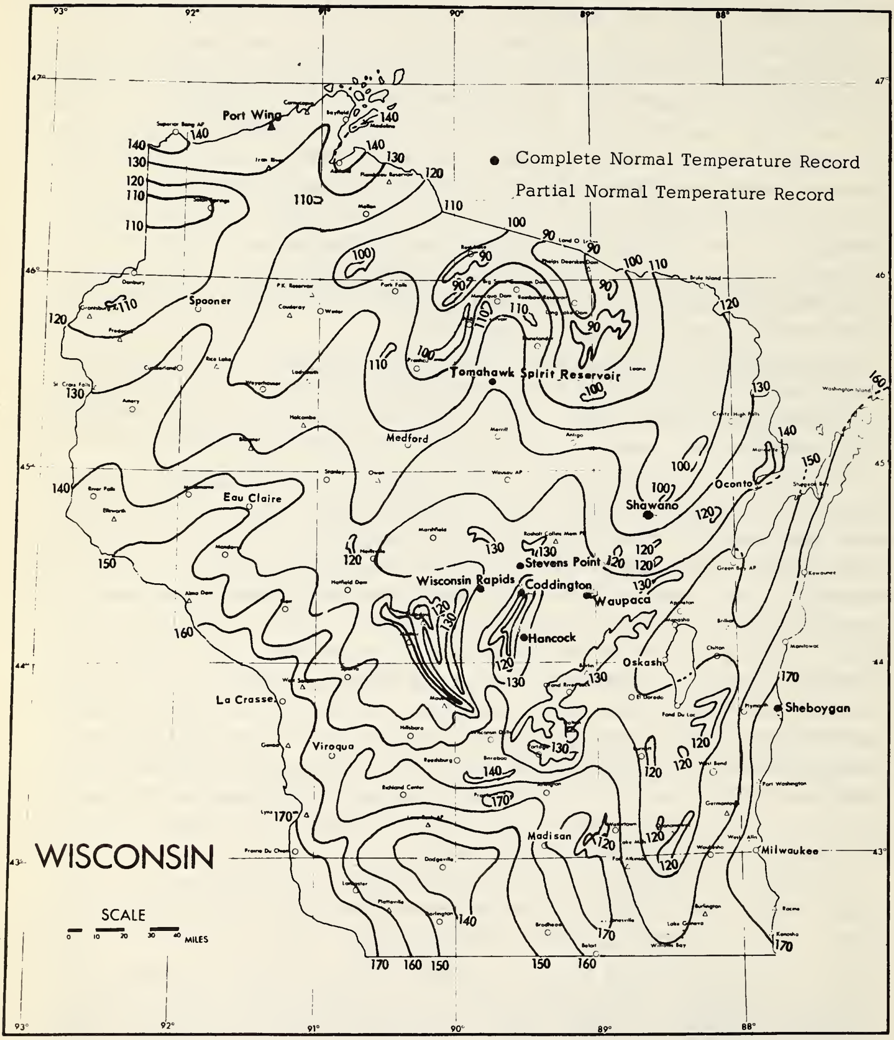

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Fig. 4-11. Average length of growing season.

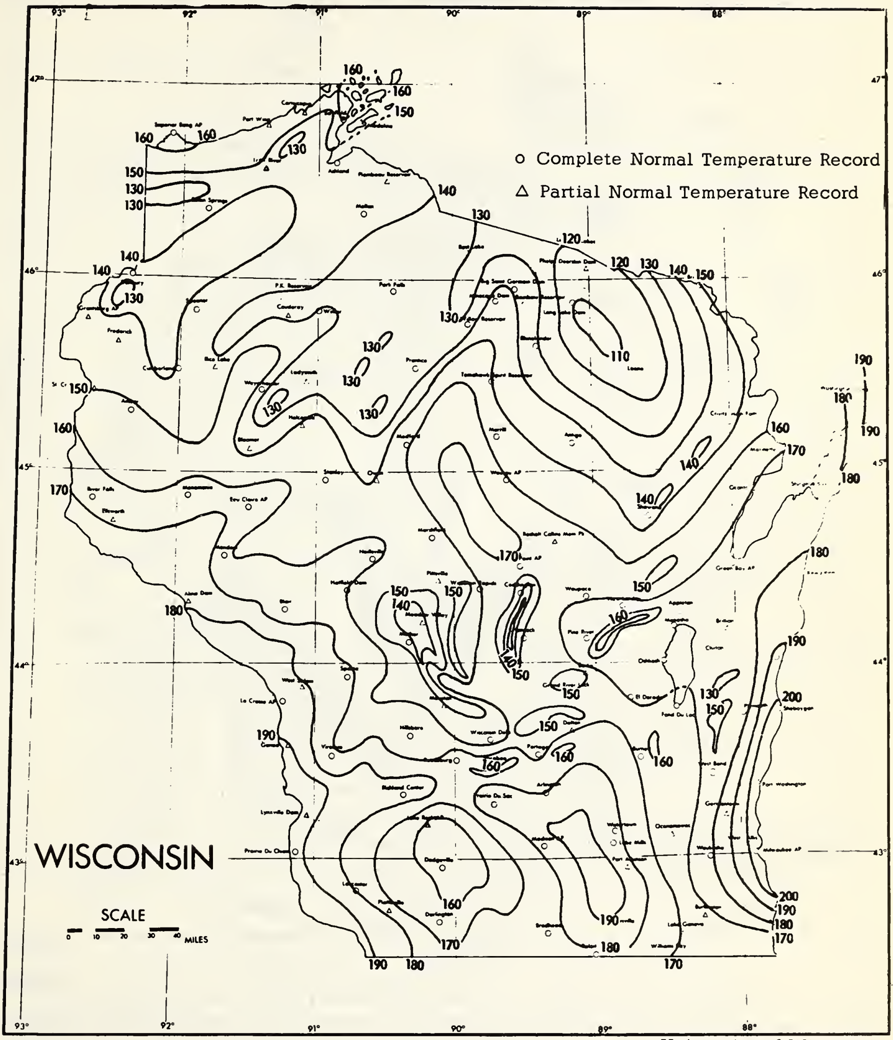

Fig. 4-12. Normal annual growing season for native plants.

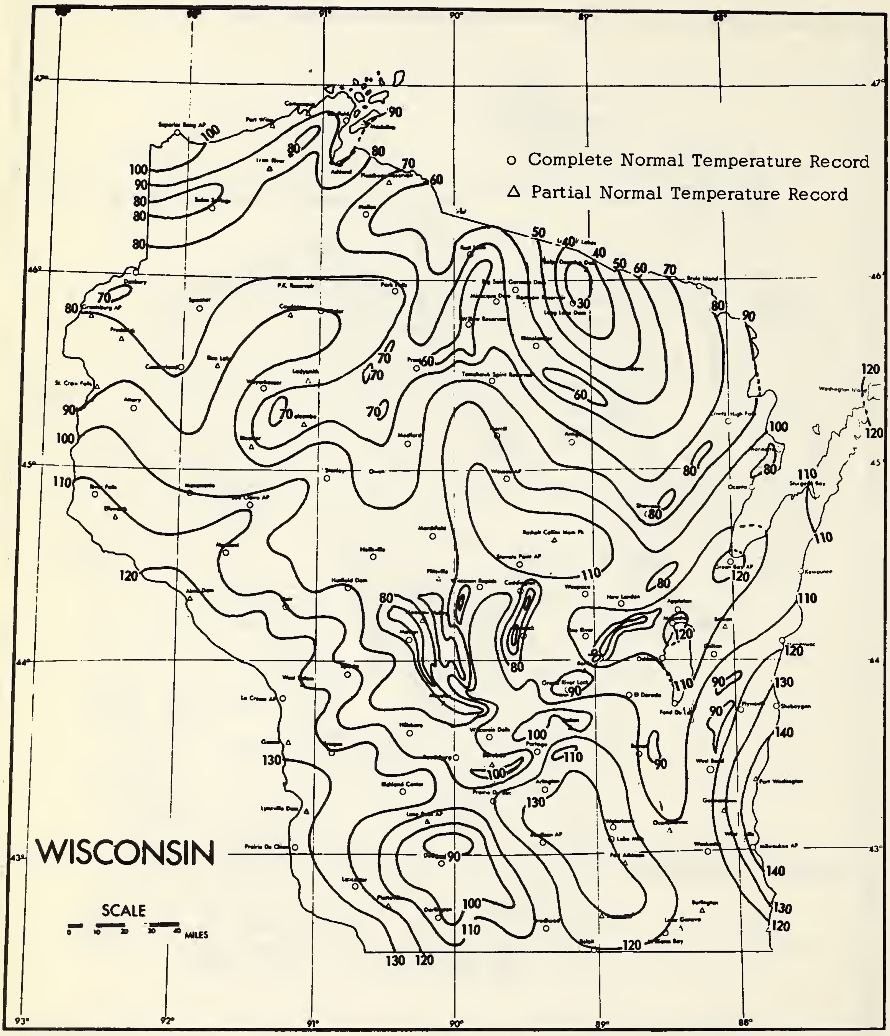

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Fig. 4-13. Normal annual growing season for cultivated plants.

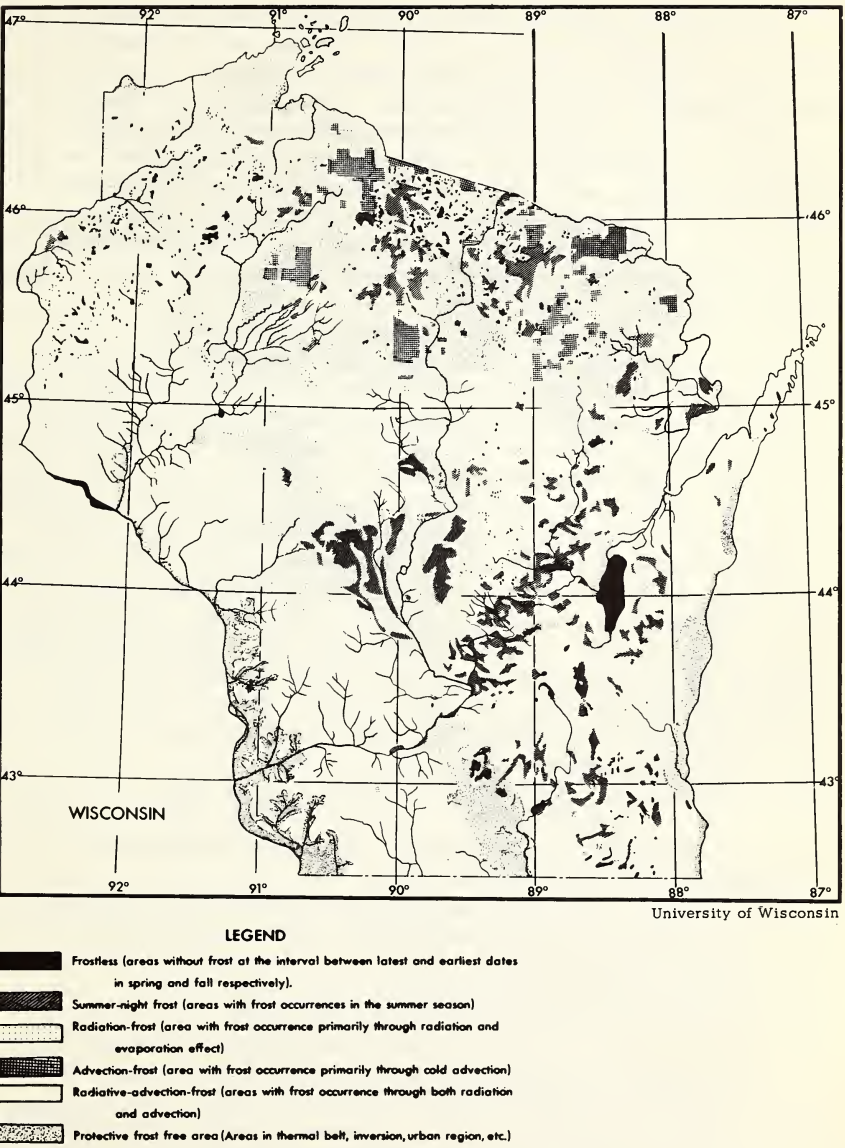

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Fig. 4-14. Distribution of frost zones.

The analysis using the above considerations was done in the following way: First, data from primary stations were plotted alone on an overlay sheet, while secondary stations were used for references. This produced a rather smooth pattern. This pattern was placed over a contour map for modification in the gaps between stations by considering topographic factors, which formed an irregular, yet more representative, pattern. Then this overlay sheet was transferred to a soil map for further change. This was followed with vegetative coverage maps. Finally, the analysis ended with consideration of the micro-environment of each station and its proximity to bodies of water, using air photos.

Figs. 4-12 and 4-13 are the growing seasons of native and cultivated plants, respectively. The base temperature for native plants is 26°F; for cultivated plants, 40°F. Thus, for native plants the length of growing season in days is located between the last occurrence of 26°F in the spring and the first occurrence in autumn. Similar computation is made for cultivated plants, where 40°F is employed. These figures are determined according to the generalized "lower threshold temperature" of a group of native and a group of cultivated plants.

All the above discussions and figures were based upon frost data and temperatures, both of which are subject to environmental differences and changes of weather. The formation of frost, either black or white, is a complex relationship between environmental and meteorological factors related to the flow of heat away from the plants. The results are classified into the groups shown on Fig. 4-14. The bases for the construction of Fig. 4-14 can be illustrated by an energy equation on the heat storage of plants:

$$F_p = K(R_n + Q + E + G)_V + K'(D_h + A)_H . \qquad (4\text{-}34)$$

Here F_p = net heat flux, both vertical and horizontal, towards a group of plants; $-F_p$, away from the plants.

The vertical heat budget designated with subscript V consists of:

R_n — Net radiation for all wavelengths. This applies both to plants and to the surface of the earth. It is usually positive during the day and reversed at night.

Q — Heat added to the air, i.e., sensible heat.

E — Evaporation, in terms of heat of evaporation. It usually is negative during the day. The condensation of dew at night will give a positive value.

G — Soil heat conduction. It is positive at night if it is toward the surface of the soil, and negative during the day if it is away from the surface of the soil. This also applies to water surfaces when lakes and rivers are considered.

K — A proportionality constant of vertical flux.

The horizontal heat budget designated with subscript H consists of:

D_h — Heat which is removed by cold air drainage. It usually is negative at night.

A — Heat advected into a large region due to pressure force, i.e., weather situation. It is negative if it is a cold air advection; positive, if a warm air advection.

K' — A proportionality constant of horizontal flux.

All of the above factors can be expressed in energy per unit area per unit time. The sign "positive" signifies that heat flux is toward a group of plants, while "negative" is away from them. Data for the quantitative evaluation of the above energy equation are unavailable for the preparation of Fig. 4-14. However, they can be estimated qualitatively as in the following examples:

(1) In areas of lakes and rivers, the heat capacity of water is extremely large in comparison with that of soil. Therefore, there is an enormous heat flow out of the water surface when the air temperature is lower than that of water. In this case, the G term is so large that the other terms are negligible. This may be called the "frostless zone." It covers some three percent of Wisconsin.

(2) Marshy areas, where peat soil predominates, are usually wet and have low vegetative coverage. In cranberry bogs, uprights are on the average less than eight inches high; in addition, the bogs are lower than the surrounding upland areas. Here the heat flux F_p will have a high negative value during the night. This is because heat storage in peat soil during the day is low, since it is a poor conductor.

Also, because of the high transpiration during the daytime with the presence of low vegetative coverage and high moisture content, much less heat is stored in the soil. Additional cooling occurs due to cool air drainage from the surrounding upland areas. Therefore, frost forms occasionally in summer. In these marshy areas, the growing season is always shorter than in surrounding regions. These areas have been labeled "summer night frost zones" in Fig. 4-14. These zones cover a little over three percent of the state.

(3) In areas with sandy and sandy loamy soil without much vegetative coverage, both R_n and E terms will be negative during typical nights. In this case, frost is formed through long wave radiation. This occurs over 50 percent of Wisconsin. It can be called the "radiative frost zone."

(4) In areas lying under thick virgin forest with heavy coverage of weeds, litter, debris, duff, etc., the long wave radiation will be insignificant in the presence of a large crown of trees. However, both horizontal terms A and D_h will be important if they are negative. An amorphous structural form of frost is the common type of frost. It covers some two percent of Wisconsin.

(5) In pasture and general farm land, as well as second growth timber areas, all the terms in the foregoing equation have to be

counted for both the vertical and the horizontal heat flux. Frost can be formed by either radiation or advection only when the terms combine to give a large negative flux. In this way, either a white or a black frost can form. The area might be called "radiative-advection frost zone." It covers somewhat more than 30 percent of Wisconsin.

(6) In urban and thermal belt regions, all the terms of the above equations will be somewhat reduced. Thus, killing frost damages are delayed and a longer growing season is expected. This area can be called "protective frost zone." It covers some 12 percent of the state.

4.2.3 *Heat unit system*

The "heat unit system" is a scheme for studying plant-temperature relationships by the accumulation of daily mean temperatures above a certain threshold temperature during the growing season. If a plant has a base temperature of 40°F and the mean temperature on a given day is 55°F, the difference in degrees for that day is termed "degree-days" or "heat units."[16] In this example, we would have 15 degree-days. If 1200 degree-days are required for maturity, the plant should reach maturity by the time 1200 degree-days have been accumulated. The sum required for a particular crop variety has been assumed by heat unit workers to be a constant value and is termed the varietal constant. By knowing the varietal constant, users predict the date on which their crops should be harvested. This linear relationship, known as the "remainder index method," gave rise to a number of expressions, such as "degree-days," "heat units," "growing degree-days," "growth units," and others, relating plant responses to seasonal thermal levels.

Since much of the valuable work done in the past 230 years has been neglected by many modern users, a worldwide survey of major contributions[17] to the heat unit approach is in order.

Around 1730, René A. F. de Réaumur invented a temperature scale on which 0° marks the freezing point and 80° the boiling point of water. Although his temperature scale, known as the Réaumur scale, is now almost obsolete except among some cheese-makers, his ideas on the quantitative study of plant-temperature relationships are worthy of mention. He summed up the mean daily air temperatures for 91 days during the months of April, May, and June in his locality and found the sum to be a nearly constant value for the development of any plant from year to year. This summation of temperatures, published in 1735,

[16]It is necessary to distinguish the terms "degree-days" or "heat units" from "heating degree-days." The former is the summation of temperatures above a certain threshold value, and is used in studies of plant-temperature relationships; the latter is the summation of temperatures below a certain limit value, and is used in studies of heating design and engineering. Climatological data of the U. S. Weather Bureau designated as "degree-days" refer to the latter.

[17]For a comprehensive review, see J. Y. Wang, 1960, A critique of the heat unit approach to plant response studies, *Ecology* 41 (4): 785-790.

was later known as Réaumur's thermal constant of phenology. He assumed that his thermometric constant expressed the amount of heat required for a plant to reach a given stage of maturity. This idea gave rise to the heat unit system of today.

Since then, Réaumur's idea has been adopted and modified by disregarding all temperatures below 0° C and taking only the sums of positive temperatures on the Centigrade scale. This resulted in the establishment of a "remainder index method," expressed as

$$T_t = \sum_{s}^{h} (T - T_C), \qquad (4\text{-}35)$$

where T_t is the heat sum, s the date of sowing, h the date of harvesting, T the daily mean temperature, and T_C the critical temperature.

Fritsch (1852-1871) adopted Kabsch's (1863) reasoning on plant growth and formulated the following thermal constant:

$$x = t \pm (ht/12)c - C. \qquad (4\text{-}36)$$

All the above symbols except C indicate a summation of one phase to the next, such as germination to flowering, of which x is the thermal constant, t is the total number of days, c is the total sum of mean daily temperatures, and h is the average number of hours from sunrise to sunset for the period concerned. C is the total heat sum between planting and germination. In 1861, Fritsch determined thermal constants for the blossoming and ripening of 889 different plant species. This was done by totaling the mean daily temperatures above 0° Réaumur from January 1 onward.

Coutagne (1882) believed that the plant growth rate (v) depends upon a certain maximum temperature, which is assumed to be determined by sunlight, wind, and moisture. It diminishes as that temperature approaches the freezing point of water. Thus,

$$v = a\,e^{-[(x - c)/n]^2}, \qquad (4\text{-}37)$$

where a is the coefficient of the rate of development, e the base of natural logarithms, x the plant temperature, c the optimal temperature, and n the coefficient of the sensitivity of plant response. Hence, the total growth, L, is expressed as

$$L = \int_{x_1}^{x_2} a\,e^{-[(x - c)/n]^2}\,dx. \qquad (4\text{-}38)$$

The reciprocal of a defines the longevity of a plant, while c and n determine the temperature range of plant acclimatization, and x_1 to x_2 represents the temperature range under consideration.

Price (1909) emphasized the application of the van't Hoff-Arrhenius principle[18] in the study of physiological constants and established an exponential index. Livingston (1913) worked out a scale of weighted temperature values between 40° and 90°F. Later, he made use of Lehenhauser's (1914) observations on the rate of elongation of maize seedlings at different temperature levels, and in 1916 devised a new index called a "physiological summation index." His index u is represented as

$$\log_2 u = \frac{(T - 40)}{18}, \qquad (4\text{-}39)$$

where T is the temperature in degrees Fahrenheit, 40 the threshold temperature, and 18 a constant based on the van't Hoff-Arrhenius principle.

Many workers have applied the "remainder index method" to numerous native and cultivated plants over the past four decades. A cross-section of these researchers since 1919 is listed in Table 4-13.

In 1948, Nuttonson attempted to improve the remainder index approach by applying the concept of the "photothermal unit" or P. T. U. in climatic analogue studies. This has been expressed by Wang (1958) as

$$PTU = \sum_{s}^{h} (\bar{T} - T_C) D, \qquad (4\text{-}40)$$

where s is the date of sowing, h the date of harvesting, $\bar{T}$ the daily mean temperature, T_C the critical temperature, and D the day length in hours.

Lindsey & Newman (1956), in a study of the flowering dates of native plants, attempted to improve the simple daily mean method of accumulating heat units. Their method of temperature summation is based on the diurnal spread and was designed to reflect the approximate duration of different temperature levels during the statistical day. The effective diurnal spread is converted into degree-hours (D_h) and can be expressed as

$$D_h = \frac{12\,(T_M - T_C)^2}{T_M - T_m}, \qquad (4\text{-}41)$$

where T_M is the daily maximum temperature, T_m the daily minimum temperature, and T_C the critical temperature.

Podol'skiĭ (1958), studying the phenology of cotton in the USSR, found that neither the heat sum nor the threshold temperature is a constant value. By constructing a pheno-temperature nomogram to eliminate this non-linearity, he achieved a greater accuracy in phenological prognosis. His findings are shown in Fig. 4-15. The abscissa n is the interphasic period in days. The ordinate t_{cp} is the

[18] Jacobus H. van't Hoff & Svante A. Arrhenius found that for each temperature rise of 18°F, the rate of the reaction involved increased by a multiple of two. It was further developed by Arrhenius in 1887 as "The rate of change of the logarithm of the velocity constant for a chemical reaction is inversely proportional to the square of the absolute temperature."

Table 4-13. A Cross Section of Remainder-Index Method Researchers, 1919-1952

Year	Researcher	Plant	Contribution
1919	Kincer	Wheat	Regional studies in USA; base temperature 43°F.
1921	Appleman & Eaton	Sweet corn	Summing daily mean temperatures to ripening.
1929	Boswell	Peas, Spinach	Base temperature 36°F for peas, and 42°F for spinach.
1939	Winkler & Williams	Grapes	Maturity test.
1944	Baker & Brooks	Apricots, Plums	Number of days required from flowering to harvest.
1946	Scott	Peas, Corn	Quality control.
1948	Seaton	Peas	Scheduling of planting.
1948	Barnard	Tomatoes	Base temperature 50°F.
1948	Bomalaski	Peas	Growing degree-day.
1950	Gould	Snap beans	Base temperature 50°F.
1952	Lana & Haber	Sweet corn	Degree-hour summation.

long term mean temperature of the interphasic period in °C. Based on many years of average data of one locality, the grid is constructed. The Roman numerals stand for the months, and the Arabic figures, the days of the month. Line EF, for instance, is one of the phenological developmental curves which refer to cotton plants during the flowering to boll-unfolding period.

Holmes & Robertson (1959) introduced a generalized formula for the computation of weekly degree-days above 42°F for nine stations in Canada. Their formula is

$$\bar{D} = N[(\bar{T} - T_C) + L\sigma/\bar{N}], \qquad (4\text{-}42)$$

where $\bar{D}$ is normal degree-days accumulated for the months concerned, N the number of days in a month, $\bar{T}$ the monthly mean temperature, T_C the base temperature (42°F), L a proportionality coefficient, and σ the standard deviation of the monthly mean temperature. The coefficient L can be obtained from a table prepared by Holmes & Robertson in 1959.

Arnold (1959), in his determination of significance for the base (or critical) temperature in a linear heat unit system, found that the base temperature commonly used was too high. He made a regression equation from temperature and the rate of development. The equation is

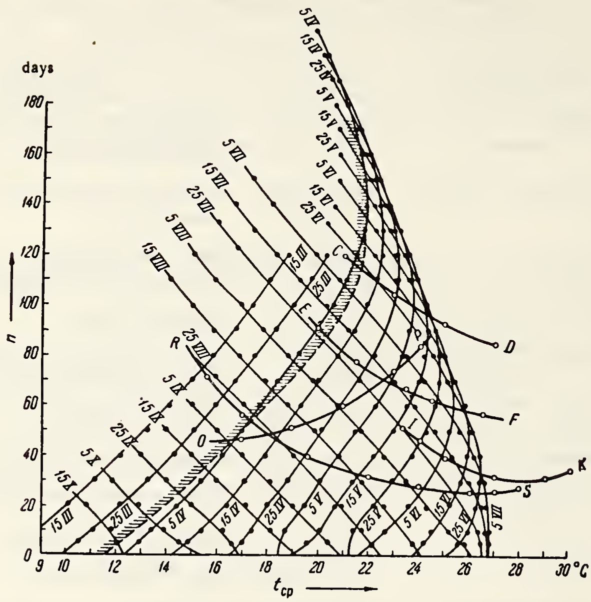


Fig. 4-15. A pheno-temperature nomogram for the Gissarskii Valley.
After Podol'skiĭ, 1958

solved for the temperature when the rate of development is zero. The temperature obtained is defined as the base temperature.

Although a great amount of work has been done on heat unit studies, there has been little integration of such work. Consequently, further investigation and understanding of the results of past research are necessary.

In the past three decades, the heat unit system has been adopted by many in the canning industry, especially as a means of scheduling planting dates to insure an orderly flow of raw materials of optimal maturity to the cannery. Further applications are seen in the scheduling of spraying programs for insects, disease, and weed control. The system is also of use in the selection of suitable farming areas and of appropriate crop varieties for these areas.

Researchers have applied this system to a wide variety of plants, both native and cultivated, and have made many refinements in methodology. The results have been correlated with various phenological events of the plants studied. Also, entomologists, plant pathologists, ornithologists, zoologists, and others have used the system in their fields of investigation.

The heat unit system has been widely adopted because of its value in satisfying practical needs, rather than for its accuracy or its theoretical soundness. Because no other system has been found which can adequately replace it, it continues to enjoy widespread popularity.

In spite of the many applications and intensive investigations, the heat unit system has been subject to serious criticisms. Its disadvantages may be summarized as follows:

(1) Plants respond differently to the same environmental factors during various stages of the life cycle. Varietal constants obtained from heat unit computations fail to take into account these time sequences. For example, Alaska-type peas yield well in Wisconsin if grown under warm spring conditions during the seedling stage and cool summer at their reproductive stage. Under the opposite environmental conditions (i.e., in cold springs and hot summers), a poor yield results. This is illustrated schematically in Fig. 4-16. Here, area ABC represents the summation of the daily temperatures above 40°F in the case of a cold spring followed by a hot summer, while the area DEFC represents that of a warm spring and cool summer. Since areas DEOA and OBF are equal, the heat sums for both cases are identical and neither can be used to differentiate the time sequences of plant responses to temperature. Under such conditions, the heat unit system would not work. For example, a study of the monthly temperatures of Ethiopia, known as the pea-producing center of the ancient world, shows that only very small temperature changes occur from month to month (Wang & Bryson, 1956). From January to April, the temperature line for Ethiopia is flatter than line EOF in Fig. 4-16. Thus, the orientation of line EOF further toward the horizontal might indicate a better pea-producing season.

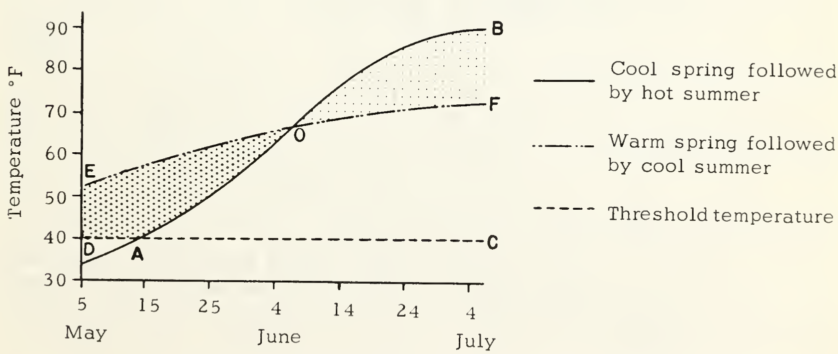


Fig. 4-16. Schematic diagram of heat summation.

(2) The threshold temperature as employed in the heat unit computations is considered a constant, applied to the entire life cycle of a plant. The generally accepted value for the threshold temperature

of peas is 40°F; that for corn is 50°F. This is unsound, since the threshold values change with the advancing age of the plant. This will be explained in Section 7.4.3.

(3) Thornthwaite (1952) pointed out that when all possible threshold values from 32° to 50°F were tested systematically, none was found which would give any improvement in the heat unit system. Various upper temperature limits were also tested in the same way and no better findings resulted. Neither was Wang (1957) able to achieve any improvement in the system by making heat unit summations over growing periods of various lengths. Podol'skiĭ (1958), too, reached the same conclusion in his study of cotton plants.

(4) Daubenmire (1959) pointed out that the heat unit requirement of a given process is constant only for that range within which a direct proportionality exists between growth rate and temperature. A lack of such proportionality is usually found near the upper and lower threshold temperatures. Moreover, over the growing season the growth of a plant is a continuous function; thus, the growth versus time is sometimes a near-linear function. This function is similar to the summation of heat units versus time. Because of their linearity, these two physiologically unrelated factors [19] sometimes happen to coincide. Usually, however, the temperature responses in terms of the growth curve are sigmoid and not linear; in fact, the extremely high temperatures to which plants are sometimes subjected have negative effects on the rate of development. Podol'skiĭ (1958) found that when the optimal temperature for growth is reached, the heat sum is no longer linear.

(5) The heat unit system does not take into account many factors which influence plant growth and development, such as soil moisture, vapor pressure deficit, etc. Some workers have pointed out the importance of environmental factors other than temperature, for example, sunlight by Gasparin (1844), solar radiation, wind, and moisture by Coutagne (1882), and duration of light by Nuttonson (1948). Even the exponential heat sums of Livingston (1916) and Katz (1952) are valid only between the upper and the lower threshold temperatures for a given crop variety, since above or below these thresholds the van't Hoff-Arrhenius constant no longer applies. The heat unit system is usually computed on the basis of the mean daily temperature and does not take into account the effects of extreme day or night temperatures, interdiurnal temperature changes,[20] or the difference between day and night temperatures.

[19]We refer here to the heat sum and not the temperature itself. Heat sums average out and thereby disguise the singularity of temperature changes.

[20]The interdiurnal temperature change is defined as the difference between the maximum temperature of one day and the minimum temperature of the following day.

(6) Finally, the microclimatic problems regarding the representative quality of the temperature records used for the heat unit evaluation are among the most complicated problems yet to be solved.

To improve the heat unit system:

(1) Representative temperatures should be taken. The height of observations should vary from time to time according to the height of the plants. Observations should be made at random in various locations throughout the field. The number of locations to be sampled would depend upon the size and topography of the field as well as the variation in its microenvironment.

(2) The threshold temperature used should be changed according to the age of the plants. The upper threshold limits also need to be considered. A quantitative evaluation should be made of the negative effects of temperatures beyond the threshold values for both upper and lower extremes. The length of the period for the accumulation of temperatures using any one threshold value should not be more than a week. More phenological events should be recorded in order to accommodate the short period of temperature accumulation.

(3) Growth and development should be differentiated, as has been mentioned in Section 3.1.

(4) The environmental parameter should be adjusted. Computations of heat units by other than the remainder method are by Fritsch (1861), Linsser (1867), Coutagne (1882), Livingston (1913), Nuttonson (1948), and Lindsey & Newman (1956). For details, see Section 7.4.2.

(5) The non-linearity of plant-environmental relationships should be corrected. Wang (1958) has established a "sorter" as the first approximation for the study of non-linearity. His method is explained in Section 7.5.1. There are several methods which could also be employed for solving the problem of non-linearity (Katz, 1952; Podol'skiĭ, 1958).

(6) The environmental parameters, such as rainfall and temperature, should be combined. Before this can be done, rainfall and temperature must be reduced to a common unit and each weighted as to crop response. Such a method has been devised by Wang & Tibbitts (1956), and will be explained fully in Section 7.5.2.

Greater familiarity with available literature dating back to 1735, and wider adoption of these improvements, should further advance the study of plant temperature relationships.

For over two centuries, air temperature had been employed for research on plant response, but during the past 30 years the use of soil temperatures has received much attention. In a way, soil temperature has proved a far better parameter than air temperature, particularly when applied in germination studies. The purpose of the following section is to summarize existing knowledge on soil temperature as an environmental factor in plant growth.

4.2.4 *The soil temperature*

The thermal properties of the soil surface layer, as has been mentioned in Section 2.1.1.b, involve two major processes, heating and cooling. The major physical factors governing the heating of the bare soil surface are solar radiation, warm air advection, latent heat of condensation, and fusion, as well as chemical heat. For cooling, they are long wave back radiation, convection, cold air advection, drainage, latent heat of vaporization, evaporation, and sublimation. When vegetation is present, the shading effect diminishes the solar intensity greatly, and the transpiration of plants lowers the air temperature which eventually results in the cooling of the soil surface. A deeper layer, namely the root zone, can be controlled mainly by the process of conduction. The alternation of heating and cooling gives rise to a heat cycle diurnally and seasonally. This heat cycle is delayed and weakened as it penetrates deeper into the soil. The time lag of the maximum and minimum of the heat cycle of homogeneous soil is expressed by equation (4-43):

$$t_{m_2} - t_{m_1} = (z_2 - z_1)\frac{T}{2\pi}\sqrt{\frac{\pi \rho c_s}{Tk}}, \qquad (4\text{-}43)$$

where t_{m_1} and t_{m_2} are the time (in seçonds) required to reach the maximum soil temperature at a depth of z_1 and z_2 (in centimeters) respectively, T is the oscillation period of the heat cycle in seconds (for a diurnal cycle, it is 86,400 seconds), ρ is the density of the soil, c_s is the specific heat, and k is the heat conductivity. If the difference between the maximum and minimum soil temperatures at a depth z_1 equals T_{I_1}, and if that of depth z_2 is T_{I_2}, then the weakening of the diurnal temperature spread at z_2 is

$$T_{I_2} = T_{I_1} e^{(z_1 - z_2)\sqrt{\frac{\pi \rho c_s}{Tk}}}. \qquad (4\text{-}44)$$

The ratio $\frac{k}{\rho c_s}$ of equation (4-44) defines the thermal diffusivity (τ), where the numerator k is the thermal conductivity and the denominator ρc_s, the thermal capacity. In the consideration of the thermal properties of soil, ρ, c_s, and k are the basic properties while τ and $\sqrt{k\rho c_s}$ are the derived properties. In the derived units, τ is the diffusivity, while $\sqrt{k\rho c_s}$ is the thermal admittance. In the C. G. S. system, τ is in $cm^2\ sec^{-1}$, and the unit of $\sqrt{k\rho c_s}$ is ly $sec^{-1}\ deg^{-1}$. The speed of heat propagation is determined by $\sqrt{n\tau}$ expressed in cm sec^{-1}; the depth of heat penetration is determined by $\sqrt{\frac{\tau}{n}}$ expressed in cm where n is $\frac{2\pi}{T}$, T being the period in seconds. The expression $\sqrt{n\rho c_s k}$ is equal to $\Delta F/\Delta T$ where ΔT is the amplitude of temperature and ΔF is the amplitude of heat flux. The above expressions $\sqrt{n\tau}$, $\sqrt{\frac{\tau}{n}}$, and $\sqrt{n\tau c_s k}$ are extremely important in the determination of soil thermal properties. For dry soils, the thermal diffusivity may be expressed as

$$\tau = \frac{48.5408\,k}{\rho c_s}. \tag{4-45}$$

For wet, frozen and unfrozen soils it may be calculated by equations (4-46) and (4-47) respectively.

$$\text{Frozen:}\quad \tau = \frac{48.5408\,k}{\rho(c_s + m/100)} \tag{4-46}$$

$$\text{Unfrozen:}\quad \tau = \frac{48.5408}{\rho(c_s + m/200)}, \tag{4-47}$$

where m is the moisture content of soil. For a description of soil thermal properties, both soil conductivity and diffusivity would be proper parameters to use. For these two parameters, the order of magnitude of various soils is shown in Fig. 4-17. This is a generalized picture based upon measurements made by a group of authors. Since the thermal capacity, ρc_s, of soil differs, the linearity between τ and k should not exist. Each of the zones A, B, and C indicates a rough idea of the similarity of the thermal properties of soil.

The variations of normal soil temperature in different seasons of the year with depths for La Crosse and Rainbow Snow Course, Wisconsin, are shown in Figs. 4-18 and 4-19. Note the similarity in the pattern of the soil profile of these two stations which are located in different soil types, vegetative coverages, latitude, altitude, and even growing seasons. Thus, April and September for these two localities are the two months when soil temperatures are nearly isothermal throughout all depths up to 60 inches. This isothermal effect is shown as a turning point in these two figures. When the mean soil temperature is plotted against the depths, which are given in Fig. 4-20, again the isothermal line for the months of April and September is almost a straight line. A world-wide survey of soil temperature has been made by Chang (1958). His two volumes published under the title *Ground Temperature* include measurement, distribution, and method of modification of the soil temperature, as well as thermal properties, heat flux, and frost in the ground. A comprehensive collection of monthly mean soil temperature data on a world-wide basis is also included. Chang's work is thus valuable for soil research studies.

In the study of plant responses, soil temperature is commonly used instead of the heat in the soil. A summary of the influence of soil temperature on the growth and development of a crop is given below.

Specifications on the application of soil temperature to plant growth are: (a) the cardinal temperature or the limits of critical temperature, including the optimal range and the upper and lower lethal temperature limits; (b) the duration of the critical temperature in association with the rate of cooling and warming; (c) the alternation of warmness and coldness; and (d) the influence of factors other than soil temperature,

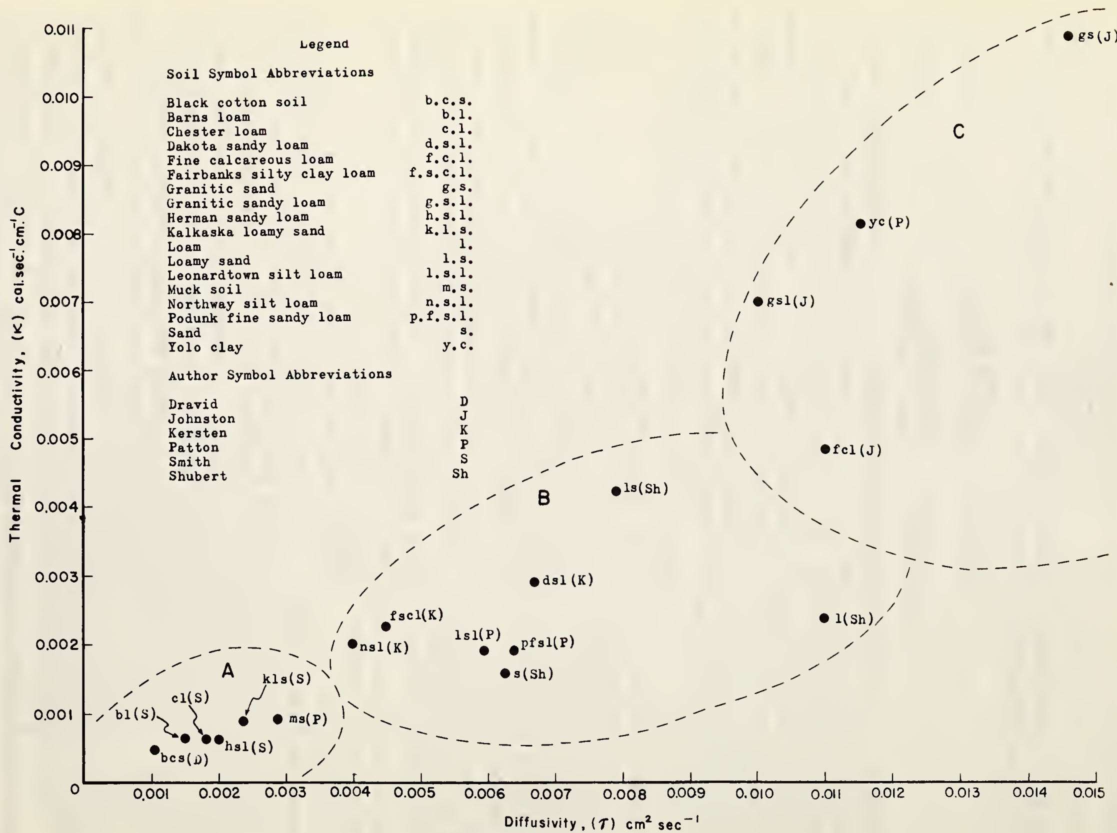


Fig. 4-17. Thermal conductivity versus thermal diffusivity of soils at average bulk density.

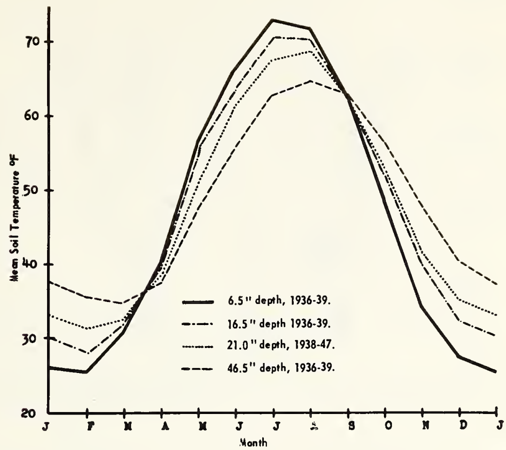


Fig. 4-18. Annual course of monthly soil temperature at La Crosse.

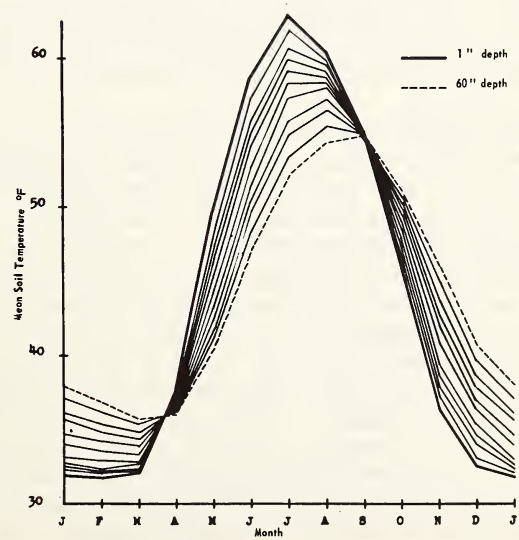
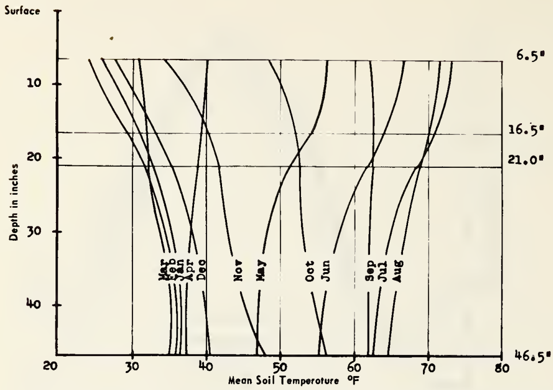


Fig. 4-19. Annual course of monthly soil temperature at Rainbow Snow Course.



'Fig. 4-20. Annual course of soil temperature at La Crosse.

such as intensity of radiation, duration of light, air humidity, soil moisture, and air temperature.

The cardinal temperatures which have been defined previously in the study of air temperature and plant response are somewhat similar to those used in the study of soil temperature, but are, of course, at different levels. The major difference between the air and soil temperatures is that the former is susceptible to change while the latter is more or less stabilized. Moreover, air is more homogeneous than soil, and therefore the cardinal temperature should be specified according to the type of soil. In fact, it is much more complicated to use soil temperature rather than air temperature because, as has been mentioned, the root temperature can be quite different from the soil temperature for one thing, and aeration as well as the soil moisture condition will also modify the development and growth of plants. Studies on the duration of soil temperature in association with the rate of warming and cooling have been conducted by numerous investigators. For example, Kramer (1949) found that plants which were cooled nearly to the freezing point in four to five hours, or even overnight, wilted severely. On the other hand, those cooled over a period of four to five days wilted only slightly. This demonstrates that a process of slow cooling will inflict less injury than rapid cooling. Also, Hubbard & Herbert (1933) observed that cotton plants in the San Joaquin Valley of California wilt on warm days following cold weather, even in the presence of ample soil moisture. Wilting disappeared as soon as the soil warmed up, and no damage resulted other than a possible temporary retardation in growth. It is well known in plant physiology that the physiological drought is caused by the combination of a low temperature and bright sunshine in the winter time. This results in high transpiration and low absorption of the moisture supply, which is independent of the presence of soil moisture.

The alternation of high and low temperatures will be another aspect of this study. In the case of germination, alternating temperatures appear to be more favorable for seeds of some plants. For celery, parsnip, redtop Mitchellgrass, orchard grass, Kentucky bluegrass, Johnson grass, and Bermuda grass, seeds germinated better with favorable temperature alternations than at a constant temperature, as has been reported by Harrington (1923). With carrots, parsley, timothy, bromegrass, meadow fescue, and several kinds of flower seeds, a constant temperature is just as effective as the alternating temperatures. Myers (1942) discovered that Mitchellgrass seeds, which favor alternating temperatures, will germinate satisfactorily at a high constant temperature of 90°F. In other words, this constant temperature of 90°F maintained the same results as in the case where alternating temperatures were applied. It is a common commercial practice to test seeds by alternating about six hours of high temperatures with rapid cooling.

Factors other than soil temperature also have a bearing on the study of plant growth. High intensity of sunshine combined with a low soil temperature is a cause of wilting in plants, but the association of a high relative humidity with a low soil temperature does not cause wilting. Daylength is another growth factor; hence, the combination of various daylengths with different temperatures gives varying effects. Therefore, various factors should be considered when soil temperature is applied.

Physiological effects of soil temperature have been studied in terms of water absorption, nutrient uptake, assimilation, and respiration. The rate of photosynthesis is relatively unaffected within the normal range of soil temperatures, whereas the rate of respiration increases rapidly with temperature. Low temperatures favor accumulation of photosynthetic products; high temperatures deplete carbohydrate material. Since soil physical and chemical properties are affected by the seasonal and diurnal changes of soil temperature, the growth and development of plants will also be affected. The major characteristics of these properties are soil moisture movement and soil aeration. This is particularly true in the study of germination. The horizontal and vertical soil temperature gradient is a factor in moisture movement. Soil aeration determined by gas exchanges at the soil-air interface is controlled mainly by various levels of soil temperature. Low soil temperatures reduce the absorption rate of water and ions by plants. Uptake of nutrients through the root is also retarded when temperature is too low. Several mechanisms are involved in these effects: (a) Rate of water movement from soil to root is reduced. Kramer (1934) claimed that the water supply of soil as measured with porous ceramic pieces is only 1/3 to 1/2 as great at 32°F as at 77°F. Thus, root elongation is retarded due to the fact that soil moisture is low. (b) The viscosity of water is twice as great at 32°F as at 77°F (Kramer, 1949). (c) The viscosity of protoplasm is also much greater at 32°F than at 77°F. This retards the water movement of cells lying between the epidermis and the xylem of the root. (d) Permeability of cells to water generally decreases with the decrease in soil temperature.

The interaction of these mechanisms is too complicated to be reconciled, and controversies will always exist. For example, a plant physiologist cannot successfully separate the effect of low temperature on the absorption process from its effects on translocation and the utilization of the nutrients within the plant. Agrometeorologists do not intend to investigate these mechanisms, but these results, and a knowledge of their cause and effect relationships, would be helpful.

As far as plant growth and development is concerned, germination and seedling emergence, elongation of stems and roots, growth of shoots, initiation of flowers, the quantity and quality of fruit production, etc., are the major topics of interest. The effect of soil temperature on plant diseases and on such microbial activity as ammonification, nitrification, and development of legume nodules has been studied. The morphology of plant seedlings and roots is also affected by the daily variation of soil temperature.

Studies related to soil temperature and plant growth are numerous. It is not the intention of this book to describe all the existing findings, but simply to bring out the important features and significance of soil temperature.[21]

4.3 MOISTURE IN THE AIR

In agriculture, the continuous circulation of water is known as the hydrologic cycle which represents a balance between the amount of water received and the amount lost by the soil surface layer. Elements of the hydrologic cycle, as explained in Section 2.1.1.c, are precipitation, condensation, sorption, evaporation, transpiration, surface runoff, subsurface runoff, infiltration, percolation, and capillary action. The net result is the balance of moisture in the surface layer of the soil. For example, precipitation represents a gain, and percolation a loss. A diagram of the hydrologic cycle is shown in Fig. 4-21. The positive sign shows water moving toward the layer of the soil, whereas the negative sign indicates water flowing away from the layer.

[21]For further studies one may consult B. T. Shaw's *Soil Physical Conditions and Plant Growth* (1952), published by the Academic Press, Inc., and Wang & Barger's *Bibliography of Agricultural Meterology* (1962), published by the University of Wisconsin Press. The former gives a very comprehensive summary of soil temperature and plant growth, while the latter gives some 300 references on the same subject.

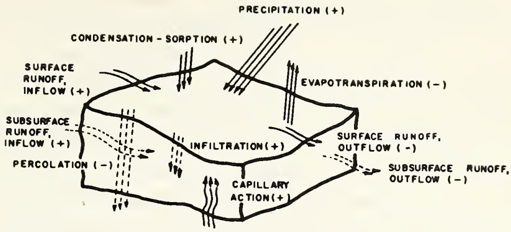


Fig. 4-21. Hydrologic cycle.

Precipitation and evapotranspiration are the two most important elements determining the balance of moisture in the soil surface layer. Precipitation denotes any aqueous deposit, in either liquid or solid form, derived from the atmosphere and reaching the ground. It includes rain, snow, hail, sleet, and their modifications. Evapotranspiration is evaporation at the air-soil and air-water interface plus transpiration from plants.

Precipitation is the primary source of water in agriculture, while evapotranspiration provides the chief water loss from soils and crops. The amount of moisture available in the soil surface layer and the amount of crop cover govern the rate of evapotranspiration. If the soil is wet and sunshine abundant, a large part of the solar energy is used in evapotranspiration; if the soil is dry, much of the energy is consumed in heating the soil surface and the air. In specific cases, however, other elements of the hydrologic cycle are noticeably important. With sandy soils, for example, percolation is an important element of the hydrologic cycle. So is runoff on steep land, and capillary action on lands where the water table is high.

Moisture in the soil as affected by precipitation and condensation are treated in the following section. This includes studies of water balance. Moisture in the air is determined mainly by evaporation, which is discussed in this section. Relative humidity, on the other hand, is an important expression of moisture in the air for the study of the growth and development of plants. The crop response to relative humidity is summarized below.

4.3.1 *Relative humidity*

Although there are several ways to express moisture in the air (as explained in Section 2.2.2), the most useful expression is the relative humidity. Plant responses to the relative humidity and to its combinations with other factors have long been investigated, particularly plant pathological studies; however, absorption of moisture from the air by plants needs more attention. This is especially true in the arid region and will be further elaborated in the next section when dew is discussed.

Most studies of crop response to humidity are associated with high and low air temperature and sometimes with the wind. Examples of the combined effects of relative humidity and air temperature are: Miliani (1932) studied the effects of tillering of spring wheats in Italy; Minina et al. (1940) noticed the influence of soil and air humidity as well as air temperature on the spikelet formation of wheat in the USSR; Alberts (1926) found the moisture content of corn to be affected by the combination of humidity and temperature. Dole (1924) observed that the transpiration rate of white pine is also affected. The growth of kidney bean seedlings has been investigated by Patterson (1922). Similar studies for storage problems have been conducted by a number of authors. Poptzoff (1953) studied tobacco seeds' viability in relation to humidity and temperature. Rygg (1948) studied the storing date problem for the same effect. The quality of white burley tobacco during and after curing is controlled by temperature and humidity effect. The study of relative humidity alone on the texture, weight, and volume of filberts has been done by Hartman (1924), on the growth of bamboos by Lock (1904), on the enlargement of grapes by Chaptal (1930), on metabolism in tomatoes and apples by Nightingale & Mitchell (1934), on sugar concentration in nectar of various plants by Park (1929), on the rate of carbon fixation by Mitchell (1936), on root growth by Breazeale & McGeorge (1953), on cracking and decay of Bing cherries by Gerhardt et al. (1945), and on the fermentation of tobacco by Smirnov (1927). The combination of humidity and dry wind will be another aspect of the study. In the interior valleys of the arid Southwest and California, abscission of immature navel oranges is due to a combination of high temperature and low humidity, according to Coit & Hodgson (1919). Webber (1938) found that high humidity and low wind tend to make navel oranges smoother, thinner-skinned, juicier, and richer in quality. Reed & Bartholomew (1930) have summarized the literature on the effects of desiccating winds on citrus trees, and concluded that wind causes defoliation, death of twigs, and loss of fruit.

The vapor pressure deficit (d), stated in equation (2-4) as the difference between the actual vapor pressure and the saturation vapor pressure, or $(e_s - e)$, can be expressed for the convenience of the user as

$$d = e_s(100 - r) \qquad (2\text{-}5)$$

where r is the relative humidity and e_s is the saturated vapor pressure of water. Equation (2-5) may also be expressed by $T_d - T$, where T_d is the dew point temperature and T is the actual temperature. Since e_s is a function of temperature alone, vapor pressure deficit expresses both air humidity and air temperature, and in turn, evaporation. Some experiments along this line were conducted as far back as 1802 by Dalton. His statement of the functional relationship of evaporation and vapor pressure deficit is

$$E = a(e_s - e)(1 - bU), \qquad (4\text{-}48)$$

where a and b are empirical constants and U is the one-dimensional wind velocity component.[22] Since then, some investigators have used vapor pressure deficit as a climatic element to describe regional climate. In recent years, Albrecht (1951) has formulated an equation similar to Dalton's for the estimation of monthly evaporation. Kucera (1954) found that the evaporation rate correlates well with the vapor pressure deficit, at low wind velocity. As far as plant growth is concerned, pressure deficit is a far better parameter than relative humidity. Unfortunately, not much work has been done in this area of study.

Many experiments have been conducted during the last century on plant diseases and relative humidity relationships. Downy mildew of onion, for example, is most prevalent and spreads most rapidly under conditions of moderate temperature and high humidity. During bulbing, harvesting, and curing of onions, fairly high temperatures are desirable, and when harvesting and curing begin, the humidity should be low. Yarwood (1939) found relationships between relative humidity, downy mildews, and rusts. Humphrey (1941) stated that humidity is of next importance to temperature in promoting cereal-rust epidemics. High humidity is necessary for the germination of rust spores. Development of the asparagus rust pathogen in relation to temperature and moisture has been studied by Beraha et al. (1960). There were many studies in the 1930's and earlier, using relative humidity as a parameter in plant disease studies. However, in recent years researchers have begun to realize that relative humidity is not a good parameter to use. They found that the water deposit on plants (i.e., dew) is a more reliable factor to consider. There is no intention in this book to summarize problems related to plant disease and moisture.[23]

4.3.2 *Evaporation*

The word "evaporation" has been loosely used as the amount of

[22]In 1929 the Russian worker Maximov presented Dalton's equation as

$$E_o = a(e_s - e)\,760/P \cdot S$$

This equation is somewhat similar to Equation (4-48) without the U term. But it has terms S and P, where S is the area of the evaporating surface pertaining to an indefinite large water surface, such as a large lake or the sea, and P is the observed barometric pressure with a normal atmospheric pressure as 760 mm of mercury. In 1881 Stefan made Dalton's equation useful to a small area, such as a leaf or an evaporating pan. His formulation is

$$E_o = 4ar(e_s - e)$$

where r is the radius of the evaporating surface. In fact, there is no evidence that Dalton expressed his result in the form of an equation. It seems that his equation has been put out in the form most suited to the user's purpose.

[23]The reader may refer to ***Plant Pathology; Problems and Progress, 1908-1958***, edited by Holton et al., and published by the University of Wisconsin Press (1959).

water evaporated from a given land or water surface. Unavoidably, this implies that transpiration of plants is also involved. Thus, "evapotranspiration," which is evaporation at the air-soil and air-water interface, and transpiration from plants, should be used as more accurate definition of types of evaporation. When the source of water is unlimited it may be termed as potential evapotranspiration. Sometimes, evaporability and evaporative power have been used alternatively for evapotranspiration. Strictly speaking, evaporation (vaporization) is defined as the physical process by which a liquid or solid is transformed to a gaseous state. However, in meteorology, it usually is restricted in use to the change of water from liquid to gaseous state. In short, it is the source of the water which determines the terminology — from plants, it is transpiration; from surfaces of water and soil, it is evaporation; and from all evaporative surfaces, it is evapotranspiration.

Since evapotranspiration is affected by such factors as radiation, available soil moisture, temperature of evaporating bodies, wind velocity, and air humidity, it involves a wide field of study. It is not only a simple physical problem, but also a meteorological, hydrological, agronomical, and pedological problem. As early as 1867, Symons declared that evaporimetry was the most desperate branch of the most desperate science of meteorology. However, the increasing number of publications on evapotranspiration shows that to scientists it is one of the most interesting and contentious problems.

Some physical and empirical formulas for the computation of evaporation have been derived by scientists. Dalton (1802) was the first to state clear views on the nature and properties of vapors. His formula, as indicated previously (see equation (4-48) and footnote 22), is based on the proportionality between evaporation and vapor pressure deficit or saturated deficit. The use of vapor pressure deficit in evaporation studies has no significance as a physical quantity in a process of vertical diffusion of water vapor. It is obvious that the drier the evaporating surface the less will be the evaporation, but, largely in consequence, the greater the saturation deficit. In such circumstances, the saturated deficit might be considered as an inverse index of evaporation. However, Dalton's formula had its physical significance and it stimulated other scientists to pay further attention to the evaporation problem either by revising his formula or by forming other empirical formulas.

In the United States, Thornthwaite (1948) expressed the potential evapotranspiration as an exponential function of the mean monthly air temperature and applied a daylength adjustment to correct the relation for season and latitude. He disregarded other climatic factors by stressing the fact that they vary together with air temperature. It has been verified that in most parts of the United States and Canada (Sanderson, 1950) the Thornthwaite formula is generally applicable, while in Alabama and a few other places (Davis, 1956) it has been found that the formula can be improved by applying an adjustment factor. The popularity of Thornthwaite's approach is due to its simplicity rather than its soundness. In Germany, Albrecht (1951) assumed a linear relationship between the potential evapotranspiration and the vapor pressure deficit, but with a different proportional factor for the wind velocity. His formula is suitable only for a short time interval; this proportionality disappears when averages over a longer duration are taken. In Russia, Ivanov (1954) derived an empirical climatological formula which expressed the monthly potential evapotranspiration in terms of the average monthly temperature and the average relative humidity, so that it is almost the same as the saturation deficit formula. In England, Penman (1948) formed his formula based mainly on four factors — net radiation, temperature, humidity, and wind.

Besides those formulas mentioned briefly above, there are many other empirical evapotranspiration formulas derived in the past two decades. Most of the evaporation formulas are applicable only for certain areas and seasons. This means those constants or factors involved in the formulas vary from place to place as well as from time to time.

Comparing those evaporation formulas, Penman's method has been widely used because it has some theoretical foundation and has more general applicability than any other method proposed. According to Guerrini's analysis (1957) of evapotranspiration observations at Valentia Observatory, the Penman formula gives satisfactory results over the whole period, while Thornthwaite's is adequate in the spring and summer. Van Bavel (1953-1959) has applied Penman's method in the study of agricultural drought. Areas such as the Carolinas, Virginias, Georgia, and the Lower Mississippi Valley have been used for the study. King (1956) found Penman's equation yields better results than Thornthwaite's formula in Wisconsin. Penman's equation, involving the daily mean value of percent of possible sunshine, air temperature, wind speed at two meters' height, and relative humidity, is

$$E_T = a\,E_0\,, \tag{4-49}$$

where E_T is the evapotranspiration in millimeters per day, a is the seasonal constant, and E_0 is

$$E_0 = (H\Delta + \gamma E_a)/(\Delta + \gamma)\,, \tag{4-50}$$

where E_0 is the evaporation from open water surfaces in millimeters per day; H is the net radiation, i.e., $H = R(1 - A)(0.18 + 0.55\,n/N) - \sigma T_a^4(0.56 - 0.092\sqrt{r e_s})(0.10 + 0.90\,n/N)$; R is the mean monthly

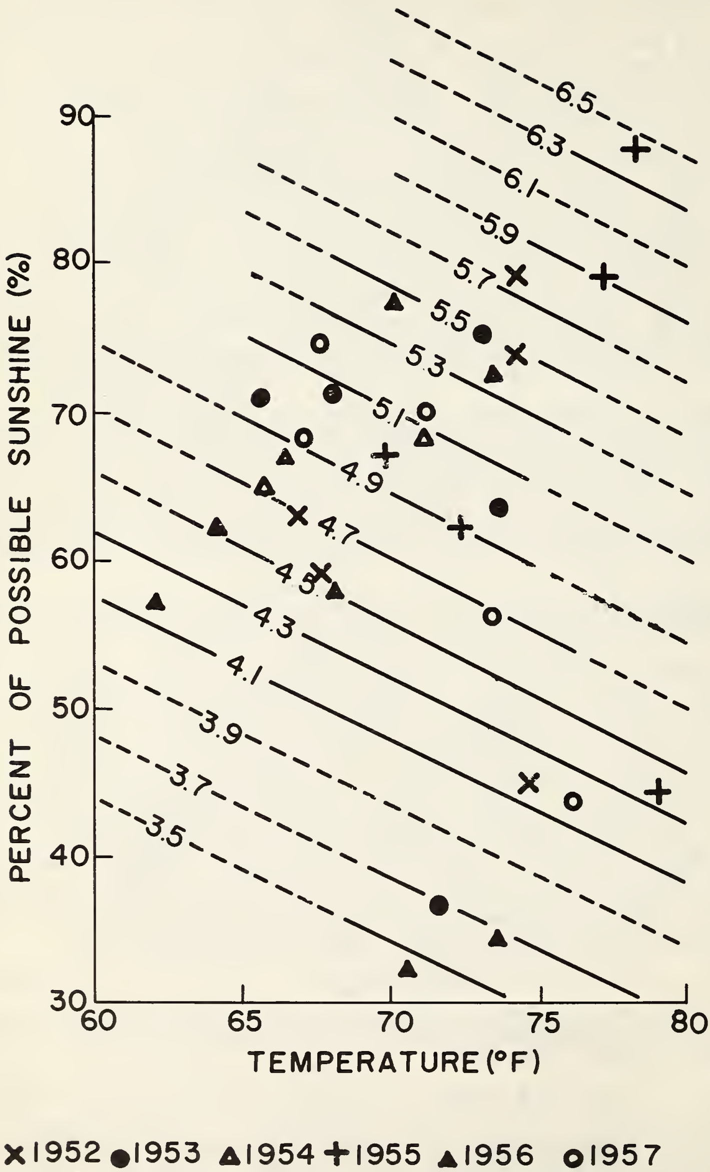


Fig. 4-22. Nomogram for the estimation of evaporation in Wisconsin and vicinity for the month of July.

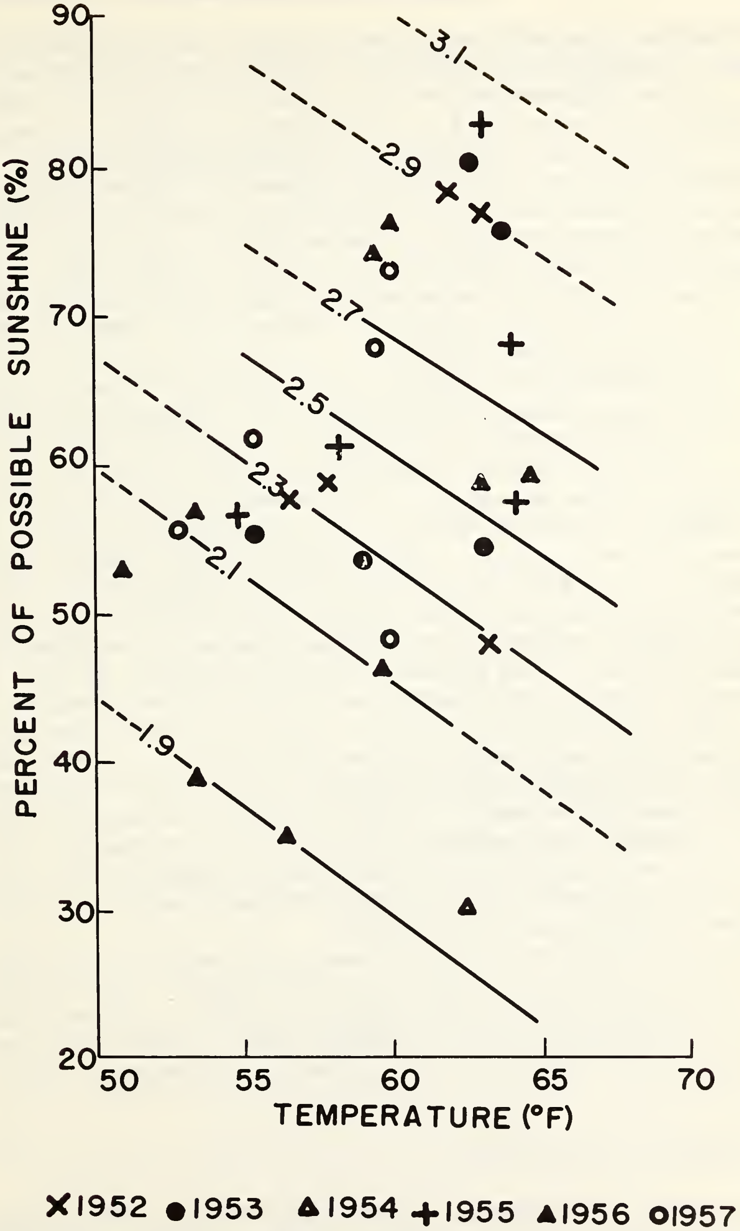


Fig. 4-23. Nomogram for the estimation of evaporation in Wisconsin and vicinity for the month of September.

extraterrestrial radiation in millimeters per day; A is the albedo (0.05 for water, according to Penman); n/N is the percent of possible sunshine; σ is the Stefan-Boltzmann constant (2.01×10^{-9}mm/day/deg^4); T_a is the air temperature in °K; r is the relative humidity in percent; e_s is the saturated vapor pressure of air in millimeters of mercury; Δ is the slope of saturated vapor pressure curve at the air temperature; γ is the psychrometer constant (0.27, here); E_a is defined as a product of wind function and vapor pressure deficit, i.e., $E_a = f(u)(1 - r)e_s$ in millimeters per day, where $f(u) = 0.262[0.5 + 1.2(U_2/100)]$; and where U_2 is the wind speed at two meters height in miles per day and f(u) is the factor that is dependent on wind velocity, surface roughness, and stability of the air layer.

The only objection to Penman's method is in equation (4-49), where he assumed a single linear relationship to exist between E_T and E_0. Also, he assumed the seasonal constant a to be less than 1, i.e., $E_0 > E_T$. It has been found that day-to-day variation in E_T is sometimes larger than the season-to-season variation, and thus the seasonal constant a does not exist. As far as the estimation of E_0 is concerned, Penman's equation (see equation (4-50)) is satisfactory. The nomogram derived by Rijkoort (1954) in The Netherlands is a simple method to evaluate the Penman equation. Purvis (1961) also presents a graphical solution of the Penman equation, as adapted for Columbia, Missouri. His graphical solution is given in the form of three graphs which may be used for any locality with some modifications. Wang and his associates (1958-61) have derived an even simpler method in estimating evaporation for nine localities in Wisconsin. They found that the daily mean evaporation can be estimated from the percent of possible sunshine. But the evaluation of monthly mean evaporation needs both temperature and the percent of possible sunshine. Figs. 4-22 and 4-23 show the graphical method for five stations with an estimation of evaporation for the months of July and September, respectively, in Wisconsin.

Not much work has been done on direct application of evaporation to crop response studies. Most studies are confined to the subject areas of drought, irrigation, and effective rainfall. Nevertheless, actual evapotranspiration is an important factor in plant growth and development, and more research should therefore be done in this direction.

4.4 MOISTURE IN THE SOIL

The available or potentially available water for plant growth comes from two sources, namely, from the air and from the soil. That from the air to the soil is in the form of rain, snow, dew, and fog. Other available water from the air which has been described in Section 2.2.2

is comparatively minor in importance and will not be discussed here. The available water in the soil, on the other hand, which is paramount in importance to plant growth, will be discussed later.

4.4.1 *The available moisture from the air*

The influences of rainfall, snowfall, dew, and fog on plants are quite different from each other because they are individually associated with specific weather patterns. Summer rainfall may be associated with severe wind and an intense and short-duration thunderstorm while spring rainfall, in some areas, may be associated with a light and prolonged rainy season. Therefore, more sunshine is to be expected with the former, much less sunshine with the latter. Snowfall is usually associated with cold weather, overcast sky, and, sometimes, severe winds. Dew is formed usually on a calm, clear night, while fog is sometimes associated with a warm or cold air advection. It usually occurs late in the afternoon or early in the morning. The weather condition together with the duration, intensity, and frequency of rainfall, snowfall, dew, and fog contributes different effects on plant growth and development.

(a) Rainfall. The many forms of precipitation are of little significance to the plant if they are unavailable for its use. Soil moisture received as rainfall represents the most important of these forms and the bulk of the literature has been published on its various aspects. Some studies treat rainfall by seasons, others by month. Further division may be weekly, daily, hourly, or the differentiation of day and night rainfall. The intensity, duration, and amount of rainfall at various seasons and months should be studied. Agricultural applications of rainfall studies include, among others, soil fertilization and rainfall, spraying and rainfall, rainfall and crop yield, rainfall damage, control of rainfall, and interception of rainfall by plants. Unfortunately, monthly rainfall was employed for most of the study of crop response during the past. Although two months can have exactly the same amount of rainfall, the distribution can be completely different. This will give different plant responses to the same amount of rainfall. Therefore, statistics of rainfall should consider the physiological laws of plants. Those rainfall statistics which have been found useful are frequencies of weekly and daily rainfall, relative minimum rainfall, relative maximum rainfall, crop rainy days, crop drying days, and frequency of occurrence of extreme rainfall. The terminology of rainfall statistics will be explained shortly.

Probability analyses of weekly rainfall for 125 stations in the U. S. by means of incomplete gamma function computations have been done by Barger et al. (1959). Their rainfall probability data have been analyzed by Wang (1961) to show the isopleths of the distribution in the North Central region of the United States. Essenwanger (1960) studied the daily data of rainfall for Munich, December through February, in logarithmic scale, shown in Fig. 4-24. The graph displays a mode at 2.51 mm, and the frequency for the small amount of rainfall is left open, as no complete records are available for this range. The rainfall distribution indicated on the top curve is broken down into three normal distribution curves. The latter present different types of rainfall associated with types of weather pattern. In other words, the time sequence of maximum rainfall frequencies associated with various types of air masses and their movements is shown. This kind of study groups rainfall of the related types together, giving a meaningful physical interpretation of the observed data. It is useful for agricultural purposes. In fact, similar studies have been done by Schneider-Carius (1954), Essenwanger (1956), Wischmeier & Smith (1958), Chow (1954), and others. Wang's isopleth analysis gives the area-wide probability of weekly rainfall; Essenwanger's Gauss normal curve indicates the history of weather pattern for a single station. These are useful analyses for agricultural operations.

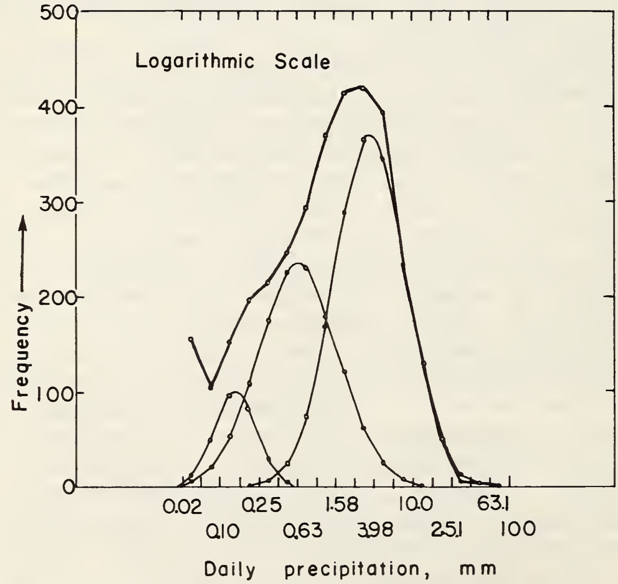


Fig. 4-24. Frequency distribution of daily precipitation amount at Munich in December-February 1880-1950, logarithmic scale.
After Essenwanger, 1960

Wang has studied the frequency distribution of weekly rainfall for 23 Wisconsin stations. The duration and magnitude of the first and second peaks of this weekly rainfall have also been studied. The first and second peaks are defined as the first and second high weekly rainfall accumulations for each year. All subsequent peaks are ignored,

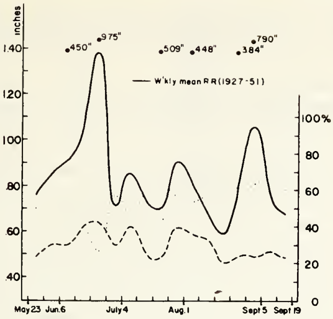


Fig. 4-25. Frequency distribution of weekly accumulated rainfall, Ashland, Wisconsin, 1927-1951.

even though they may be higher. There are generally two to five peaks, with two predominating. From year to year, the time of the first and second peaks is highly variable, but there are certain relationships in the time interval between the first and second peak for each station. These can be expressed by the absolute interval (the longest and the shortest interval), as well as by the percentage expectancy of the longest and shortest interval. The range of the magnitude of each percentage expectancy has also been computed, and is given in Table 4-14. Fig. 4-25 shows the frequency distribution of weekly accumulated rainfall for Ashland, Wisconsin, 1927-1951. The solid line indicates the all-years weekly mean rainfall (M). The dash line is the probability of weekly rainfall at or above 1/5 standard deviation (σ) plus the mean (or $M + \sigma/5$), while the dot line is that at or below $M - \sigma/5$. The highest weekly rainfall recorded for that particular week,

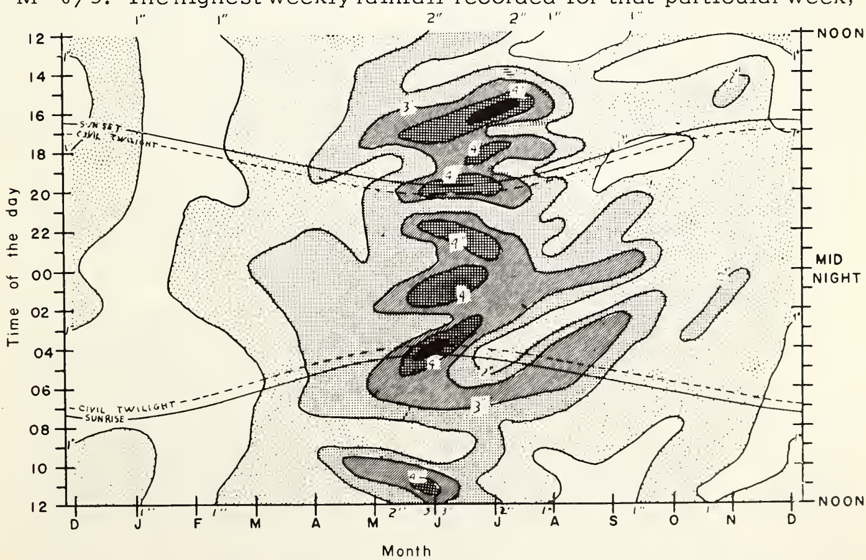


Fig. 4-26. Distribution of hourly rainfall totals, Madison, Wisconsin, airport, 1942-1958.

1927-1951, is also entered in Fig. 4-25, and Table 4-14 shows time intervals and magnitudes for 23 Wisconsin stations. Note, in Table 4-14, that the magnitude is based on fixed expectancy, while in Fig. 4-25, it is based on fixed time. Therefore, peaks in Fig. 4-25 are much lower than in Table 4-14.

In application, the farmer should avoid planting during and immediately after the first rainfall peak. He should schedule his planting dates so that the grand growth stage (the stage when most plants require more moisture, just before and during flowering) comes during the second rainfall peak. In addition, he could make economical use

Table 4-14. Expectancy of the Weekly Rainfall Peaks; Time Intervals and Magnitudes

A. Time Intervals

(a) Stations with about 50 years of record:

Stations	Mean Interval (Days)	Absolute Interval (Weeks)	Expectancy in Time-Intervals 90%	80%	70%	60%
Antigo	92	9-17	13-14*	13-14	13-13	13-13
Beloit	84	6-19	10-14	11-13	11-13	11-13
Broadhead	85	6-20	11-14	11-13	11-13	11-13
Burnett	67	3-18	8-11	9-11	9-10	9-10
Eau Claire	72	4-16	8-13	9-12	9-12	9-11
Grantsburg	54	2-14	6- 9	7- 9	7- 9	7- 8
Hillsboro	62	3-21	7-11	7-10	8-10	8-10
La Crosse	64	2-20	7-11	8-11	8-10	8-10
Lancaster	58	2-19	6-10	7-10	7- 9	7- 9
Manitowoc	59	3-20	7-10	7- 9	8- 9	8- 9
Merrill	72	3-17	9-12	9-11	9-11	9-11
Prairie du Chien	70	3-19	9-11	9-11	9-11	9-11
Racine	69	3-20	8-12	9-11	9-11	9-11
Waupaca	67	4-19	8-11	8-11	9-11	9-10
Wisconsin Rapids	62	3-18	7-11	8-10	8-10	8-10

*With 90% of confidence the peak will lie between 13 and 14 weeks, if very large samples are taken.

(b) Stations with about 30 years of record:

Stations	Mean Interval (Days)	Absolute Interval (Weeks)	Expectancy in Time-Intervals 90%	80%	70%	60%
Ashland	72	9-15	8-13	8-12	9-12	9-12
Green Bay	56	3-20	6-10	7- 9	7- 9	7- 9
Madison	62	2-22	6-12	7-11	7-11	7-10
Marshfield	65	3-16	7-11	8-11	8-10	8-10
Medford	61	4-16	7-10	8-10	8-10	8- 9
Richland Center	74	4-20	8-13	9-12	9-12	9-12
Williams Bay	67	4-18	7-12	8-11	8-11	8-11

Table 4-14 (continued). Expectancy of the Weekly Rainfall Peaks; Time Intervals and Magnitudes

B. Magnitudes

Stations	Lowest and highest peaks (in. of rain)		Expectancy in amount of rain (inches) 90%		80%		70%		60%	
	1st peak	2nd peak	1st peak	2nd peak	1st peak	2nd peak	1st peak	2nd peak	1st peak	2nd peak
(a) Stations with about 50 years of record:										
Antigo	0.57-4.57	0.79-7.49	1.78-2.88*	2.05-3.37	1.94-2.72	2.24-3.18	2.02-2.64	2.33-3.09	2.06-2.60	2.38-3.04
Beloit	1.27-4.73	0.92-8.05	2.33-3.19	2.33-3.45	2.46-3.06	2.49-3.29	2.51-3.01	2.51-3.21	2.55-2.97	2.61-3.17
Brodhead	1.06-5.03	0.79-7.82	2.43-3.25	2.36-3.72	2.55-3.13	2.56-3.52	2.61-3.07	2.65-3.43	2.64-3.04	2.70-3.38
Burnett	0.99-9.36	0.92-8.09	2.16-3.38	1.94-3.08	2.34-3.20	2.11-2.91	2.42-3.12	2.18-2.84	2.53-3.01	2.23-2.79
Eau Claire	1.12-4.87	1.38-5.77	2.33-3.51	2.35-3.55	2.50-3.34	2.53-3.37	2.58-3.26	2.61-3.29	2.63-3.21	2.65-3.20
Grantsburg	0.59-5.15	1.18-5.31	2.39-3.25	2.16-3.12	2.52-3.12	2.30-2.98	2.57-3.07	2.63-3.07	2.61-3.03	2.40-2.88
Hillsboro	1.26-5.93	1.36-6.68	2.40-3.30	2.31-3.23	2.53-3.17	2.45-3.09	2.59-3.11	2.54-3.03	2.63-3.07	2.54-3.00
La Crosse	1.17-5.15	0.80-6.71	2.32-3.18	2.29-3.25	2.45-3.05	2.43-3.11	2.51-2.99	2.49-3.05	2.54-2.96	2.53-3.01
Lancaster	1.30-6.76	1.39-6.44	2.35-3.25	2.63-3.69	2.49-3.11	2.79-3.53	2.54-3.06	2.86-3.46	2.58-3.02	2.90-3.42
Manitowoc	1.05-7.22	1.06-7.76	2.05-3.53	1.91-3.03	2.27-3.31	2.08-2.86	2.37-3.21	2.15-2.79	2.42-3.16	2.19-2.75
Merill	0.87-5.59	1.14-6.34	2.24-3.12	2.07-3.21	2.37-2.99	2.24-3.04	2.43-2.93	2.31-2.97	2.46-2.90	2.36-2.92
Prairie du Chien	1.75-5.46	1.58-6.78	2.45-3.13	2.63-3.65	2.55-3.03	2.78-3.50	2.59-2.99	2.85-3.43	2.62-2.96	2.89-3.39
Racine	1.14-4.37	1.12-6.52	2.32-3.02	2.23-3.23	2.43-2.91	2.37-3.09	2.47-2.87	2.44-3.02	2.50-2.84	2.48-2.98
Waupaca	0.90-9.91	0.97-6.26	2.36-3.56	2.10-3.08	2.53-3.39	2.24-2.04	2.61-3.31	2.31-2.87	2.66-3.26	2.35-2.83
Wisconsin Rapids	1.27-5.13	1.06-6.55	2.45-3.23	2.25-3.27	2.57-3.11	2.40-3.12	2.62-3.06	2.46-3.06	2.65-3.03	2.51-3.01
(b) Stations with about 30 years of record:										
Ashland	0.94-4.50	0.50-9.75	1.32-3.00	1.78-3.98	1.56-2.76	2.10-3.66	1.68-2.64	2.25-3.51	1.74-2.58	2.33-3.43
Green Bay	0.77-6.07	0.95-5.64	2.04-2.96	1.86-2.62	2.18-2.82	1.97-2.51	2.24-2.76	2.02-2.46	2.27-2.73	2.05-2.43
Madison	1.17-4.75	1.32-9.09	2.20-3.22	2.21-3.87	2.35-3.07	2.45-3.63	2.42-3.00	2.56-3.52	2.46-2.96	2.63-3.45
Marshfield	1.05-8.19	1.13-5.48	2.49-3.99	2.18-3.10	2.71-3.77	2.32-2.96	2.81-3.76	2.38-2.90	2.87-3.61	2.41-2.87
Medford	1.39-6.55	0.97-9.82	2.18-3.24	2.26-4.00	2.33-3.09	2.52-3.74	2.40-3.02	2.63-3.63	2.45-2.97	2.70-3.56
Richland Center	1.03-4.69	1.60-7.68	2.16-3.10	2.63-4.29	2.30-2.96	2.88-4.04	2.35-2.91	2.98-3.94	2.40-2.86	3.05-3.87
Williams Bay	0.96-7.24	1.27-5.81	2.11-3.39	2.16-3.20	2.30-3.20	2.32-3.04	2.38-3.12	2.38-2.98	2.43-3.07	2.42-2.94

*The amount of rain (inches) of the first peak will lie between 1.78 and 2.88 90% of the time.

of irrigation by consulting Table 4-14 on the expected amount of rainfall.

The annual course of hourly intensity of rainfall for Madison, Wisconsin, is shown for illustration in Fig. 4-26. The abscissa indicates the monthly totals of hourly rainfall for 17 years, the ordinate, the local hours of the day. Isohyets (lines of equal rainfall amount) are drawn, and the times of sunrise, sunset, and civil twilight are entered. The hourly rainfall at Madison illustrates these variabilities.

(1) The total hourly rainfall at any particular hour of the day for any month can be obtained from Fig. 4-26 at the intersection of the month (abscissa) and the hour (ordinate). Thus, the total hourly rainfall at 4 p.m. in July is above five inches (actually 5.35").

(2) The total nighttime rainfall for the month of April over 17 years is 26.07". This is simply an accumulation of the hourly rainfall between lines of sunset and sunrise (i.e., 7 p.m. to 5 a.m.). Daytime rainfall in April totaled 21.05" (6 a.m. to 6 p.m.). Thus, the night total surpasses the day total by 5.02". The September difference is 10.29". Of course, if civil twilight lines are used to separate day from night, results will differ slightly.

(3) The mean rate of hourly rainfall, night or day, can be evaluated from the figure. For instance, the average daytime rate of rainfall on June days is 0.17" ($37.02/13 \times 17$) per hour; the nighttime rainfall is 0.22" ($40.61/11 \times 17$) per hour. In contrast, the average rate of rainfall on January days is 0.07" per hour and 0.05" at night.

The changes in total rainfall from hour to hour with months can also be estimated from Fig. 4-26.

The chances of occurrence of hourly rainfall per day in the 17-year period below 0.03" for various times of the day and months of the year, expressed in percentages, are given in Fig. 4-27 for Madison, 1942-1958. The chances of occurrence can be higher than 100 percent, because this is the total of all cases in a 17-year period for a certain threshold value, such as below 0.03". Thus, the maximum possible percentage could be 170 percent. If the expressions were on a per year basis, the pattern would remain the same, but the percentages would be too low to compare readily.

In the study of crop-weather relationships, a summary of rainfall variation is not sufficient. The abnormality of rainfall is the prime factor. These abnormalities, better termed as extremes, are described as relative minimum rainfall, relative maximum rainfall, crop-drying day, and crop-rainy day.

The relative minimum rainfall is the lowest accumulation of n-week rainfall in a particular growing season, or the total rainfall in the driest period. "Relative minimum" refers to the values of certain weather elements on a daily or weekly basis which are the lowest relative to the growing season of a crop.

Studying relative minimum rainfall is necessary because it deals

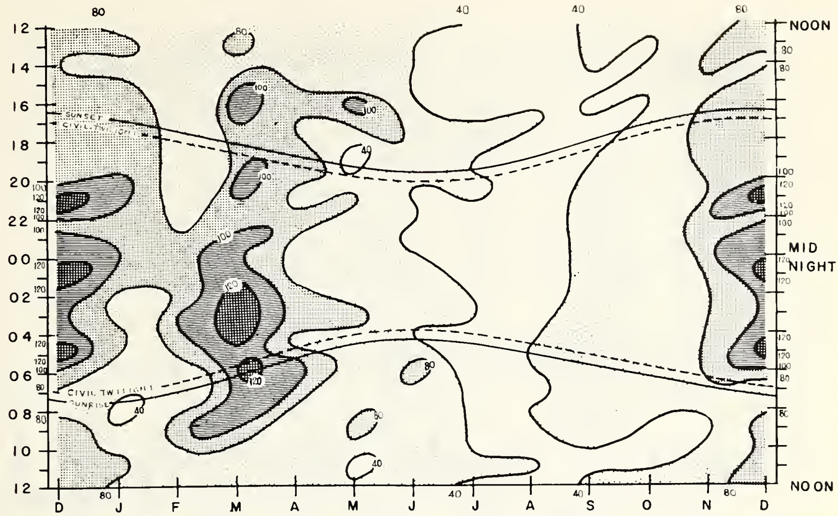


Fig. 4-27. Percentage frequency of hourly rainfall below .03", Madison, Wisconsin, airport, 1942-1958.

with the limiting[24] as well as the retarding[25] factors of plant response. Barger & Thom (1949) initiated relative minimum rainfall evaluation and applied it to the study of drought intensity versus yield of Iowa corn. Wang has applied this idea to several weather elements and several different crops which will be discussed in Section 7.4.3.

Fig. 4-28 illustrates relative minimum rainfall. The 1950 growing season for Alaska peas at Janesville ran from May 2 (the planting date) to June 26 (the harvesting date). For a one-week interval, the relative minimum rainfall falls between May 15 and May 21 and totals zero inches. For a two-week interval, it is 2.55 inches and covers the driest period, between May 5 and June 8, as indicated. Note that the time intervals for the evaluation of relative minimum rainfall can be overlapping, but they must be successive days. In Table 4-15, the percentage frequency of different amounts of relative minimum rainfall during the growing season at 3-, 5-, 7-, and 9-week intervals has been listed. Table 4-16 indicates the mean as well as the highest and lowest relative minimum rainfall for the same stations.

Similarly, the relative maximum rainfall is the highest accumulation of week rainfall in a particular growing season. "Relative maximum" refers to the values of certain weather elements on a daily or weekly

[24]Limiting factor: a certain element of the weather, the lack of which restricts the growth and development of a plant even though all the other factors are sufficient.

[25]Retarding factor: the restriction of the growth and development of a plant due to the excess of any weather element.

Year	1	2	3	4	5	6	7	8	9	Week
1950	.00	.07	.85	1.58	2.55	4.54	5.39	6.34	--	
1951	.00	.33	1.05	1.35	2.83	4.62	5.32	6.55	—	
1952	.00	.00	.92	1.19	3.16	3.38	3.44	6.74	--	
1953	.00	.12	1.17	1.45	2.22	2.74	2.84	3.89	—	
1954	.00	.12	.32	1.32	2.71	5.03	5.90	7.23	—	
1955	.00	.13	1.29	1.49	2.78	3.45	6.10	6.14	7.37	
1956	.00	.00	.40	.60	.90	1.95	3.12	5.81	6.59	

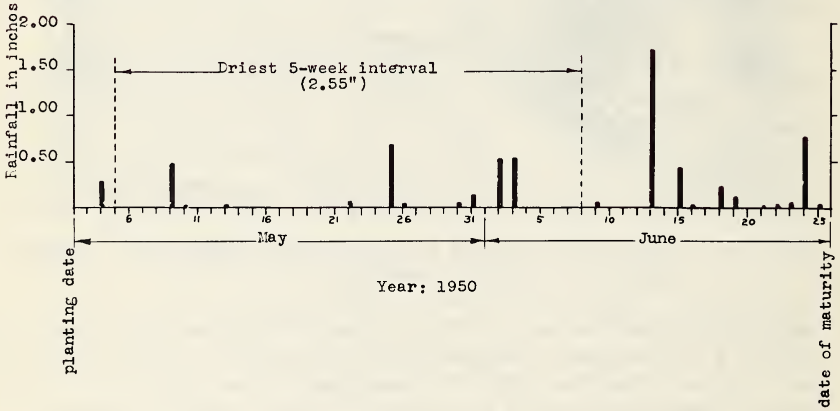


Fig. 4-28. Weekly relative minimum rainfall in inches, Janesville, Wisconsin, 1950-1956.

Table 4-15. Percentage Frequency of Relative Minimum Rainfall During the Growing Season for 10 Wisconsin Stations, 1927-1956

Weekly Interval	3			5			7			9		
Chance Expectancy (%)	60	75	90	60	75	90	60	75	90	60	75	90
Amount of rainfall in inches:												
Ashland	0.50*	0.75	1.00	1.72	2.43	3.88	3.28	4.31	6.29	6.48	8.49	9.66
Beloit	0.28	0.50	0.66	1.39	1.82	2.69	2.59	3.29	4.67	3.84	5.96	7.30
Eau Claire	0.41	0.63	1.01	1.53	2.03	2.72	3.22	3.90	5.38	4.53	5.56	8.06
Grantsburg	0.57	0.85	1.39	2.45	3.34	4.01	4.50	5.69	6.97	6.67	8.37	9.92
Green Bay	0.32	0.43	0.60	1.28	1.66	2.00	2.52	3.06	4.48	3.74	4.80	5.47
Madison	0.27	0.43	0.63	1.29	1.74	2.17	2.75	3.29	4.11	4.11	5.26	6.02
Medford	0.69	0.86	1.03	2.03	2.51	2.94	3.35	4.34	4.91	5.74	6.84	7.79
Racine	0.18	0.40	0.59	1.22	1.52	2.20	2.08	2.97	5.03	3.75	5.05	5.90
Richland Center	0.29	0.42	0.65	1.49	1.81	2.35	2.91	3.47	4.34	4.67	5.66	6.10
Waupaca	0.44	0.63	0.91	1.56	1.98	2.55	3.24	3.94	4.27	4.63	5.90	6.42

*Read as: 60% chance of obtaining 0.50 inches or less of rainfall in three successive weekly intervals.

Table 4-16. Mean and Extreme Successive Crop-Rainy Days During the Growing Season for 10 Wisconsin Stations, 1927-1956

Successive Days		1	2	3	4	6	8
Ashland	L*	13	2	0	0	0	0
	H	40	17	7	4	1	0
	M	27	10	4	1	0.1	0
Beloit	L	20	4	0	0	0	0
	H	52	25	10	6	4	1
	M	32	12	4	1	0	0
Eau Claire	L	23	6	0	0	0	0
	H	47	23	12	7	3	1
	M	41	13	5	2	0.2	0
Grantsburg	L	16	3	0	0	0	0
	H	44	22	11	6	4	2
	M	29	11	4	2	0.4	0.2
Green Bay	L	20	2	0	0	0	0
	H	40	21	9	5	3	1
	M	30	11	3	1	0.2	0
Madison	L	24	6	0	0	0	0
	H	45	22	9	6	4	2
	M	36	14	4	1	0.3	0
Medford	L	23	5	0	0	0	0
	H	45	25	11	8	5	3
	M	34	14	4	2	0.4	0.1
Racine	L	25	5	0	0	0	0
	H	58	27	13	7	3	1
	M	35	14	4	1	0.3	0
Richland Center	L	23	5	0	0	0	0
	H	44	21	9	5	1	0
	M	35	12	4	1	0.1	0
Waupaca	L	21	3	0	0	0	0
	H	44	18	9	5	2	0
	M	29	9	3	0.8	0.1	0

*L, H, and M refer to the lowest, the highest, and the mean value of crop-rainy days during the normal growing season.

basis which are the highest relative to the growing season of a crop. Some applications of relative maximum rainfall to vegetable crops will be described in Section 7.4.3.

A crop rainy day is a day in which the amount of rainfall is effective for plant response. In other words, the customary definition of a rainy day — a day with rainfall of 0.01" or more within 24 hours — is sometimes noneffective. Since a crop-rainy day is a measure of plant response to rainfall, certain criteria should be set up to redefine the rainy day.

The criteria suggested by Wang (1956) for the definition of crop-rainy day are:

1. Isolated crop-rainy days:
   a. When P_t (total precipitation per day) is greater than or equal to .20", it is counted as one R_c (crop-rainy day).
   b. When P_t is equal to or greater than .15", but less than .20", and the separation from an R_c is not more than two fair days, count as one R_c. It would not be counted, otherwise.
   c. When P_t is less than .15", it is not counted.
2. Continuous crop-rainy days:
   a. When P_t is greater than or equal to .10", it is counted as one R_c.
   b. When P_t is equal to or greater than .05", but less than .10", and the total amount for the two successive days' precipitation is more than .20", then these two days are counted as two R_c, provided the greater total falls on the first day. These two days will count only as one R_c when the smaller total falls on the first day. (It is assumed that there is no R_c previous to this lesser one.)
   c. When P_t is less than .05", it is not counted.

These criteria can be used for any crop, but the amount of precipitation (total precipitation per day) or thresholds should be adjusted to (a) type of crop, (b) climatic pattern of the locality (particularly evapotranspiration versus rainfall), (c) the topographic features, and (d) the microenvironment of the locality. The user must get the right thresholds for his criteria.[26]

[26]One way to obtain appropriate thresholds is by experimental or statistical crop-response studies. The establishment of crop-rainy day criteria is founded on two major aspects of weather conditions. In a wet spell, when continuous rainy days prevail, the weather is generally cloudy, and there is high humidity and low evaporation. In a dry spell, when the single rainy days are sporadically scattered and rain usually lasts for only a few hours, the reverse weather conditions occur. Thus a small amount of rainfall in the former case is as effective as a large amount of rainfall in the latter, as far as crop responses are concerned. Crop-rainy days may be "isolated" (usually occurring in a dry spell) or "continuous" (always occurring in a wet spell). Further division depends upon the number of fair days which isolate a single crop-rainy day, the total amount of rainfall in a single day or in two successive days, and the rate of diminishing or of increasing rainfall. These considerations are illustrated in the criteria of a crop-rainy day.

A crop-drying day is used to define a dry spell which is here designated as a period when rainfall is at or below a certain threshold value. Two rainfall threshold values, 0.20" and 0.40", were chosen arbitrarily to fit the use of crop-drying weather. A day with 0.20" or less rainfall is considered a day with no rain. This applies to 0.40" threshold when so chosen. Therefore, a day with no rainfall or with rainfall at or below the threshold is termed a "crop-drying day."

The dry spell is expressed in successive days. The runs of these successive intervals are 1, 2, 4, 6, 8, 10, 15, 20, 25, 30, 40, 50, and 60 days. It is obvious that rainfall alone is inadequate to describe crop-drying weather. Other factors such as relative humidity, evaporation, wind, and sunshine must be considered. In computing a crop-drying day, an overlapping system has been adopted. As illustrated in Fig. 4-29, for the growing season at Ashland, 1950, there are 106 crop-drying days in one-day runs, and five 20-day runs, the latter occurring in an overlapping system that is readily seen between August 25 and September 17.

Successive Days	1	2	4	6	8	10	15	20	25	30
1950	106	91	69	53	40	31	15	5	0	0
1951	91	72	45	29	15	6	0	0	0	0
1952	106	89	60	42	32	24	11	3	0	0
1953	99	80	52	35	25	19	7	2	0	0
1954	99	79	56	45	35	25	11	1	0	0
1955	106	94	76	63	51	39	23	19	9	4
1956	104	93	75	61	49	43	33	23	13	5

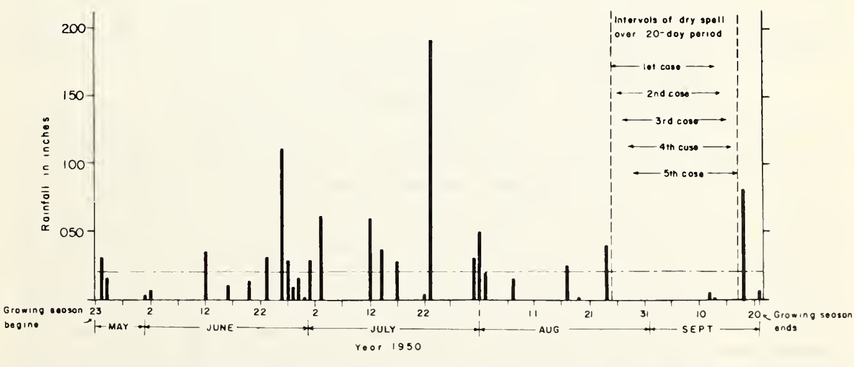


Fig. 4-29. Illustration for the computation of crop drying days, Ashland, Wisconsin, 1950-1956. Threshold value 0.20".

In 90 percent of the years 1927-1956 there were 33 or more cases of six-day runs per growing season in Ashland. This is seen in Table 4-17a, column 6, at the intersection of 90 percent occurrence and

Ashland. The frequency curves can be obtained by weighting the maximum value[27] of each run.

The frequency of extreme rainfall which causes a hazard can be in any of the following categories:

a. An intense rainfall within a short period, e.g., 5" of rainfall within a 15-hour period. (The highest intensity of rainfall ever recorded for 15 hours duration was $34\frac{1}{2}$" in Smethport, Penna.)
b. A light rainfall over a long period, e.g., 5" of rainfall within 40 days with continuing cloudy days.
c. A heavy rainfall accompanied by hydrometeors and others, e.g., a hailstorm, freezing rain, or severe wind.
d. A heavy rainfall of short duration after a drought and followed by bright sunshine and high temperatures.

The hazards come either from mechanical or physiological damage. Statistics along this line are needed.

Table 4-17a. Percentage Frequency* of Crop-Drying Days During the Growing Season for 10 Wisconsin Stations, 1927-1956 (Threshold Value ≤ 0.20")

Successive days	2			6			15			30		
Chance expected (%)	30	60	90	30	60	90	30	60	90	10	30	50
	Minimum occurrences per growing season											
Ashland	93	88	77	53	46	33	15	6	0	6	0	0
Beloit	129	121	109	81	72	45	27	17	3	14	0	0
Eau Claire	112	105	95	63	52	31	15	9	1	11	0	0
Granstburg	92	81	73	51	37	23	13	4	0	2	0	0
Green Bay	122	116	112	77	64	53	28	16	6	7	0	0
Madison	133	129	121	80	70	55	24	11	5	6	0	0
Medford	91	85	80	46	38	27	9	3	0	1	0	0
Racine	141	138	125	88	81	57	28	15	8	15	2	0
Richland Center	122	116	112	72	58	45	23	12	2	10	1	0
Waupaca	109	102	95	64	50	39	11	5	1	0	0	0
All stations**	121	104	83	68	52	33	19	8	0	5	0	0

Table 4-17b. Percentage Frequency of Crop-Drying Days During the Growing Season for 10 Wisconsin Stations, 1927-1956 (Threshold Value ≤ 0.40")

Successive days	2			6			15			30		
Chance expected (%)	30	60	90	30	60	90	30	60	90	10	30	50
	Minimum occurrences per growing season											
Ashland	106	100	93	76	65	53	37	25	10	24	5	0
Beloit	142	137	121	105	94	66	47	37	12	32	18	8
Eau Claire	127	124	113	90	80	63	44	25	14	16	9	2
Grantsburg	102	97	85	73	58	43	33	14	8	19	9	0
Green Bay	135	130	125	100	91	81	52	37	24	30	18	11
Madison	149	143	137	112	95	83	63	41	22	35	17	5
Medford	107	102	95	73	63	53	30	21	10	13	6	2
Racine	158	154	141	121	107	81	64	49	25	49	29	9
Richland Center	138	133	127	97	86	72	45	35	19	25	11	3
Waupaca	124	117	113	83	79	64	38	22	13	9	5	0
All stations**	136	121	97	94	78	57	44	27	12	26	10	2

*The percentages were computed in terms of the year of the highest occurrence in the 30-year period.
**Refers to chance expected (%) for the above 10 stations.

[27]The frequency curves can be obtained by plotting the number of days of runs as abscissa and the percent of chance of occurrence as ordinate on a scale of 0-100 percent (for details, see Wang, 1961). On the other hand, if one divided by the number of days in each growing season, there would be a very low percentage frequency for the minimum case (especially in runs of 10 or more days), and the significance of the figures would be lost.

(b) Snowfall. Snowfall prior to the normal growing season is one of several physiological preconditioning factors necessary for plant growth.

The total accumulated snow and rainfall during the freezing season (i.e., The period other than the growing season), which begins from the first day of the normal freezing season of the previous year and continues to the end of that same season, is normally considered as the amount of moisture reserved for plants at the time of sowing. Mallik (1955) studied the pre-sowing rainfall and germination of wheat in India, and Salom Calafell (1951) indicated that years of snow are the years of prosperity. That a good year of snow is an indication of abundant harvest has been common knowledge to most farmers and growers for centuries. This probably results from the contribution of the available moisture, the reduction of insects and diseases, and the increase in fertility. Strictly speaking, this is not true because evaporation, percolation, and runoff are the dominating factors in soil moisture depletion. In other words, the total accumulation of precipitation minus depletion from these factors would give the actual amount of available moisture prior to planting. If the soil is frozen continuously throughout the freezing season without any thawing days, the difference in snow depths would facilitate the computation of evaporation over snow surface. Thus the remainder indicates the actual available moisture. For example, if the snow water equivalent is D_s (in inches of water) at a specific date and after t days it is D_s' (with no snowfall during the period of t), then the rate of evaporation (E_s) over snow surface is

$$E_s = (D_s - D_s')/t \qquad (4\text{-}51)$$

where E_s is expressed in inches per day.

Snow cover, which is a good insulator, acts as a blanket of natural mulch for the root and stocks of vegetation during the winter and has been studied by a number of authors. The physical and physiological aspects of snow cover are explained thus: Snow is almost a black-body for infrared radiation at a wavelength of 10 microns, and is a good reflector for visible radiation. As shown in Table 4-1, the albedo of freshly fallen snow is 81 percent. Thus by day it reflects most of the short-wave radiation and receives little heat for storage. By night it radiates strongly, thus lowering the surface temperature. However, the direct solar and sky radiation can penetrate through the snow just as well as through water. The little storage heat will gradually build up and give considerable heating. This heating increases with the combination of a clear day and cloudy night. Observations show that the soil under snow is very much warmer than the air immediately above the snow. The temperature of the ground under snow has been observed to be above the freezing point of water, and this causes the overlying snow to melt from below. The heat enters the snow layer by infiltrating water from melting or so-called pseudo-conduction, while heat transmits upward through snow by true conduction. It is well known that snow is a poor conductor; thus a heat wave attributes more heat to snow than cold can take away from it. Also, the former is a much faster process than the latter. Moreover, the cooling process which

Table 4-18.

a. Percentage Probability of Snowfall for Five Stations (1904-1959)

Stations	Threshold Values in Inches: 0.0-1.0	1.1-2.0	2.1-3.0	3.1-4.0	4.1-5.0	5.1-6.0	6.1-7.0	7.1-8.0	8.1-9.0	9.1-10.0	10.1-15.0	Above 15.0
Dubuque, Iowa	31.4	7.5	8.3	8.3	6.0	6.2	4.2	6.5	4.2	3.6	7.8	6.0
Duluth, Minn.	23.6	5.9	5.7	5.2	5.9	6.1	4.3	5.0	3.9	4.1	15.5	14.8
Green Bay, Wis.	26.8	6.8	4.9	5.2	7.3	4.4	4.9	6.0	6.5	3.6	14.8	8.8
La Crosse, Wis.	29.4	5.5	6.5	4.2	4.9	5.7	5.7	4.4	5.7	3.9	15.3	8.8
Madison, Wis.	29.6	6.5	8.1	6.2	5.7	5.7	6.8	6.8	2.3	4.7	11.7	5.9

b. Mean Accumulated Snowfall for Five Stations, in Inches (1930-1952)

Stations	Freezing Season	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May
Duluth, Minn.	66.4	66.4	64.8	56.4	45.5	30.4	18.7	6.4	0.5
Green Bay, Wis.	42.1	42.1	41.8	38.8	31.4	20.6	10.5	1.7	--
La Crosse, Wis.	44.9	44.9	44.8	40.2	31.9	21.1	11.6	1.5	--
Madison, Wis.	37.0	37.0	37.0	33.4	26.5	16.5	9.7	1.1	--
Spooner, Wis.	49.2	49.1	47.7	41.4	31.9	22.1	13.6	3.6	0.1

c. Mean Snow-Rain Ratio* for Five Stations (1931-1952)

Stations	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	Mean
Duluth, Minn.	1.44	2.70	3.13	3.32	1.67	0.89	0.35	1.69
Green Bay, Wis.	0.15	0.78	1.32	1.05	0.74	0.42	0.10	0.63
La Crosse, Wis.	0.69	0.94	1.19	1.19	0.81	0.48	0.14	0.68
Madison, Wis.	0.52	0.61	0.89	0.84	0.61	0.37	0.13	0.49
Spooner, Wis.	0.83	1.36	1.84	1.29	0.84	0.53	0.13	0.85
Range	0.15-1.44	0.61-2.70	0.89-3.13	0.84-3.32	0.61-1.67	0.37-0.89	0.10-0.35	0.49-1.69
Mean	0.73	1.28	1.58	1.58	0.93	0.54	0.17	0.87

*The ratio refers to the fraction of the total amount of monthly water equivalent of snowfall as to the total amount of monthly rainfall in inches for the period 1931-1952.

takes place during the night by long-wave radiation is confined to only a thin top layer of the snow, as is also true for evaporative cooling during the day. Short-wave radiation, on the other hand, penetrates deep into the snow. When alternation of freezing and thawing occurs, thin ice sheet layers are formed. In this case, snow is still acting as a natural mulch, but it is harmful to vegetation because air circulation is retarded. This is detrimental to plant growth because of suffocation, due to the presence of concentrated carbon dioxide, rather than to the freezing. The other harmful effect of snow is due to mechanical damage by the dead weight of the snow. During bright sunny days in the winter the physiological drought, a result of low ground temperature, is still another aspect of alternation in the freezing and thawing of snow. When the snow is completely melted on successive days and frozen at night, the frost penetration goes deep into the ground. This phenomenon is lethal to most evergreens during the winter.

Much literature on the relation of snowfall to plant growth and injury has been published. Root (1919) considered the total snowfall and mean temperature as factors determining the yield of wheat. He found that winters of light snowfall are followed by good wheat yields, and the winters of heavy snowfall by light wheat yields. He attributed this partly to the fact that the temperature is less severe in the winters of light snowfall. Smith (1919) in his study of the effect of snow on winter wheat in Ohio, also emphasized the importance of low temperature. Many reports are found on snow injury to forest trees and grasses (e.g., Benedict, 1916; Day, 1940; Curtis, 1936; Tyson, 1936; and Radwańska, 1952). The interception of rainfall and snowfall by second-growth ponderosa pine has been studied by Rowe and Hendrix (1951).

For statistical value, the accumulation of the snow cover during the freezing period, the percentage probability of snow threshold value, and the snow-rain ratio should be computed. This has been done for the Wisconsin area, and is shown in Table 4-18.

(c) Dew and fog. Both dew and fog are sources of water for plant growth (particularly in semi-arid areas); they also contribute to the development of diseases and insects, and are sometimes a source for intensifying air pollution. Their benefits as well as their harmful effects depend upon the type of vegetation, the time of occurrence, and the region concerned. Stone (1957) has made a comprehensive review of the literature on the absorption of dew by plants. He and Shachori in 1954 demonstrated experimentally that the ponderosa pine seedling has the ability to reverse the usual procedure of plant transpiration. Both men indicated dew as being an important ecological factor. Steubing (1953) reconfirmed the importance of dew for plant growth. Chaptal (1928-1930) considered dew as a secondary source of soil moisture. Went (1955) believed that the condensation of dew and coastal fog in the narrow strip of the Southern California coast supply enough soil moisture for the growth of tomatoes, peppers, beans, and other vegetable crops. These crops develop well without irrigation, although no rain falls during the growing season from May to October. Ashbel (1936) indicated the importance of dew in Palestine. Gilead & Rosenan (1954) published ten years of dew observations in Israel, where dew occurs frequently and is sometimes rather heavy. Duvdevani (1954) conducted experiments on the coastal plain of Israel, where he found that plants such as squash and corn produced about twice the usual amount when they received dew during the night. The young leaves seemingly have a greater power of absorption than the old. It has often been observed that after a night of heavy dew, the young leaves are dry while old ones are wet. Dew, its measurement, estimation, gradient, and formation, has been intensively studied in Israel; for example, Duvdevani has designed an optical method of dew estimation. His wooden block has a standardized painted surface which is exposed to dew at night, on which the occurrence and quantity of of dew can be read in the morning according to the pattern of dew droplets deposited. The heavier the dew, the more the droplets coalesce. By comparing the dew patterns with photographs, one can standardize the observation. He found that in Israel the annual amount of dew is about one inch and that it is greater during dry summers and less in wet winters. In the dry and hot Jordan Valley, dew frequently occurs and lasts about half the night. In the southern desert, it is even more frequent.

In the consideration of microclimatic conditions, dew increases with the height of plants in the summer and vice versa in the winter. Topographic factors also have a bearing on dew deposition. Long (1955) studied guttation and dew. Balcar (1956) showed the significance of dew for tobacco plants. The absorption and loss of water by tomato leaves in a saturated atmosphere were studied by Janes in 1954. Haines (1952) also studied water absorption by leaves in a humid atmosphere. For desert shrub, Spalding (1906) indicated an ability to absorb atmospheric moisture. In dry soil, Stone et al. (1950) proved that plants can survive by absorbing moisture from the air. Sutton (1919-1920) studied the absorption of moisture by wheat grains and its relationship to the humidity of the atmosphere. Went (1955) found that when the relative humidity in the forest was 95% or more, several kinds of tropical orchids took up water vapor and increased in weight. He indicated that the relative humidity lasts for over 12 hours and is a significant source of water for plants. Harrold & Dreibelbis (1945, 1951, 1953) used a monolith lysimeter in Coshocton, Ohio, to measure the presence of soil moisture over a six-year period, and found 9.1" of dew deposit per year. This value is about 20% of the total yearly precipitation. Theoretically, the deposit of dew per year for clear nights has been computed as amounting to 15". Some workers believe that a great amount of atmospheric moisture can be absorbed by dry soil and that this is a secondary source of water for plant growth.

It has been observed that the optimal physical condition for dew formation is a clear calm night, where the relative humidity is 100%. The dew is formed on an object which is cooler than the ambient air temperature; for example, the leaves of the vegetation are slightly cooler than the air temperature because of their transpiration. The important mechanism for dew formation is mainly the long-wave back radiation. Thus the drier the air the stronger the long-wave radiation will be; also, the higher the temperature of the object, the greater the long-wave radiation is. The presence of heavy dust and cloud will reduce long-wave radiation greatly and no dew will be formed. It does not matter what the absolute humidity of the air is. Air always has enough moisture to saturate and condense as dew. As has been observed in the polar region, the relative humidity is very close to 100%, while the absolute humidity is exceedingly low. This is why there is more dew deposit in semi-arid regions than in the humid tropics. At the time when dew is formed, the evaporation rate of the air is usually low and, in turn, the duration of dew is prolonged. The spread of some fungi and carriers of plant diseases that require liquid water for growth are affected markedly. De Fina (1942) pointed out the agricultural value of dew in terms of plant disease problems. Many studies have been done in recent years along this line. Dew rather than relative humidity is important, as has been recognized by plant pathologists in recent years.

Fog is another source of available water from the atmosphere to the soil. It is a hydrometeor consisting of a visible aggregate of minute water droplets suspended in the air near the earth's surface. In meteorology, fog has been defined according to visibility below 1 km (0.62 miles). The difference between fog and cloud is only that fog is at the earth's surface, while clouds are above the surface. Haze, on the other hand, is fine dust or salt particles dispersed through a portion of the atmosphere characterized by its dampness and gray color. Mist is also an aggregation of dust of microscopic size. But it is fog with which we are concerned in this section, and not haze or mist.

There are two possible processes of fog formation: (a) addition of water to the air through evaporation, and (b) precipitation of water from the air by cooling. Steam fog and frontal fog belong to the first category; advection fog, radiation fog, and upslope fog, the second. Steam fog, which is usually observed near large bodies of water, occurs when evaporating water is condensed in the relatively cold air. It also forms over warm, wet lands immediately after a rain and over grass sods when wet. Siegel (1936) and Geiger (1959) indicated the formation of a three- to six-foot thickness of fog over grass, known as meadow-fog, by nocturnal cooling near the ground. In the tropics it forms shortly after a thundershower. Ogiwara (1947) studied relationships between the temperature and the rate of evaporation of fog, cloud, and raindrops. He found that fog is caused by the evaporation of raindrops. Frontal fog forms during warm rain falling into the dry air at the frontal boundary between two types of air masses. When the temperature of the vapor drops to dew point, or nearly so, the air becomes saturated and subsequently condenses. At this time turbulence in the lower air influences the extent and persistence of such a fog. Both steam fog and frontal fog result from adding warm water to cold air. On the other hand, radiation fog is a result of nocturnal radiation cooling. It usually occurs on a calm, clear night. Advection fog is produced when the humid warm air current passes over a cold land surface. Upslope fog is formed when the orographical ascension of humid and warm air along the slope is cooled down moist adiabatically.[28] Various types of fogs occur at different times of the day, different seasons of the year, and in different localities.

A study of the frequency, persistency (or duration), and intensity, as well as the rate and amount of precipitated water condensed would be an important problem to plant pathology and a secondary source for plant growth. Fog drip precipitates to the ground from trees or other objects which have collected the moisture from the drifting fog. The minute droplets of fog which are far enough apart that they do not readily collide, are suspended in saturated air so that they do not evaporate, and are light enough not to settle. But the needle-like leaves of conifers are better adapted to the removal of droplets from the drifting fog than the broad leaves of many deciduous trees. The collection efficiency has been explained by the aerodynamic principle that fog droplets follow the saturated air current and deflect over a large solid surface but are collected by a small surface. Means (1927) studied fog precipitated by trees. Cooper (1917) and Byers (1953) studied fog drips in redwood forests. In the Northern Coast of California, as much as 0.05" of fog drip, equivalent to a moderate shower, has been collected by redwoods in a single night. Redwoods, which occur only in a narrow belt, are located predominantly within the influence of sea fogs. Pine and oak forest also condense fog-drip. Just north of San Diego there is a small area where the Torrey pines grow. The trees are limited to the upper parts of the slopes facing the ocean whereas, at the lower parts of the slopes within a few hundred feet, beyond the reach of sea fog, the pines disappear. In Austria, Grunow (1955) measured fog drip collected by the forest and computed the total annual amount of water deposits on forest soil.

Fog precipitation on Table Mountain at Capetown, South Africa, has been studied by Nagel (1956). When mountain fog swept over the Table Mountain, 0.2" of precipitation was collected in a regular rain gage;

[28]For explanation of the term "moist adiabatic," see the Glossary of Terms at the end of the book.

but 0.6" fell in a fog collector, which is a rain gage equipped with a set of fine wire or a bundle of twigs. Observations have been made by Marloth as early as 1905, to the effect that fog forms on the windward side of the mountain and dissipates again on the lee side. His observation demonstrated that the rain gage with a bundle of twig covers received 16 times as much as the open gage. Now it is generally recognized that water gains by fog precipitation through the forest in the Table Mountain. Mordy & Hurdis (1955) indicated the possible importance of fog-drip in Hawaiian watersheds. In Japan, Hori (1953) studied advection sea fog in relation to fog-prevention forest in terms of fog density, particles, and atmospheric turbulences.

Studies on diseases related to moisture are numerous. However, not many of them are confined to a specific moisture factor such as rainfall, relative humidity, soil moisture, dew, or fog. Hirt (1942) studied the infection of eastern white pine by the blister-rust fungus in terms of various meteorological factors. He claimed that among the three moisture factors, namely, rainfall, fog, and dew, fog ranks second in importance. The duration, intensity, and time of occurrence of fog were studied. He believed that the occurrence of fog during cool summer nights with a long duration is a favorable weather condition for successful infection. This was a conclusion of six years' research (1930-1936) in northern and central New York.

4.4.2 *The available moisture in the soil*

Moisture is among the most difficult problems for meteorologists and agrometeorologists today. In spite of numerous studies, many problems are still unsolved. It is more so for soil moisture than for moisture in the air, because soil moisture is subject to change in a smaller area, whereas air moisture represents comparatively large areas, even though the air moisture gradient is large. Moreover, in terms of accuracy and representativeness, soil moisture is difficult to measure. Shaw & Arble (1959) have compiled a bibliography on soil moisture measurement in which a large number of measuring techniques were introduced, and yet soil moisture measurements are still uncertain. However, the most fundamental problem involved in the water requirements of a crop is a knowledge of the presence of available soil moisture.

Studies of soil moisture with respect to agrometeorology cover a multitude of subjects but can be grouped into four principal categories:

(1) Studies relating to the growth and development of plants: photosynthesis, respiration, transpiration, chloroplast formation, plant structure, chemical composition, photoperiodism, maturation, reproduction, fruiting, seed setting, germination, root development and distribution, permanent wilting point, quality, and yield.

(2) Studies relating to the physical properties of soils: field capacity, moisture deficit, moisture equivalent, hygroscopic coefficient,

water and vapor movement, capillary action, drainage, infiltration, leaching, dispersion, exchange of ions, pH, soil moisture tension and stress, mineral availability, salinity, soil porosity, tillability, and ground water.

(3) Studies relating to weather-soil relationships: soil moisture and rainfall, evaporation, evapotranspiration; diurnal, seasonal and long-range variations in soil moisture; prediction of soil moisture and improvement in observations and instrumentation.

(4) Studies relating to agricultural practices: mulching, maintaining fertility, and control of soil moisture.

This vast field may be illustrated in the following two aspects: plant response to normal and hazardous soil moisture, and the water budget of a crop field and the crop itself.

(a) Soil Moisture Excess, Deficit, and Normal Condition. In view of plant response, soil moisture studies may be divided into three categories: (1) moisture excess at its maximum — a flood; (2) moisture deficit at its maximum — a drought; and (3) normal moisture condition — a field capacity.

It is evident that under the prolonged retention of excessive moisture, plants are affected by (i) lack of aeration, which results in a high carbon dioxide and low oxygen concentration (Permeability of plant roots to water is decreased through the reduction of root respiration. The absorption of nutrients by plants is retarded.); (ii) loss of soil fertility, which results from the processes of infiltration, percolation, and runoff; (iii) depression of microbiological activity, which is caused by lack of oxygen and low soil temperature; and (iv) increase of plant diseases and the retardation of root development. In short, either high water tables or wet soils affect soil aeration, and consequently root growth, microbial activity, nutrient availability, and nutrient entry. Except for aquatic plants, the physiological processes of most plants, such as photosynthesis, respiration, cell enlargement, and divisions, would be influenced by excessive moisture. Therefore, when soil is either flooded by heavy rainfall or by irrigation for a critical duration, the condition is detrimental to plant growth and development. The physiological adaptations of crops to excessive moisture vary with species and variety. More studies have been done on drought resistance than on excessive moisture resistance because the former occurs more frequently. In agricultural fields, excessive moisture is usually associated with either an intensive heavy rainfall in a short time or a prolonged light rainfall, or both. Sometimes, in the case of a very heavy downpour of rain, water erosion results and in turn the agricultural crop would definitely be destroyed. In this connection, some mechanical damages may also occur, such as interference of flowering and pollination. The compaction of the soil by raindrops prevents the uniform emergence of seeds. This gives poor stands and poor quality in production. Small grains are often waterlogged by rain so that harvesting becomes difficult. Waterlogged grain is susceptible to spoilage and disease. The effect of rain on the hay harvest and the storage of grains is a problem. In case of a light rainfall of long duration, which generally occurs in conjunction with gloomy, cloudy and humid weather, the spread of diseases and a delay of flowering or maturity of crops are to be expected. These are the indirect effects of excessive moisture conditions. The worst case is a dry spell followed by an intensive wet spell, or vice versa. Numerous evidences demonstrate effects harmful to development of crops.

At the other extreme is the soil moisture deficit at its maximum stage, known as a drought. The word "drought" is hard to define. It depends on the user; for the agriculturist, it may be defined according to the type of crops concerned. For example, certain types of dry weather conditions may be called a "dry spell" for sorghum, but it is a drought for sweet corn. In Great Britain, a relative drought period of at least 29 consecutive days during which the average daily rainfall does not exceed 0.01" is termed "partial drought." In the United States a "dry spell" is a period that lasts for not less than two weeks, during which no measurable precipitation is recorded. In British climatology, dry spell is defined as a period of at least 15 consecutive days, none of them having a record of 0.04" or more precipitation. An agricultural drought may be defined as a period of abnormally dry weather sufficiently prolonged for the lack of water to cause a serious hydrologic imbalance (i.e., crop damage, water-supply shortage, etc.) in the affected area (Tannehill 1947). Drought severity depends upon the kinds of crops, degree of plant wilting, duration of drought, and the size of the affected area. Therefore, "drought" designates the period between rainfalls. It can be described by the dessicating power of the air and the availability of moisture from the soil. Veihmeyer & Hendrickson (1948) have suggested using the permanent wilting percentage of a plant as a reference for the measurement of soil moisture. Garnier (1951) and van Bavel et al. (1957) have defined soil moisture deficiency in terms of evapotranspiration. Van Bavel considers the field capacity of soil, the depth of the root zone, and the moisture content of the soil at the lower limit of the availability. Thus, the maximum storage capacity of soil depends upon the value of these factors, and the variation of which from one to several inches has been recognized by him. He defined drought-day as a day in which the evapotranspirations overcome the maximum amount of water that a soil can hold and make available to the crop to use. Such computation he made available for several states such as North and South Carolina, Georgia, and Virginia. However, evapotranspiration which he used is based upon Penman's method, which is potential evapotranspiration and is always overestimated. Should the actual evapotranspiration be measured accurately, the drought would be properly defined.

Newton & Martin (1930) have reviewed the early literature on the drought tolerance or drought resistance of a crop. Their summary of the major factors affecting drought resistance in plants is absorption, transpiration, wilting endurance as related to physiological adaptations, morphological structure, and environmental factors. Maximov (1929) has made intensive study on plants in relation to water. He has summarized water balance and drought resistance of plants including the efficiency of transpiration, drought resistance in plants, and the relationship between water and leaf structure. Shaw (1952) studied soil physical conditions and plant growth and has a chapter-long review on soil water and plant response. Major topics considered by Shaw are efficiency of water use by plants, drought tolerance, the influence of soil moisture on the physiological processes at various phases of plant growth and on microbiological activities, nutrient accumulation in plants as related to soil moisture supply, and mineral nutrition to plants. Soil moisture stress in relation to plant growth as well as the significance of the wilting percentage have also been reviewed.

During drought (or moisture deficit) soil moisture acts as a limiting factor, and during flood (or moisture excess) it is a retarding factor for plant growth. These are the extremes of moisture condition. At the field capacity, the available soil moisture is sufficient to support the growth and development of a plant and thus is at the optimal level. Therefore, the influences of soil moisture on germination, vegetable growth, and maturation differ according to the availability of soil moisture. Illustrations of the three phases of plant growth are given below.

Although seeds have a remarkable imbibitional power, most seeds will not germinate if the soil moisture is below the wilting percentage. Doneen & MacGillivray (1943) studied the germination and emergence of over 20 kinds of vegetable seeds in Yolo fine sandy loam at different moisture levels. The field capacity of the soil is 15.7 percent and the permanent wilting percentage is 8.6 percent. They found that the rate of germination is dependent upon the rate of water intake. Thus, the imbibitional power of seed is conditioned by the amount of soil moisture present within the range of available moisture. Half of the vegetable crops tested were inhibited when the soil moisture content was slightly below the permanent wilting percentage. Copenhagen Market cabbage seeds germinate 80 percent of the time at soil moisture of eight percent, whereas cucumber, onion, spinach, lettuce, snap beans, lima beans, and celery do not. Celery seeds did not germinate well when the soil moisture content was slightly below field capacity. As far as vegetable crops are concerned, the permanent wilting point is an appropriate threshold value for germination.

Mallik (1955) studied pre-sowing rainfall and the germination of wheat. Harrington (1923) studied forced germination of freshly harvested wheat and cereals as affected by temperature, water content and oxygen pressure. Wilson & Hottes (1927) also studied the effects of temperature and moisture on wheat germination. Helmerick & Pfeifer (1954) studied the differential varietal responses of winter wheat germination and early growth to controlled limited moisture conditions.

A series of studies on the germination of desert plants as related to temperature and rainfall have been done by Went et al. (1948-1956). They also studied the fire and biotic factors affecting germination of native plants. Germination and emergence of some native grasses in relation to litter cover and soil moisture have been studied by Glendening (1942). The effect of varying altitudes on germination were studied by Bonnier (1920). Decreased physiological availability of water arising from lowering of soil temperature affects the germination of seeds of various crops quite differently. Germination at low temperature at various soil moisture levels was one of the important farming operations for lengthening the growing season, for avoiding hot summer temperatures during the reproductive stage, and for supplying the early market. Literature on the germination of seeds exposed to low temperatures is abundant — Roberts (1924), Crescini (1928), Booth (1929), Busse (1930), Petunin (1950), Learner & Wittwer (1952), Harper (1955), and Toole et al. (1957). Busse (1930) studied the effect of intense freezing on sweet clover and alfalfa seeds. Booth (1929) studied the daily growth of oat kernels affected by varying duration of exposure to low temperature. Crescini (1928) studied the effects of low temperature on grain germination. Petunin (1950) determined the condition in the field for winter sowings in order to take protective measures against frost or to substitute spring sowings. He took soil containing seeds by soil bores, and germinated them under various temperature and light combinations. Harper (1955) studied effects of the interaction of soil moisture content and temperature on the mortality of corn grains. Learner & Wittwer (1952) studied the comparative effects of low temperature exposure, limited soil moisture, and certain chemical growth regulators as hardening agents for tomatoes grown in greenhouses. More studies along these lines should be done with adjoining effects of soil moisture and low temperature. These two are the major factors of seed germination.

Physiological efficacy of uptaken nutrient and water by roots will also be inhibited by the increased concentration of solutes in the soil solution. Ayers & Hayward (1948), Ayers, Wadleigh & Magistad (1943), and Ayers (1952) studied seed germination as affected by soil moisture and salinity. They pointed out that soil salinity impedes the rate at which seeds germinate and also decreases the number of seeds that do germinate. Among alfalfa, sugarbeets, corn, kidney beans and barley, sugarbeets are most sensitive to saline soil, whereas barley has high tolerance to salinity. Wadleigh, Gauch & Strong (1947) studied root penetration and moisture extraction in saline soil by crop plants. Henderson (1951) studied the effects of salinity on moisture content and freezing-point depression of soil at permanent wilting of plants. There are many studies along this line. Plants which have high tolerance to saline soil have been classified as halophytes in ecology.

Intensity, duration and quality of light as well as light-temperature interaction also have bearing on germination. Elliott & French (1959) studied the germination of light-sensitive seed in crossed gradients of temperature and light. Studies of over-all environment factors including moisture should be done in future research.

Root elongation (or extension), distribution, and absorption of soil moisture are other aspects of the study of moisture-plant relationships. Hunter & Erickson (1952) studied effects of seed germination on soil moisture tension. Absorption of water by plants and the forces involved have been evaluated by Shull (1930). Kramer (1941) considered soil moisture as a limiting factor for active absorption and root pressure. Davis (1940) studied the absorption of soil moisture by maize roots. The influence of dry soil on root extension has been studied by Hendrickson & Veihmeyer (1931). In a later year, they studied root distribution in deciduous orchards and found that soil moisture is a good indication of the distribution. Volk (1947) made an interesting study on the significance of moisture translocation from soil zones of low moisture tension to zones of high moisture tension by plant roots.

In the study of the relationship of the vegetative growth of plants and soil moisture, two physiological aspects are commonly used: the net assimilation rate and the transpiration rate. The net assimilation rate, which was first designated by West, Briggs, & Kidd in 1920 as unit leaf rate, is defined as the rate of increase in dry matter per unit area of leaf surface. This is the difference between the total photosynthetic product in the leaves and the total loss in the entire plant by respiration. The transpiration rate, which determines the growth of a plant, is defined as the amount of water loss by evaporation from the leaves or other organs of the plant. The amount of water used by plants has no comparison at all with the amount transpired. Wadleigh (1955) claimed that a cornfield in Iowa transpires 12" to 16" of water to cover that field in a season. The production of one ton of dry alfalfa hay on the Great Plains may involve the transpiration of about 700 tons of water. The major source of water to supply the transpiration process in order to maintain the growth of plants comes from the soil moisture reservoir. The capacity of soil moisture reservoirs is limited by the field capacity (the upper limit) and the permanent wilting percentage (the lower limit). The soil moisture deficit affects cell enlargement more than cell division. Thus growth of plants will be inhibited without adequate moisture supply. In this connection, studies of wilting percentage are important in the consideration of vegetative growth. Brown (1912) studied the evaporation of water content of the soil at the time of wilting. Caldwell (1913) emphasized the condition for permanent wilting as a result of the decrease in the soil moisture content and loss of water from plants by transpiration. A similar study has been done by Shive & Livingston (1914) on the relation of atmospheric evaporating power to soil moisture content at permanent wilting point. Work & Lewis (1936) investigated the relationships of soil moisture to pear tree wilting in a heavy clay soil. Kenworthy (1949) studied soil moisture and growth of apple trees. Botelho da Costa (1938) used the "freezing point method" to determine the "wilting coefficient." Blair et al. (1950) studied the rate of elongation of sunflower plants and the freezing point of soil moisture in relation to permanent wilt. The range of soil moisture percentages through which plants undergo permanent wilting in some soils from semiarid irrigated areas has been investigated by Furr & Reeve (1945). The wilting and soil moisture depletion by tree seedlings and grass has been studied by Lane & McComb (1948).

Various aspects of soil moisture effects on crops have been studied by many investigators. Halkias, Veihmeyer, & Hendrickson (1955) determined the water needs of crops from climatic data. After investigating ten kinds of crops, they believed that the best measure of water use by crops is by soil sampling to obtain the changes in soil moisture. Haynes (1948) studied the effects of availability of soil moisture upon vegetative growth and water use in corn. Woodhams & Kozlowski (1954) studied the effects of soil stress on carbohydrate development and growth in plants. Barnes (1936) found that a combination of soil moisture content and other environmental factors influence the growth and color of carrots. Woodman & Johnson (1947) noticed that the growth and bolting of lettuce are results of the time of sowing and water supply. Effects of moisture supply and soil texture on the growth of sweetgum and pine seedlings have been studied by Wenger (1952). The radial growth of shortleaf pine in Northern Mississippi has been investigated by McClurkin (1948).

Plants respond differently at various phases of their development. For most plants, high soil moisture content is generally favorable for vegetative growth but not always for germination and maturation. The yield of the crop may be increased by increasing irrigation, but the quality is generally lower. In Utah, Taylor (1952) found that a continuous supply of soil moisture to the growing crop gives the highest yield. He used mean soil temperature tension to evaluate the effect of soil moisture on crop yields. But Adams et al. (1942) found that the yield of cotton seeds was not affected by increase of irrigation. Barker & Berkley (1946) found that better (i.e., shorter and stronger) cotton lint is produced under moisture stress than with adequate soil moisture. Overley et al. (1932) in the state of Washington found that a lightly irrigated plot produced the highest quality of Jonathan apples as compared to medium and heavily irrigated plots. Similar findings on peaches and prunes were obtained by Hendrickson & Veihmeyer (1929, 1934). Although yields of peaches and prunes were higher on frequently irrigated plots, the storage quality was lower. They were more prone to bruises and decay. With a continuously high level of soil moisture on Bartlett pear orchards, it was observed by Ryall & Aldrick (1938) that pear trees are low in percentage of dry matter, less firm, and succumb easily to core breakdown.

In spite of the complications and of the various angles involved in soil moisture-plant relationships, a knowledge of the water balance will give a bird's-eye view of the over-all picture.

(b) Water Balance. The study of *water balance inside a plant* as well as *over a field* is the fundamental approach to plant-water relationships. The effect of the former on plant growth takes only a matter of hours, while that of the latter takes a few days. In other words, the water balance of a plant is maintained by containing the transpiration and absorption through processes of water translocation in plants. The constancy of the balance lasts only for a few hours, depending upon the environmental condition of the plant, and the rate of absorption to the rate of transpiration. The water balance in a field or the root zone layer of a field which lasts from one day to over a week depends upon the climate of air and soil type and structure and upon the field management. When the transpiration overcomes absorption, wilting of a plant results, and vice versa, vigorous growth continues. The diurnal water balance of a plant is generally a "loss" during the day, a "gain" at night. As has been commonly observed, leaves are turgid early in the morning and wilted during a mid-sunny-day. Montfort (1922) has computed the transpiration-absorption ratio (Q) by dividing transpiration (T) by absorption (A), or $Q = T/A$; where $Q = 1$, an exact water balance occurs. When $Q < 1$, there is more absorption than transpiration. When $Q > 1$, it is the other way around.

In order to understand the water balance in a plant, it is necessary to measure the transpiration and absorption as well as the translocation of water in plants more accurately. Translocation is a rather complex physiological phenomenon. A number of theories concerning the mechanism by which the ascent of the xylem sap is brought about in plants have been suggested. For example, the "Vital Theories" indicate that living cells of the xylem maintain the upward movement of water through stems (Ursprung, 1912; Bose, 1923). The "root pressure" theory explains exudations of xylem sap under the influence of root pressure (Priestley, 1930; Gibbs, 1935). The "cohesion of water" theory designates that the translocation of water is possible because of the cohesion between water molecules and their adhesion to the walls of the xylem ducts (Askenasy, 1897; Dixon, 1914, 1924; and Renner, 1911, 1915). Many investigators believed that temperature was the main cause of translocation from leaves (Curtis & Herty, 1936; Hewitt & Curtis, 1948). The use of radioactive tracers in experiments in recent decades throws light on the mechanism of water translocation in plants. Potometer determination, which is used to measure absorption and transpiration simultaneously, as employed by Vesque (1876), can be conveniently useful only for experiments with cut shoots or small seedlings. Many improved instrumental designs for such measurements have been developed in recent years. Further study is needed for the measurement of absorption and transpiration of plants in a natural field. This furnishes the best parameter for the study of crop responses.

Water balance in a field over a large area is generally a study in hydrology. The hydrologic accounting on a large scale, more simply "water budget," consists of precipitation, evapotranspiration, soil storage, percolation, runoff, and the like (see Fig. 4-21). The success of the water balance approach depends upon the accuracy of the measurement of the hydrologic terms. Many investigators have made use of the estimated potential evapotranspiration and actual precipitation in the study of water balance. Thornthwaite & Mather (1955) studied the water balance with a daily bookkeeping account for water gain by precipitation and loss by potential evapotranspiration. The difference between these two gives an approximated value of what remains in the soil (i.e., the soil water storage). They have made a global water balance by this method. However, the estimated potential evapotranspiration is much higher than the actual evapotranspiration.

Another approach is the heat balance method which was originally suggested by Schmidt in 1915 and has been elaborated in recent years. This method is similar to the energy balance method described in Section 4.1.1. Investigations using the heat balance method in various fields of study may be summarized as follows: Kohnke (1946) made practical use of the energy concept in the estimation of the soil moisture; Hofmann (1956) considered evaporation and dew as terms of the heat balance equation; Huber (1935) studied the heat balance of plants; Sapozhnikova (1948) found that the application of heat balance method in a wheat field would be an agricultural evaluation of the climate; Horney (1951) proposed measurements on heat and water economy of crop stands; he concluded that three phases of research are necessary: statistical methods, surface temperature and heat, and moisture balance. Kumai & Chiba (1953) studied the heat energy balance of the paddy field in Japan. The heat budget over a corn field has been studied and measured by Suomi (1953) in Madison, Wisconsin. The microclimate and heat balance of an irrigated field has been studied in the U. S. S. R. by Chudnovskii in 1953. In 1954 he reviewed the application of energy methods on agronomic problems. Investigation on heat and water balance of young fir stands has been done by Geiger (1952). Forest influences on thermal balance over the snowpack have been investigated by Miller (1952).

In order to understand problems related to water balance more fully, studies of mass transfer of moisture as related to the displacement of oxygen and carbon dioxide and movement of soil ingredients are necessary.

4.5 MOISTURE AND RELATED MASS EXCHANGE

In the present section, dynamic concepts are applied to plant response studies. In other words, plants and their environments, the air, water, and soils, are considered in everlasting motion. The vector quantity including speed and direction is employed, instead of the scalar quantity. The right speed and an appropriate direction of the movements contribute to a favorable response, and vice versa.

4.5.1 *The displacement of oxygen and carbon dioxide*

Constituents of the gaseous phase of the soil which have been recognized as factors in plant growth are water, oxygen, and carbon dioxide. The total amount of the three is determined by the pore space of the soil. The change of water vapor is conditioned by the amount and temperature of soil water. Whenever there is sufficient water to evaporate, water vapor is always saturated. The saturation of water vapor pressure is determined by the temperature of the soil atmosphere. Therefore, soil temperature is one of the dominating factors. This is true for the presence of oxygen and carbon dioxide. The mass exchange of oxygen and carbon dioxide at the soil-air boundary should be discussed.

The interchange of oxygen (O_2) and carbon dioxide (CO_2) below and above the soil surface is controlled by both biological and physical processes. In the biological reactions, the consumption of O_2 by plant roots and microorganisms and the release of CO_2 tend to increase the concentration of the CO_2 content. On the contrary, the process of diffusion decreases the CO_2 concentration and eventually increases the O_2 concentration until equilibrium is reached. The partial pressure of CO_2 is high where the CO_2 is concentrated. It tends to diffuse the gas upward and to lower the concentration. The O_2 molecules, on the other hand, move downward due to the higher partial pressure of this gas above the ground. When the partial pressures of O_2 and CO_2 are equal, a state of equilibrium is established. This is the major mechanism, as was pointed out in Section 2.1.1a. The other minor and occasionally major mechanism is the dynamic and thermodynamic forces, such as soil and air temperature gradients, surface wind pressure (both horizontal and vertical movements), air pressure variations, and water movements caused by various intensity and duration of precipitation. At a time when the temperature is high, as during the summer, the O_2 content is high and the solubility of O_2 in soil water is low; when the temperature is low, it is the opposite.

When the soil moisture content is above average, relatively high CO_2 and low O_2 contents exist. Generally, the CO_2 content increases with depth, and conversely, the O_2 content decreases. The change of the moisture and temperature gradient gives only a slow but steady movement of the gases.

A more abrupt mass flow of soil air occurs at times when soil is completely saturated by water. Either rainfall or irrigation water displaces almost all gases formerly occupying the soil pore space. The velocity of the displacement depends upon the type and the structure of the soil. Sandy soils percolate faster than clay soils and thus a rapid renewal of gases results. But this associates with low water-holding capacity. In clay soils, on the other hand, the water-holding capacity is high and water drainage is low. This results in poor aeration, and the growth of plants is affected by (a) lowering the nutrient and water absorption by plants; (b) accelerating the formation of toxic inorganic compounds; and (c) curtailing the root growth. For example, oxygen deficiency in soils has been found to curtail nutrient and water absorption by plants (Hoagland, 1944; Kramer, 1945).

The major effect of poor aeration on microbiological processes is a reduction in the rate of organic matter oxidation, due to the lack of oxygen. This in turn reduces the available nutrient for plant growth. In rice paddy fields, the soil is submerged in water. The oxygen and other gases from the air above are dissolved in the water and are conducted through it by diffusion or mass movement to the soil. The excess of unwanted gases in the root zone, such as CH_4, CO_2, N_2, and a small amount of H_2 and CO are rising from the soil surface and bubbling through the water surface. When soil has been saturated for 24 hours and then drained, the remaining air in the soil has been defined by Kopecky (1927) as the air capacity, usually referred to as the volume of non-capillary pores. The air capacity requirements of plants for optimum growth as suggested by Kopecky are: Sudan grass, six to ten percent, wheat and oats, 10 to 15%, barley and sugarbeets, 15 to 20%. Most root crops, such as potatoes, carrots, and sugarbeets, need more air capacity for growth. These are measures of aeration. Baver & Farnsworth (1940) found that total yield and sugar content of sugarbeets were increased with better aeration. Yoder (1937) found that highest yield of cotton on artificial seedbeds was obtained with over 30% of non-capillary porosity. Page, Willard & McCuen (1946) improved the soil structure of Paulding clay for growing corn, which almost doubled the yield. They also noticed that good aeration should be followed by proper cultivation practices.

Improper tillage may destroy granulation, leaving conditions that lead to inefficient nutrient utilization. Melsted, Kurtz & Bray (1949) compared the effects of aeration on corn and soybean by growing them in large lysimeters. In 1947 the yield of corn per acre was 94 bushels without aeration and 144 bushels with forced aeration. But in 1949, the yield of soybeans per acre was 41 bushels without aeration and 44 bushels with forced aeration. Boynton, DeVilliers & Reuther (1938) found that apple tree roots required three percent or more oxygen to subsist, five to ten percent for the growth of existing roots, and at least 12 percent for next root growth. Finally, the renewal of soil air as it relates to plant response is of considerable practical significance. Factors which govern the displacement of oxygen and carbon dioxide have been discussed in Section 2.1.1a, and also in the present section. As was pointed out in the former section, more accurate measurements on the time change of carbon dioxide and oxygen contents in the root zone instead of the volumetric measurement of these gases in the pore space are the most important task in this line of research.

4.5.2 *The movement of water and its vapor*

The movements of *liquid water* in the soil, such as percolation, runoff, capillary action, and the water table have been treated most intensively by soil physicists, hydrologists, and hydrometeorologists. In the air the interception of rain by the crown of vegetation, the velocity of clouds, the formation and movement of fog, and the like have been thoroughly studied in micrometeorology and meteorology. The movements of *water vapor* in the lower layer of the air have been treated in micrometeorology, its formation by physical meteorology, and its forecasting by synoptic meteorology. The movements and phenomena of *solid water*, such as frost heaving, frost penetration (or depth), snow cover, hailstone, the dissipation and formation of icesheet have also been treated in micrometeorology and physical meteorology. Textbooks in the above-mentioned fields should be used for further study. But water vapor in the soil has not been so widely treated, and it will be discussed below.

Water vapor moves around the soil pore space in all directions, driven mainly by the process of diffusion; it is blocked by capillary water or solid soil particles. This is similar to the behavior described for oxygen and carbon dioxide transfer. The process of carbon dioxide diffusion is governed by the difference of vapor pressure gradient.[29] The greater this difference, the more rapid diffusion tends to become and the greater the movement. The soil-air temperature (or the ambient air temperature of the soil pore space) and moisture of soil-air (or the water vapor pressure in the soil pore space) determine the vapor water transfer. When the soil-air on one horizon is cool and dry and the immediate horizon is warm and moist, the vapor movement tendency

[29] The water vapor gradient in three space dimensions is the vector normal to surfaces of constant value of the water vapor pressure and directed toward decreasing values, with magnitude equal to the rate of decrease of water vapor pressure in this direction. In short, this is the difference in vapor pressure of two points a unit distance apart.

would be possible if the liquid water in the soil capillaries does not interfere. The reason is that both the moisture and temperature gradients tend to move from moist to dry and warm to cool, respectively. When one horizon is moist and cool while the neighboring horizon is dry and warm, the opposite situation occurs. In this case, the tendencies are more or less negative to each other, and no vapor transfer is expected. Since beyond the permanent wilting point the water is near saturation, or with a relative humidity of over 99 percent, and since at the field capacity the water vapor is always saturated, the water vapor pressure gradient is very small, if any. Therefore, the movement due to diffusion is small. The other possible mass transfer similar to that of carbon dioxide and oxygen is caused by cold air drainage into the soil, penetration of rain water, the suction force due to wind, and barometric pressure. Above all, vapor loss by evaporation from the topsoil will be the major mechanism for the upward movement of water vapor. Also, since plant roots can absorb water in liquid and vapor form, transpiration by plants will cause water vapor to be pumped out from the soil to the air.

Studies conducted on how plants respond to the movements of soil water are illustrated below:

(1) The daily and seasonal fluctuation of the water table by wind drag, precipitation, evaporation, and even transpiration of plants have been studied by many investigators. Through capillary action, water reaches the capillary fringe and supplies enough moisture for plants to grow. In semiarid areas where rainfall is inadequate, a supply of water from the water table is necessary. Fox & Lipps (1955) studied alfalfa root distribution in the Platte River Valley, Nebraska. They found that a large acreage of relatively high yielding alfalfa is produced in a region where the alfalfa roots reach the moist soil, which is about five or six feet above the free water surface. Fletcher & Elemendorf (1955) reviewed the problems of phreatophyte growth in the semidesert area of the western U. S. They indicated that these water-loving plants can survive well by sending their roots down to the water table or the capillary fringe just above the water table. Many investigators believe that a high consumption of limited water supplies by phreatophytes is one of the most serious problems facing the irrigated West. White (1932) measured wells in the Escalante Desert in Utah and found a number of evidences that the daily water table fluctuation was caused by the evapotranspiration of phreatophytes. In areas where the total evapotranspiration overcomes precipitation during the growing season, the daily and seasonal movement of the water table determines the survival and growth of plants. However, in humid or semihumid areas where precipitation overcomes transpiration, the rise of water table would be harmful to plant growth. Poor aeration will cause the death of roots under free water surface and eventually new shallow

roots are developed. During a dry spell, the water table recedes and the available moisture in the shallow soil zone can be depleted quickly. These shallow-rooted crops fail to obtain available water for survival. Thus, the seasonal fluctuation of a shallow water table in humid and sub-humid regions may produce a drought effect and sometimes is detrimental.

For optimal yield of grass, Frankena & Goedewaagen (1942) found that the highest yield was associated with a table of about $7\frac{1}{2}$", but the degree to which the yield was decreased with 20" and 30" depths varied with the season. In other words, the depths of the water table for an optimal yield depend upon the degree of evapotranspiration. Therefore, the upward and downward movement of liquid water by capillary action as related to plant response should be studied in association with species and varieties of crops, types of climates, kind and structure of soils, and other environmental factors.

In the Netherlands ground water is an important source of moisture. Studies on the water table, water tension, water balance, evaporation, availability of soil moisture, and the like are numerous. Visser (1958) calculated the water requirements of crops; in 1959 he studied the crop growth and availability of moisture. He found that the percentage of estimated maximum yield of oats is increased with the depth of groundwater until the optimal depth is reached. With a further increase in depth, a low yield resulted. Hoorn (1958) reported the results of a groundwater level experimental field with arable crops on clay soil. Wesseling (1958) studied the relation between rainfall, drain discharge, and depth of the water table in tile-drained land. Butijn & Wesseling (1959) determined the capillary conductivity of soil at low moisture tension. Rijtema (1959) calculated capillary conductivity from pressure plate outflow data with non-negligible membrane impedance. Bierhuizen & De Vos (1959) studied the effect of soil moisture on the growth and yield of vegetable crops.

(2) A rapid horizontal or vertical flow of water in the soil, or over the soil surface, always creates a serious disaster to agricultural crops. Prior to planting, when the soil is bare, a heavy rainfall over a sloping crop field will cause surface and subsurface runoff. This results in depletion of soil fertility, and at times, erosion. Intense percolation over poorly-drained soil produces a waterlogged field, and in well-drained soil gives a rising water table. Becker (1937) studied the correlation between percolation and soil temperature. He found that soil temperature is a good indicator of percolation. Since percolation is more difficult to measure than soil temperature, the latter can be employed as at least a first approximation of percolation. The study of crop response and percolation is rare, if any, and should be encouraged. However, there is growing interest in recent years in study of soil compaction in relation to crop growth. Compaction is

inversely related to percolation. In the United States a joint ASAE-SSSA Soil Compaction Committee has been founded and in 1958 the concepts, terms, definitions, and methods of measuring soil compaction were officially designated. Slater & Ruxton (1955) studied the effect of soil compaction on incidence of frost damage and found that the danger of frost to young seedlings is increased with compaction. Furthermore, the impact of raindrops on bare soil tends to destroy soil granulation and encourage sheet and rill erosion. Woodburn (1948) indicated the effect of structural condition on soil detachment by raindrop action. Forests and grasses are the best natural soil-protective agencies known and are about equal in their effectiveness. Lowdermilk (1930) studied the influence of forest litter on runoff, percolation, and erosion. He found that low infiltration is associated with the presence of forest litter. Bluegrass and alfalfa are much more effective in soil erosion control than is clover. Wheat and oats are better than corn.

4.5.3 *The movement of soil ingredients*

Movement of soil particles is caused by gravitational, frictional, hydraulic, wind, molecular, and thermodynamic forces, and by mechanical forces exerted by man, animals, and plants. The natural soil profile is greatly disturbed by tillage, for good and for bad. A good tilth improves the structure and physical properties of soil so that plants will enjoy adequate aeration, sufficient moisture, and ready infiltration of rainfall. A poor tilth tends to break down granulation and increase soil compaction. The moisture content of soil, the types of soil, and the machinery used are three major considerations of tillage. Soil manipulation by man is generally effective and noticeable, whereas that by the physical forces of nature — the concern of soil geneticists and morphologists — is generally a slow process and unnoticeable. In the long run, however, this accomplishment is far greater than that of human beings. The removal of volumes of soil by macro- and micro-animals such as ants, earthworms, and microbes is also an important consideration. Thus, soils are often considered as biologic and dynamic in nature. The chemical and physical weathering of soil, as treated in soil genesis, are the major processes of soil formation. They add up to an enormous amount of mass exchange, but the completion of the process takes hundreds of years. The short-term physical processes which cause movement of soil particles are illustrated below:

(1) Alternation of freezing and thawing gives rise to soil particle transfer which comes first from the thermodynamic forces of expansion and contraction and then is followed by hydraulic forces of infiltration and runoff. During the winter, frost heaving[30] originates from

[30]In geology, the churning, heaving, and thrusting of soil material is termed "congeliturbation," and the shattering or splitting of rock materials, "congelifraction."

the growth of the lenticular mass of ice within the soil. This lenticular ice, which grows by sublimation processes as well as by thawing and refreezing, can exert strong forces such as uplifting the overlying soil. The extreme result of frost heaving is known as "frost mound," which is usually caused by a great concentration of water in a relatively limited subsurface space. In the extreme case, excessive spring rainfall accompanied by thawing ground will cause a considerable amount of soil to be carried downward by infiltration and sideways by runoff. This may disturb the root system of perennials, depending upon the depth of frost heaving. It may even cause erosion if the heavy rainfall is accompanied by high winds.

However, the alternate freezing and thawing is generally thought to have a beneficial effect upon soil tilth, and to be more effective than drying and wetting. Jung (1931) believed that aggregation of soil is a result of slow freezing, and dispersion of soil a result of quick freezing. If cooling is slow, the pores are enlarged by the combined effects of crystal pressure and dehydration. When cooling is rapid, large numbers of minute crystals are formed and aggregations are broken down. Even the wilting of plants is less serious in the slow cooling process than in the rapid cooling process (Kramer, 1949).

(2) Loss of soil by runoff is usually referred to as soil erosion. The dispersive action and transporting power of water determine the degree of soil erosion. The direct influences are the dispersive effect of raindrops and the amount and velocity of runoff, while the indirect influence is the resistance of soil to dispersion and movement. The direct effects are determined by rainfall characteristics (intensity and duration), slope and area of the land (steepness, size, and length), and the ability of soil to absorb and transmit water. The indirect effects are determined by soil characteristics (structure, type, composition, etc.) and vegetative cover. Of course, soil characteristics and vegetative cover are also determined by the ability of the soil to absorb and transmit water. The important meteorological factors are rainfall and wind velocity.

The subject of soil erosion has been studied intensively by soil scientists and hydrologists. The importance of soil erosion to the national economy has been assessed. For example, Bennett (1939) estimated that 63 million tons of plant nutrients are annually swept from cultivated fields and pastures in the farming areas of the United States. Crops are affected by runoff in various degrees ranging from nutrient deficiency to the complete destruction of the crop itself.

There are other important physical and chemical processes which move huge amounts of soil over great distances. Examples are the glacial and loess deposits. The former is the subject of geological study of the parent materials of soil; the latter, of soil genetic study of one kind of wind-blown dust from the western region to the north-central region of the United States.

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PART II

METHODOLOGY AND APPLICATIONS

CHAPTER 6

Phenology and Seasonal Changes

5.1 NATURE OF AGROMETEOROLOGICAL INSTRUMENTATION

The purpose of this chapter is to introduce some useful instruments and their measurements, both physical and biological, as illustrations. It is beyond the scope of the present text to describe the theories, principles, mechanisms, and structures of instruments. The necessary information on these can be obtained from books and journals pertaining to a specific instrumentation, as listed in the bibliography at the end of this chapter.

The basic distinction between instrumentation for agrometeorology and that for pure meteorology is that the former is concerned with measurement of both living organisms and physical environment, whereas the latter's concern is only with physical environment. A coprometer for frass-drop measurements of insects, and a tenderometer for measuring hardness of peas at the time of harvesting, are obviously for the purpose of biological measurements. An Eppley pyrheliometer for direct and indirect radiation, a cup anemometer for wind speed, and an infrared absorption hygrometer for air humidity are for physical measurements. For some sensors, the distinction depends more upon the use, not upon the type of instrument itself. For example, thermistors and thermocouples can be used for both biological and physical measurements (i.e., measurements of animal skin-temperature and of leaf-temperature, or of air and soil temperature). There are many instruments of this kind. Basically, the fundamental principles and mechanisms are the same for both biological and physical instruments.

Some instruments of importance to synoptic meteorology, such as the barometer, the ceilometer, and those for measuring the upper atmosphere, are only indirectly significant to agrometeorology. Conversely, those which are valuable in agrometeorology may not even be listed as meteorological instruments. In view of the large area of coverage and the ever increasing number of new designs in agrometeorological instruments, it is impractical and not worthwhile to list and differentiate all of them. There are just too many and some of them are very similar to one another in mechanism, particularly the sensing element. Also, some important instruments have no specific names, are loosely described as an apparatus, a device, a meter, or an instrument, and are not widely known. For general acquaintance and for the selection of various instruments, the following bibliographical collections are recommended: Suomi (1962) has made a collection of over 1000 references on agrometeorological instrumentation under the classification of precipitation, heat and temperature, evaporation and moisture, light and radiation, wind and pressure, and plant and animal instruments. Baum (1948) compiled an annotated bibliography on microclimatic instruments and methods. Shaw & Arble (1959) have prepared a bibliography on methods for determining soil moisture in which they have classified instruments according to chemical, electrical, gravimetric, lysimeter, nuclear, penetrometer, tension, thermal, and other miscellaneous approaches. Other bibliographical collections of more specific type include: evaporation and evapotranspiration (Livingston, 1908 - 1909; Lull, 1953); frost and frost forecasting (Reed & Feldkamp, 1915; Zikeev, 1953); soil temperature (Zikeev, 1951); dew (Zikeev, 1952); and carbon dioxide (Stepanova, 1952). Most of the instruments cited in the above collections are for the measurement of the physical environment, and only a few for biological organisms in the natural field. Slatyer & McIlroy, in their text on practical microclimatology (1961), emphasize the aspect of measurement, particularly on plant responses within the microenvironment. Measuring techniques in both plant physiology and plant ecology are discussed in the text. It is recommended as a beginner's guide to agrometeorological instrumentation. A majority of biological instruments can be found under the headings plant and animal physiology, ecology, phenology, and food industry. The phenometer is a good example of this. In the selection of instruments, a mere recognition of various names and uses would not be sufficient. A more important factor is the judgment of their usefulness, capacity, validity, and limitations.

5.1.1 *Essentials in instrumentation*

It is necessary to know the essentials of an ideal instrument so that one may be able to (a) choose the right kind of instrument, (b) use it properly, and (c) know its accuracy, sensitivity, capacity, and other properties.

Accuracy is generally recognized as the basic requirement for all instruments. It should be stressed that evaluation of accuracy should be made in relation to the degree of area- or space-representation, type of material, and approach to a particular problem. In the measurement of soil temperature, for example, a soil temperature integrator (Suomi, 1957a) and a flat-plate heat flux meter (Deacon, 1950) would be able to sample heat flow by conduction into or out of a given soil profile rather than for a point source. The maximum-minimum soil thermometer, manufactured by the Palmer Thermometer Company, with a 13-inch sensing element, would be able to measure soil temperature both vertically and horizontally. These instruments are important to agrometeorological research because they overcome variations in soil temperature over a large area. Some laboratory temperature sensing devices with a very high degree of accuracy may be very important in detecting body temperature change of an animal, but may not be useful for determining air and soil temperature over a field. In short, sampling technique is the first thing to be taken into consideration; therefore, the average observation in space and in time is far better than high accuracy in point observations. In fact, agrometeorologists are not particularly interested in high accuracy.

The word "sensitivity" is differentiated from the word "accuracy" and may be interpreted in three ways: (i) time requirements for picking up a given signal, i.e., the time lag coefficient; (ii) the detectable amount and size of a given signal, i.e., the range and scale of an instrument, and (iii) the capability of differentiating a noise from a signal, i.e., the sharpness of a signal. In other words, a sensitive instrument may not necessarily be accurate, and vice versa. With all three qualifications, instruments should have and maintain a calibration under given environmental conditions within a desirable precision. The capability, limitation, and application should be known by the user. Moreover, the sensing device of an instrument should be so designed as to prove the significant biological environmental factors, such as a lysimeter for the measurement of evapotranspiration over a natural field, and Jennings & Monteith's sensitive recording dew-balance to determine dew deposition on foliage surface.

Instruments should be as simple, robust, and durable as possible, so as to assure low cost of installation and maintenance and an adequate length of service with reliable results.

The complete system of instrumentation — sensing, transmission, recording, and computing — should be automatically controlled. This will increase efficiency and eliminate human errors. Moreover, it will provide remote control and the possibility of observing a large network.

5.1.2 *Measurement of physical environment*

Instrumentation designs for measuring the physical properties of air and soil are numerous. Conventionally, they may be grouped according to the area of presentation: photofield, thermofield, hydrofield, and wind field, besides the physical and chemical composition of air, water, and soil. Photofield measurements involve various aspects of intensity, duration, and quality of both long and short waves from direct sunlight, diffuse sky radiation, and ground reradiation. They are also concerned with albedo and net radiation. Instruments for measuring radiation are the radiometer, pyrheliometer, net radiometer, sunshine recorder, photometer, photoelectric cell, spectrobolometer, dosimeter, and so on. Essentials in radiation measurement are the accurate determination of different components of radiation, net radiation, and radiation of various spectra. In order to minimize instrumental errors, reflections at various solar angles, differential heating at various parts of the sensor surface, and optical aberrations (in association with the use of lenses or mirrors) should be considered. Although the thermofield involves heat, not temperature, in practice only the temperature of air, soil, and water are commonly observed. Nevertheless, various aspects of heat have been studied in terms of temperature changes. They are heat exchange, heat flux, heat balance, heat control, etc. Since heat and light cannot be separated, temperature and radiation measurements are interchangeable and sometimes interfere with each other, causing some errors, e.g., radiation error of a thermometer. Instruments for measuring temperature are: thermometers, thermistor, thermocouple, thermal transducer, heat integrators, etc. The hydrofield, which involves measurement of three states of water in air and soil, is the most difficult to measure adequately. In precipitation and condensation, various devices have been made for recording the rate, intensity, and duration of rain, snow, dew, hail, and the like. For instruments to measure evaporation we have the transpirometer, evapotranspirometer, and various types of evaporimeters, such as evaporating pans, Piché evaporimeter, Bellani atmometer, Davos frigorimeter, etc. Instruments for measuring air humidity are the psychrometer, hair hygrometer, infrared absorption hygrometer, and lithium chloride dewcel. Soil moisture measurements are made with neutron and gamma-ray scattering devices, plaster of Paris (or gypsum blocks), lysimeters, moisture tensiometers, etc. In the measurement of wind field, the classical wind instruments record only the speed and direction of the horizontal wind. Since the importance of vertical wind as well as turbulences has been recognized, emphasis has been placed in this direction. Wind measurement problems are: the horizontal wind direction can be measured more accurately than speed, particularly at low wind speeds; the vertical wind can be measured, but only at considerable cost and maintenance difficulty, which is also true for the measurement of turbulence. Air and soil composition are the subjects of air chemistry and soil physics, respectively, and are highly significant to agrometeorology. Some gases, such as CO_2, O_3, and SO_2, have effects on photosynthesis and respiration, as well as on chemical injury to plants. The chemical and physical properties of soil and water are important as well.

The fundamental problem in environmental measurement is the degree of representativeness of the measurement. Ideally, a sensing device should possess the identical physical property of the medium it measures. In the case of air temperature measurement, for example, the sensing device should be made so that it does not absorb solar radiation and so that it is sensitive enough for conduction and convection heat transfer from the air. Accordingly, it is desirable to have a soil temperature sensor which possesses the physical properties of soil — heat conductivity and moisture absorption — so as to be satisfactory. The same argument holds for water temperature measurement. There have been some steps made toward the realization of this ideal goal.

There is no end to the discussion of physical environmental measurements. This chapter will emphasize the discussion of sensing devices and methods of exposure.

5.1.3 *Measurement of biotic material*

Instrumentation for biological measurements differs very much from that for physical measurements. Two aspects are noted in biological measurements: (a) physical properties of plant parts and animal bodies, and (b) growth and development of biological organs or bodies.

In view of the first aspect, a plant (or an animal) is treated as a physical material; thus, light, temperature, moisture, etc., of that material should be measured. The light reflection on leaves (or albedo of leaves) can be measured by a beam reflector (Kuhn & Suomi, 1958). The measurement of skin temperature of an animal or the leaf temperature of a tree can be made by a thermistor or a thermocouple. The recording of the amount of moisture transpired from a plant may be made by a floating balance (Pfeifer, 1956). Instruments for the measurement of temperature and humidity of plant surfaces were designed by Berger-Landefeldt in 1950.

In view of the second aspect, a plant (or an animal) is treated as a physiological body; thus, the measurement of chemical properties as well as physical properties should be considered. In other words, the growth and development of biological organs or bodies should be measured. Growth is here referred to as the increase in size and weight of a body. In plants, the elongation of leaves, shoots, and roots, as well as increments in their area, volume, and weight, are concerned. More specifically, the plant growth pattern, or even its appearance, is detected or observed by means of the phenometer, dendrometer, dendrograph, etc.

In considering the development of a plant, the appearance of developmental phases (such as germination, budding, leafing, flowering, fruit-setting, fruit-coloring, and maturity) needs to be observed for the time and form of occurrence. The former relates to plant phenology, and the latter, to plant quality. Phenology of plants is usually observed visually, and therefore the development of more objective measurements is greatly needed. Measuring the quality of plants, which is usually the concern of agriculturists, is mainly done in laboratories with the aid of instruments. Various devices have been designed by food technologists since 1937. Although these devices are restricted to laboratory usage, they can be highly valuable in agrometeorological research. In summary, instrumentation for growth and development of plant parts includes devices for measuring water consumption and water content, gas exchange, photosynthesis, respiration, maturity, and many other features.

Methods of measuring animal growth and development are numerous. In entomology, the black-light fluorescent trap is used to catch insects. The coprometer reveals frass-drop measurement of insects for laboratory and field uses. For poultry, a calorimeter can be used for direct determination of metabolism. Photoelectric measurements of transorbital penetration of visible radiation into the brain of domestic ducks can also be made. With farm animals, the beta-gauge has been used in measuring the hair of beef and dairy cattle. Frigorimetric and catathermometric research has been conducted in stables. In general, instrumentation for growth and development of animal bodies includes devices for measuring blood-flow, skin temperature, respiration, body weight, water vapor permeability, and many other aspects.

Some considerations on instrumentation for biological measurements are:

(a) For most purposes, sensing elements should be as small as possible; e.g., the use of thermistors for measuring leaf-temperature is superior to using the mercury thermometer.

(b) Continuous recording devices for a complete life-cycle measurement are necessary.

(c) If possible, measuring live biological organisms is desirable. (Note that botanists and zoologists often measure dissected parts of plants and animals.)

(d) Disturbance or injury to plants should be avoided as much as possible during observation.

(e) Sampling techniques in biological measurements are also important, even if they are more complicated and difficult.

5.2 PHOTOFIELD

Direct sunshine, sky radiation, and back radiation from the earth are three major types of measurable radiation. Their duration, intensity, and quality are characteristics important to plant response and

Fig. 5-1. Eppley normal incidence pyrheliometer.
(Courtesy of The Eppley Laboratory, Inc., Newport, R. I.)

animal behavior. When these characteristics of a locality are specified by major type of radiation or radiation as a whole, it is the photofield of that locality.

5.2.1 *Intensity*

The classical instruments for the measurement of solar intensity may be classified according to the components of total radiation. Those measuring direct sunshine are, for example, the Eppley Normal Incidence Pyrheliometer (Fig. 5-1) and the Abbot Silver Disk Pyrheliometer (Hand, 1946; MacDonald & Foster, 1954). Those which measure total radiation from the sun and the sky falling upon a horizontal plane include the Eppley pyrheliometer (Fig. 5-2), the Beckman & Whitley total hemispherical thermal radiometer (Fig. 5-3), the Kipp & Zonen solarimeter (Fig. 5-4), and so forth (Monteith, 1959; Dunkle & Gier, 1954; Houghton & Brewer, 1954). The instrument which measures reflection (or albedo) from the earth's surface is the beam reflector, used by Kuhn & Suomi in 1958, to be discussed shortly in Section 5.2.4

The Eppley Normal Incidence Pyrheliometer is similar in design to the Abbot Silver Disk Pyrheliometer, and incorporates the basic features of the latter. The Gunn-Bellani radiation integrator, a liquid distillation instrument, serves the same purpose. The Eppley normal incidence pyrheliometer measures either the total or spectral direct solar intensity. The sensitive element of the Eppley is a circular 15-junction bismuth silver thermopile with a thermistor temperature compensating circuit, the receiver being coated with Parsons' black lacquer. The temperature compensation is such that it can afford the

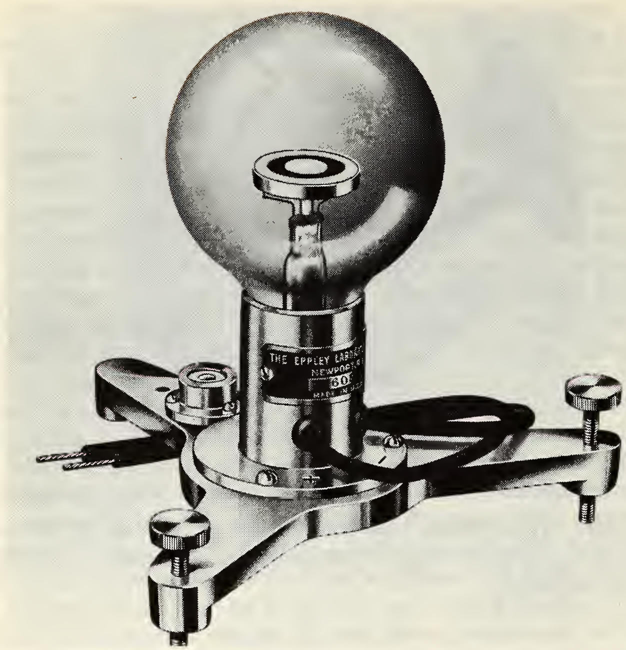


Fig. 5-2. Eppley pyrheliometer.
(Courtesy of The Eppley Laboratory, Inc., Newport, R.I.)

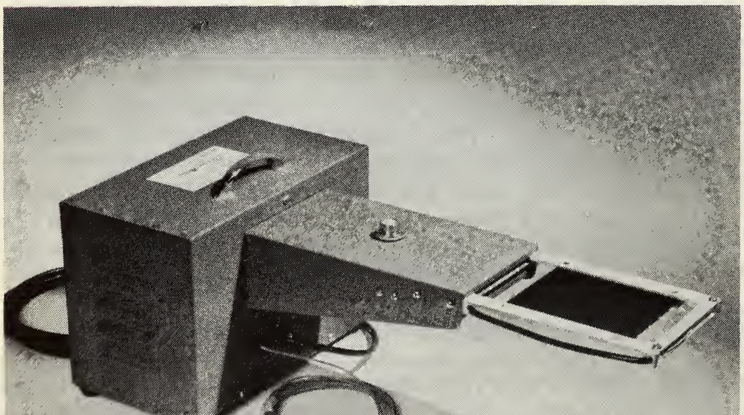


Fig. 5-3. Beckman & Whitley total hemispherical thermal radiometer.
(Courtesy of Beckman & Whitley, Inc., San Carlos, California)

Fig. 5-4. Kipp & Zonen solarimeter.
(Courtesy of P. J. Kipp & Zonen, Delft, Holland)

constancy of radiometer sensitivity over an ambient temperature range of -30°C to +50° C within one percent. The sensitivity is approximately 3 to 3.5 millivolts per langley per minute, the resistance about 450 ohms at 25° C, and the response time is in the order of 20 seconds. The thermopile is mounted at the base of a brass tube, the inside of which is blackened and suitably diaphragmed, and the outside is chromium plated. The tube is filled with dry air at an atmospheric pressure and sealed at the viewing end by a removable insert carrying a crystal quartz window that is 1 mm thick. Two flanges, one at each end of the tube, are provided with a sighting arrangement for aiming the instrument directly at the sun. A manually rotated disk which can accommodate three filters, with one aperture free for total spectrum measurements, is provided.

Requirements for the exposure of pyrheliometers and sunshine recorders are: (a) freedom from obstruction on the solar beam by natural and artificial objects at all times of the day during all seasons of the year (for example, a roof exposure on a rigid platform is preferred to a ground-level exposure, when the lower solar elevation values are considered important); (b) determination of the latitude of the site to an accuracy of at least ± 0.25 degree; and (c) accurate determination of the N-S geographical meridian. Fig. 5-5 shows the exposure of the Eppley normal incidence pyrheliometer on the Eppley equatorial mount. The mount, designed to accommodate from one to four natural incidence pyrheliometers, is electrically driven and geared to solar time for continuous measurements.

Fig. 5-5. Eppley equatorial mount.
(Courtesy of The Eppley Laboratory, Inc. Newport, R.I.)

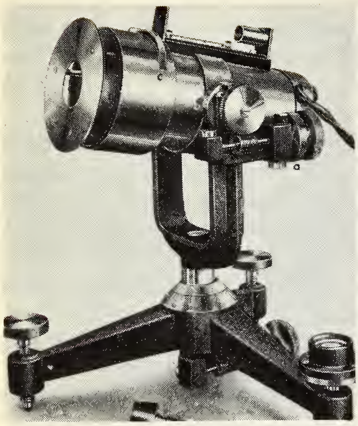
The Eppley pyrheliometer (Fig. 5-2) is designed primarily for measuring intensity of solar radiation falling upon a horizontal plane. It is a specialized thermopile made with an alloy wire of 60% gold and 40% palladium, against another alloy wire of 90% platinum and 10% rhodium. The receiving surface of the inner ring is black, and that of the outer ring is white. The receiving element is hermetically sealed in a lamp bulb of soda lime glass which transmits about 10% of incident radiation at 2900Å. The bulb, 3" in diameter, is mounted on a metal base with leveling screws. Heavy copper leads are provided for connection to the recording apparatus. The inner or hot ring is painted with lamp-black, and the outer or cold ring is smoked with magnesium oxide. Both blackened and whitened surfaces absorb long wave radiation equally well, but the magnesium oxide has a high coefficient of reflection for radiation of solar wavelength. Therefore, when exposed to solar radiation, the two rings of this pyrheliometer develop a marked temperature difference, and the resulting electric current shows an electromotive force which is not strictly proportional to the difference between the temperatures of junctions attached to the black and white rings, respectively. However, the voltage is very nearly proportional to the intensity of solar radiation. The efficiency of the thermopile appears to increase with temperature difference, and presumably with the temperature of the pile. The Eppley pyrheliometer is most sensitive to the wavelength of 0.34 to 2.6 microns, so that it can be used to measure both short- and long-wave radiation.

Although the Eppley pyrheliometer has often been used as a standard instrument for light intensity measurement, inconsistent behavior of this instrument has been confirmed (Fuquay & Buettner, 1957). According to Fuquay & Buettner, the following instrumentational errors should be avoided: (1) variable temperature coefficient, (2) variation of thermopile output with direction of gravity and effect caused by internal air convection, (3) errors caused by radiation coming from the back side and reflected by the glass cover, and (4) errors from specular reflectivity of the black receiver ring and resulting deviation of response from the cosine law. All of these deviations of this instrument can be brought under control by suitable modification or calibration (Middleton & Spilhaus, 1953).

The term "actinometer" may apply to the pyrheliometer, pyranometer, and pyrgeometer. In fact, the word "actinometer" refers to the science of radiant energy measurement, particularly that of the sun with respect to its thermal, chemical, and luminous aspects. The pyranometer measures global radiation of both diffuse sky radiation and direct solar radiation; the pyrgeometer, such as the Ångström compensation pyrheliometer, measures the effective terrestrial radiation. The Canadian bimetallic actinograph (a pyranometer) is the improved Robitzsch actinograph. Three bimetal strips, two white oxide-painted and one coated with lamp-black, are horizontally exposed to the sun's rays. When the instrument is calibrated at a uniform temperature, the recording pen remains at the zero line. Under the sun, the pen moves according to the differentiation in temperature between the black strip and the white ones. The disadvantages of the actinograph are the mechanical friction of the bimetal assembly and the recording pen, the condensation of moisture in the glass bowl, and the variability among different instruments. The only advantage is its simplicity and low cost.

The Beckman & Whitley total-hemispherical thermal radiometer (Fig. 5-3) is constructed similar in design to the Gier & Dunkle black-plate radiometer (Gier & Dunkle, 1951). It measures total hemispheric radiation, both direct and sky radiation. Its construction is the same as the Beckman & Whitley net-exchange radiometer, except that it provides a thermal radiation shielding on the lower hemispheric exposure (see Section 5.2.5).

The Linke & Feussner actinometer, manufactured by Kipp & Zonen of Delft, Holland, as shown in Fig. 5-6, is the actinometer at its best. It measures radiation from the sun and sky and also effective thermal



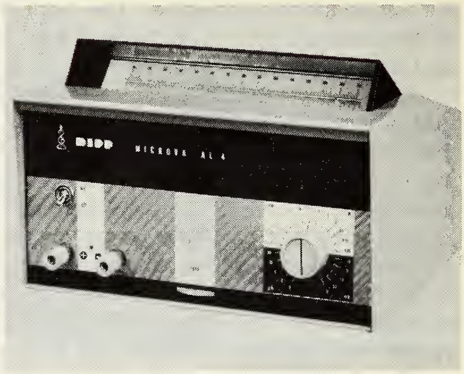


Fig. 5-6. Linke & Feussner actinometer.

Fig. 5-7. "Microva" multi-range galvanometer.

(Courtesy of P. J. Kipp & Zonen, Delft, Holland)

radiation under all weather conditions. Color filters (red and yellow) are provided for use in examining sun and sky radiation in certain wavelength regions. For investigation of thermal radiation, the long- and short-wave parts ($\lambda < 4\,\mu$) may be separated by means of a quartz window. Twenty constantan-manganin couples of each of the two Moll thermopile sections are connected in opposition. Both are exposed to temperature and pressure effects, but one of the sections is screened from radiation and thus acts as a compensating device for elimination of errors due to severe weather changes. For measuring radiation from the sun, the E.M.F. generated in the thermopile may be determined by means of a potentiometer or other suitable millivoltmeter. For measuring very weak radiation, such as sky and nocturnal radiation, the thermopile may best be connected to a mirror galvanometer, such as the multi-range galvanometer "Microva" of Kipp & Zonen (Fig. 5-7). The sensitivity of this galvanometer is sufficient to allow the measurement of highly variable red and yellow parts of the "blue" sky light, with the aid of filters. Owing to the small angle of the aperture, no disturbing dew will form on the thermopile, even with strong nocturnal radiation and a high relative humidity.

The Kipp & Zonen solarimeter, as shown in Fig. 5-4, measures total radiation of the sun and sky. The 14-element constantan-manganin Moll thermopile, mounted under two concentric hemispheric glass domes, is built in a holder on a metal base provided with leveling screws. The sensitive surface (12 × 11 mm) of the pile is placed exactly in the center of the domes. A white lacquered screen prevents the base from being heated by radiation. A small tube, connected to a drying bottle from the bottom, is used to prevent condensation within the solarimeter. The sensitivity is about 7.9 millivolts per ly per minute.

Ångström's statements on radiation measurements with regard to biological problems have been quoted in Section 4.1.1. Such problems may be minimized by introducing new instruments with proper calibration as well as by maintaining good exposure. It is obvious that different radiation instruments should be used for different agrometeorological projects. Determination of the effect of solar heating on a reservoir involves the measurement of direct solar beams on a horizontal surface. The Eppley normal incidence pyrheliometer or the Abbot silverdisk pyrheliometer will satisfy this purpose. In designing animal houses, total hemispheric radiation should be considered. An instrument such as the Beckman & Whitley total hemispheric thermal radiometer would be useful. For crop response studies, the direct sun beam, the sky diffuse radiation, and the ground back radiation, as well as net radiation, should be observed. In this case, several radiation instruments associated with various methods of exposure may be used. It is essential in plant response studies to have an instrument which would measure the absorption light alone, without being affected by the scattering light. Some instruments measure radiative energy components in all directions instead of on the horizontal surface alone. Such a measurement would be useful for describing light environments of plants more adequately.

In using radiation instruments, sites should have an unobstructed view of the full hemispheric sky, and the surface of the ground should have uniform thermal characteristics. For some instruments, both temperature and wind corrections should be known, particularly when the sensing element is wet, for evaporation cooling will give a considerable error in the recording. The instrument should be located at least five feet above the ground, depending upon its size, so that the effect of its shadow will be negligible. The direction of exposure (upward or downward, shaded or unshaded from direct sunshine), and a proper mounting adjustment which keeps the sensor horizontal and swinging into the direction of the wind, are necessary considerations for best exposure. This refers particularly to instruments with ventilated units. The instrument should be operated in the same direction of wind, although a compromise becomes necessary when such a setup brings the shadow of the blower and motor, etc., into the center of the sampling zone.

Slatyer & McIlroy (1961) summarized the operational requirements of radiation instruments and measurements as cleanliness, symmetry, freedom from internal convection, and proper exposure. A careful inspection of the exposed surface after every few weeks of operation is suggested for maintaining cleanliness, and the importance of calibration check before and after any alteration of the surface characteristics, such as coating, degreasing, brushing, and spraying, is emphasized. It is pointed out that the calibration for symmetry is necessary for any instrument, since sensing surfaces may not lie entirely in one plane and the "plane of best fit" may not parallel with any convenient reference surface. Furthermore, checking or elimination of the internal convection should be made, because a considerable error may be caused by a variation in the efficiency of internal convectional transfer between element and shield, altering the sensitivity of the instrument.

5.2.2 *Duration*

Duration of sunlight refers to the number of hours per day with sunshine. Similarly, duration of daylight is the number of hours per day with daylight. Recorders for the duration of sunlight are made under two physical principles: (a) those which operate through the heating effect of solar radiation, and (b) those based on the photographic effect of short solar wavelengths. The Campbell-Stokes (Fig. 5-8) and the Marvin (Fig. 5-9) sunshine recorders belong to the first category. The former consists of an approximately three-inch glass ball mounted with a heavy paper chart underneath. When the sunbeam strikes the ball, the rays focus on the paper chart and burn a trace on it as the sun moves across the sky. It is a type of sundial, but gives some qualitative measure of intensity by the width and depth of burning. It is not sensitive to diffuse radiation; also, the position of the paper chart must be changed to suit the season of the year. With good exposure and adjustment, a fairly accurate result can be obtained (Middleton & Spilhaus, 1953). However, because of uneven diurnal distribution of cloud coverage, a good representation of sunshine hours may not be possible. Therefore, the desirable density of the recorder placement is suggested as one every five square miles. For tropical regions, a special form of recorder should be used to measure sunshine hours for all altitudes less than 45°.

The Marvin sunshine recorder (Fig. 5-9) is a type of differential thermometer. As the black bulb is heated by the sun and the surrounding air expands, driving the mercury up past the contact points, a circuit to the recorder is closed. When the sun is obscured by clouds, the temperatures of the clear and black bulbs tend to equalize and the mercury falls below the contacts, breaking the circuit. The advantage of the Marvin recorder for agrometeorological use is that it gives both remote recording and diffuse radiation readings from all angles. The

Fig. 5-8. Campbell-Stokes sunshine recorder
(Courtesy of Negretti & Zambra, Ltd., London)

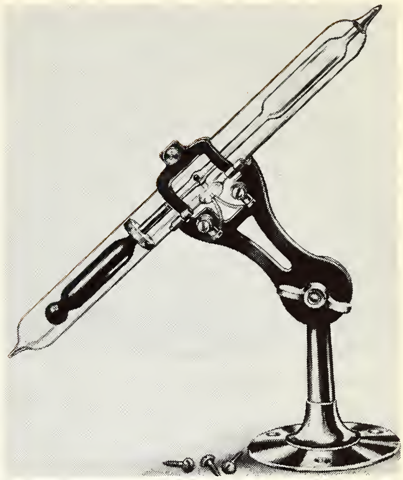


Fig. 5-9. Marvin sunshine recorder.
(Courtesy of U.S. Dept. of Commerce Weather Bureau)

Jordan and the Pers sunshine recorders are constructed on the principle of the photographic effect of short solar wavelengths. They are less reliable than the Campbell-Stokes and Marvin recorders, because the sensitivity of the photographic paper does not remain the same from year to year. One advantage of the Pers sunshine recorder is that it is usable at all latitudes. The differentials between two photo cells have been used to record sunshine, and may replace the Marvin recorder.

In order to avoid hoar frost formation on sunshine recorders, Rossi (1954) in Finland has installed a 10 watt electric lamp at the base of the instrument. This lamp maintains the temperature of the glass ball (Campbell-Stokes type) or metal cylinder (Jordan type) above the freezing point.

At best, the above instruments give the number of sunshine hours per day, but not the daylight hours of a specific level of light intensity. This is extremely important to the study of photoperiodism and photoperiodicity. Continuous recording instruments for radiation intensity can be used as a substitute (Friend, 1959; Rodionov, et al., 1949). With the aid of an electronic computer the total number of hours per day at various light intensities and at complete darkness can be summarized. Perhaps this is the best available method. The Canada Department of Agriculture at Ottawa has made measurements of the natural daylength with a Leeds & Northrup recording illuminometer on a fully exposed, flat, horizontal surface since 1953. The illuminometer, which utilizes a photocell sensing element and a recording potentiometer, gives only the range of visible wavelength.

Considerable errors are introduced at various cloudiness levels and zenithal angles of the sun. The U. S. Naval Observatory, Nautical Almanac Office, furnishes data on daylength with respect to astronomical, naval, and civil twilight times for various latitudes. These twilight times are defined as the position of the sun at 18°, 12°, and 6° below the horizon, respectively. For a detailed discussion of the subject, see Section 4.1.2. The problem in using the almanac is that no intensity level can be specified.

5.2.3 *Quality*

The Eppley normal incidence pyrheliometer (Fig. 5-1) and the Linke & Feussner actinometer (Fig. 5-6) provide measurement of radiation of various wavelengths by means of color filters. The spectrobolometer, which is essentially a spectrograph combined with a coelostat (a mirror that follows the moving sun), measures some 40 standard wavelengths, between 0.34 and 2.50 microns, by means of the bolometer without using filters. The schematic drawing illustrating the principle of the spectrobolometer is given in Fig. 5-10. A prism (or a diffraction grating) disperses the sun's ray and permits the measurement of various wavelengths of solar radiation. In practice, lenses are used to collect a large amount of energy and to focus this on slits of the bolometer (Coblentz & Stair, 1936).

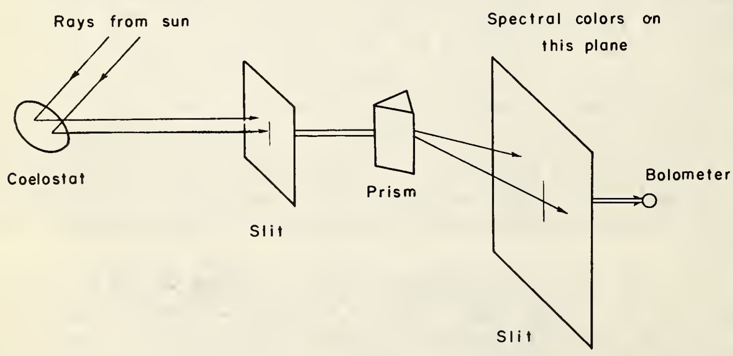


Fig. 5-10. A schematic diagram of spectrobolometer.

Many devices have been made available for measuring ultraviolet and infrared radiation. The Dosimeter is an instrument for measuring the ultraviolet in solar and sky radiation and the infrared spectrometer, for measuring infrared radiation.

Many studies have been made on the instrumentation of infrared and ultraviolet. To mention a few, on ultraviolet: Kachan (1957) found that methyl blue is very sensitive to ultraviolet radiation and it could be used to detect a wavelength range of physiological significance

Fig. 5-11a. Beam reflector. Fig. 5-11b. Exposure site of beam reflector. After Kuhn & Suomi

(0.25 to 0.40 μ) from solar radiation; Stern & Hill (1955) designed a simple radiometer for recording ultraviolet radiation from the sun and sky; and Eschke (1956) made an inexpensive portable ultraviolet dosimeter suitable for Röntgen and gamma ray measurement. On infrared: Aagard (1958) made a convection-free instrument for measuring atmospheric infrared radiation at night; Kaplan et al. (1951) designed a spectrographic camera for fluorite and near-infrared regions, which could be used to measure both ultraviolet and infrared; White et al. (1957) constructed an infrared spectrophotometer with which a wide range of wavelengths can be measured by simply changing the detectors, gratings, prisms, and windows.

5.2.4 *Albedo*

The measurement of albedo, which is usually accomplished by the inverted Eppley pyrheliometer, has been improved by a beam reflector. As shown in Fig. 5-11a, the Eppley pyrheliometer is mounted upright in the prime focus of a parabolic mirror. This permits a parallel beam to reflect light from the surface of bare soil, crown of vegetation, etc., into the sensing element of the Eppley without allowing any diffuse light to enter from the surrounding objects. Thus, measurement of albedo at low solar altitudes becomes possible. As to the exposure of instrument, it is necessary to avoid the effect of shadow cast by the instrument. Fig. 5-11b shows the exposure of Kuhn & Suomi's beam reflector exposed in a field.

5.2.5 *Net radiation*

The net radiation normal to the earth's surface is the difference between the total downward radiation and total upward radiation. Measurement of the energy balance in terms of net radiation at the soil surface reveals the general amount of energy available for changing the thermal status of the air and ground as well as the moisture associated with them. Thus, evaporation and even soil moisture can be determined by the combination of net radiation, temperature, vapor pressure, and sometimes wind (Pasquill, 1950; Albrecht, 1951; Rider & Robinson, 1951; Suomi & Tanner, 1958; Monteith & Szeicz, 1961; and many others). It is also useful for the determination or prediction of minimum temperature. This in turn determines frost formation, soil temperature, snow melting rate, and even the length of the growing season. In the study of heat budget of a field, and that of animal houses, net radiation measurement is imperative. This applies to crop freezing probability and estimates of cooling and heating loads in buildings.

Instruments to measure net radiation include the Beckman & Whitley net-exchange radiometer, Suomi's improved net-radiation instrument (Suomi et al., 1954) (Fig. 5-12), Suomi & Kuhn's economical net radiometer (Suomi & Kuhn, 1958) (Fig. 5-13), Fritschen's miniature net radiometer, and many others.

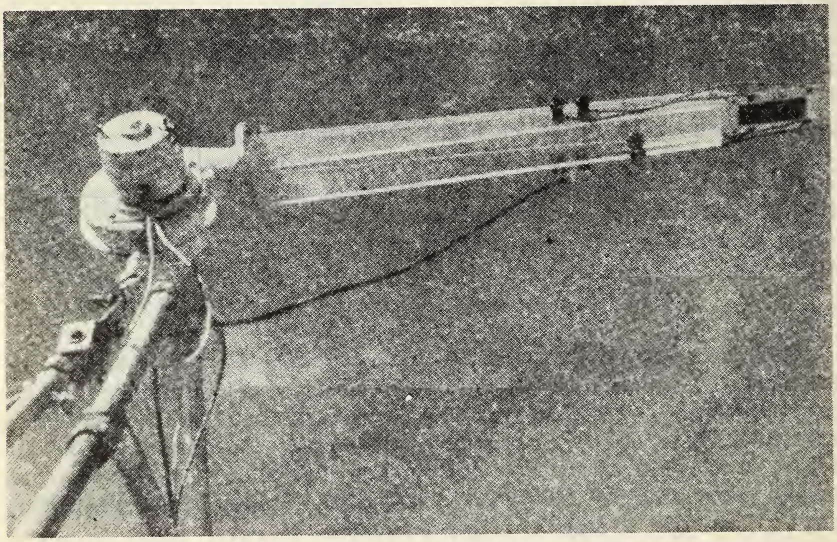


Fig. 5-12. Suomi's improved net-radiation instrument.
After Suomi, Fransila, & Islitzer

In construction, the Beckman & Whitley net-exchange radiometer is the same as the Beckman & Whitley total-hemispherical thermal radiometer (see Fig. 5-3). It consists of a $4\frac{1}{2}$'' square thermopile unit built in bakelite sheets with a black aluminum shield on top and bottom as sensing elements. The inner portion of the aluminum shield is polished. An air stream passes through the top and bottom of the sensing element in order to eliminate convection effects and to prevent collection of dew on the surface of the element. The sensitivity of

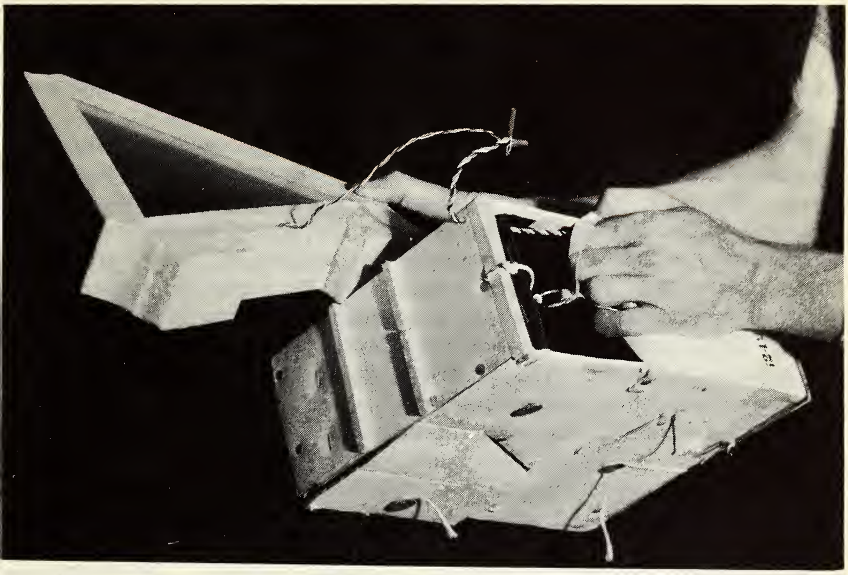


Fig. 5-13. Suomi & Kuhn's economical net radiometer (the triangle piece). After Suomi & Kuhn

the radiometer is 10 millivolts per langley per minute, and the instrument reaches 95% steady-state condition 12 seconds after sudden exposure. It has been found that the instrument is capable of giving a net radiation measurement with an accuracy of ±2%.

Suomi's net-radiation instrument (Fig. 5-12) measures the net flux of radiant energy by exposing a black plate, a radiation-absorbing sensor, parallel to the radiation source. This instrument has a specially designed vane in the nozzle throat and an electric heater on the radiation plate to furnish a sensitive control over ventilation, so that the cooling power on each side of the plate can be accurately equalized. It is somewhat similar to the Beckman & Whitley net-exchange radiometer, except that it is designed to measure broader ranges of wavelengths (0.17 to 80 microns). It measures the net radiation with an accuracy of ±2%, except for very small values. It fails to detect the water-vapor band (about 15 microns) and the shortwave band (below 1 micron), because of lack of necessary absorption data in these regions.

Suomi & Kuhn's economical net radiometer contains two black absorber surface plates (the triangular piece shown in Fig. 5-13; the equipment to which the radiometer is attached is a radiosonde). The top plate collects total downward radiation and the bottom plate, the total upward radiation; the temperatures of the absorber plates are measured by two thermistors. Two layers of thin polyethylene film are employed to insulate the thermistors from ventilation and moisture.

It has been found that this instrument has an accuracy within 5%, as compared to Suomi's improved net-radiation instrument. Because of its extreme low cost, this instrument is recommendable for large network use.

Fritschen's miniature net radiometer is constructed by enclosing a blackened thermal transducer within four polystyrene radiation windows. The outer two radiation windows are hemispherically shaped, 1" in radius, so that the response of the instrument to varying angles of incidence would follow the cosine law, and to facilitate precipitation runoff. This instrument, because of its size, can be used to measure net radiation close to a surface or within a plant canopy without introducing an appreciable effect of shading to the observation. Also, its small size greatly minimizes the effect of wind or ambient temperature on measurement.

The most critical problem for net radiometer observation is the height of operation. With a height much greater than a meter, errors may arise due to radiation divergence, i.e., due to the difference between actual net radiation at instrument height and that at surface (Slatyer & McIlroy, 1961). On the other hand, at heights much less than a meter, the net radiation may begin to appear patchy. In short, the optimal height for a net radiometer should be as low as permitted by the nature of local sampling and by the size of the instrument.

Instruments for light measurement in agrometeorological and ecological studies are numerous. Ecologists prefer portable instruments such as photometers, illuminometers (Foster, 1951), or simple light meters (Longmore & Hopkinson, 1954), and photoelectric cells, instead of the above-mentioned instruments. It is important to recognize that for an ideal station, a continuous record with a sensitive instrument is necessary for the description of the photofield.

5.3 THERMOFIELD

Temperature is generally used to describe the thermofield, because there is no available method for measuring sensible or latent heat. Conventionally, the thermofield is classified according to the type of medium to be measured, i.e., air, soil, or water temperature.

Classical instruments used for the study of temperature may be classified according to four physical properties: (a) thermal expansion (e.g., mercury-in-glass or spirit-in-glass thermometers and the deformation thermometer); (b) vapor pressure (e.g., liquid-in-steel and organic liquid-in-steel thermometers); (c) electrical resistance (e.g., platinum-, nickel-, or copper-thermometer); and (d) sonic property (e.g., sonic thermometer). These classical instruments have been used for temperature measurement in air, soil, and water.

5.3.1 *Air temperature*

In the measurement of air temperature, the thermocouple or thermistor is a much better sensor than either mercury or spirit thermometers. Neither the volume expansion coefficient of mercury nor that of glass is constant for all temperatures. The spirit and glass are poor conductors and result in a large lag coefficient, and calibration errors involved in both mercury and spirit thermometers are serious.[1] The high freezing point of mercury (-38°F) and low boiling point of spirit (172°F for C_2H_5OH) are another drawback. The low boiling point of spirit is not nearly as serious as the high freezing point of mercury. For these reasons, the thermal expansion type and vapor pressure type of thermometers are not suitable for measuring air temperature. Moreover, the size of these instruments is considerable, causing additional error by radiation.

In the Great Plains Turbulence Field Program at O'Neill, in 1953 (Lettau & Davidson, 1957), various designs using thermocouples or thermistors were employed: the shielded thermocouples used by Portman; the aspirated thermocouples used by Rhoades as well as by Cramer et al.; and the shielded thermistors used by Jehn. Studies on the use of thermistors include "The Properties and Uses of Thermistors," by Becker et al. (1946); "Thermistors as Instruments of Thermometry and Anemometry," by Hales (1948); "A Portable Thermistor Bridge for Micrometeorology Among Growing Crops," by Penman & Long; and many others.

A thermistor (i.e., ceramic temperature-sensitive resistor) is a semiconductor of high negative coefficients of resistance. In other words, the higher the temperature is, the lower the electrical resistance will be. For example, the Glennite thermistor may vary from 10,000,000 to 1 ohm in resistance for temperature ranges from -100°C to +450°C. For meteorological application, a temperature range of -79°C to +60°C would be sufficient. The Glennite thermistor (e.g., 41 CBI bead type in probe or bulb), manufactured by the Gulton Industries, Inc., for instance, has a resistance of 10,000 ± 20% ohms at 25°C with a diameter of 0.043", and a lead length of ¼". It has a temperature coefficient of resistance -3.9% per degree Centigrade, a time lag coefficient of two seconds, and a dissipation constant of 0.7 mw per degree Centigrade in still air.

There are thousands of types of thermistors available commercially these days, and they can be found in instrument catalogs.

[1]Some errors are: lack of uniformity in capillary bore; thermal hysteresis effect of glass due to calibrations of boiling and freezing points; differentials in gravitational stress by mercury column; differentials in temperature between bulb and stem and effect due to external pressure on bulb.

In comparing the thermocouple and thermistor, the latter has a greater sensitivity, which permits the use of more rugged and less expensive external indicating equipment. Besides, the thermistor does not need to maintain a hot and a cold junction of constant temperature, and permits telemetering without much resistance in the circuit because of its high impedance (Becker et al., 1946). Disadvantages of the thermistor are its susceptibility to leakage, difficulties in calibration, and nonlinearity in temperature resistance (Goll, 1958; Höhne, 1957; Steward & Kassander, 1957). The recording in the thermocouple is a measurement of electromotive force produced in the circuit by a potential meter or a millivoltmeter, while for the thermistor, it is the current that is measured. The uses of the thermistor other than for measuring air temperature are for determining soil temperature (Becker et al., 1946), wind velocity (Hales, 1948), soil moisture (Colman & Hendrix, 1949), animal body temperature (Williams & Thompson, 1948; Benjamin & Horvath, 1949), blood temperature (Drummeter & Fastie, 1947), leaf temperature (Platt & Wolf, 1950), water temperature (Platt & Shoup, 1950), and many others. A general description of the use of thermistors in living plants and animals has been summarized by Taylor (1952). The application of thermocouples for the temperature measurement of plant parts, animal skin, etc., is just as widely practiced as that of thermistors (Zakrent, 1951).

The direct measurement of vertical temperature gradient (or lapse rate) above the earth's surface describes the thermal field of microenvironment more readily and is useful to crop and animal response studies. The temperature gradient meter is one type of instrument to be used for this purpose (e.g., Krechmer, 1957; Hase, 1957).

The sonic thermometer was devised by Barrett & Suomi (1949). The system uses a short pulse of high-frequency sound, generated by application of a voltage to a piezo electric crystal propagated through a fixed distance. This pulse is received by an identical piezo electric receiver which generates a voltage. The voltage, after being suitably peaked, is fed back to the pulse generator, causing a new pulse to go out. The total time required for the sound to travel both between transmitter and receiver and within the electrical circuit from the receiver to the outgoing pulse is equal to the time between pulses. Thus, air temperature in the path is measured. Major advantages of the sonic thermometer are its independence of radiation, the elimination of time lag, and improved sampling. Its disadvantage is that it is very costly, poses a maintenance problem, and is not well adapted to field uses.

With all the advantages of modern thermal sensing devices, classical thermometry is not yet abandoned. Since air near the ground does not ordinarily maintain a constant temperature so as to warrant readings within less than 0.5°F, and since air temperature sometimes fluctuates as fast as 2° or 3°F within a few minutes, there is no need for highly accurate or sensitive measurements, especially for agrometeorological purposes. Therefore, the maximum and minimum thermometer and the Bourdon-tube type thermograph are still useful. In using these classical instruments, caution should be taken on the exposure problems of thermometers.

In order for a thermometer to measure the true temperature of the air, it must be protected from all kinds of radiation that it will absorb, for the air absorbs very little radiation. Various devices have been made for this type of protection. The weather shelter is a wooden box with louvered sides, a staggered board bottom, and a double roof of all different sizes and shapes. It is assumed to have enough ventilation and protection from the sun's radiation. However, during a calm, clear night the shelter air temperature is lower than the air temperature outside, while during a calm, clear day, it is higher. Only during a windy and cloudy day is its temperature very similar to that outside the shelter. Other exposure devices, such as the aspirated psychrometer and the sling psychrometer, give better protection than the weather shelter. This will be further discussed in Section 5.4.3.

Instruments for temperature measurement can also be classified into either one of two groups: conduction type (or conventional thermometers), and radiation sensing type (or bolometers). The bolometric method of temperature measurement is based on the assumption that the radiation flux emitted by a substance is a monotonic function of its temperature. Bolometers are claimed to possess several distinct advantages over thermometers. First, because the measurement is taken remotely, the instrument has no effect on the environment under consideration. Second, it permits the measurement of weighted area-mean temperature, whereas a thermometer is limited to a point measurement. Third, it makes possible the time response in milliseconds. It should be pointed out, however, that the radiation flux is a function of emissivity as well as temperature, and is also a function of the medium through which the radiation has passed; that the representativeness of area-mean temperature is not always satisfactory; that a reference source of radiation flux must be provided, since only the differences in radiation flux can be measured; and that the power output of a bolometric detector is relatively small and must be greatly amplified. Despite all these limitations, bolometric determination of large-area surface temperature has been employed by some investigators (Albrecht, 1952; Combs, 1961; Lorenz, 1962; and others). In order for bolometric techniques to become more useful, it is necessary (a) to correlate the bolometric data with point-source records taken on the ground; (b) to delineate natural boundaries of one type of area from the next, such as a swampy area from dry land and a forest from a lake; (c) to establish regular schedules both in time and route; and

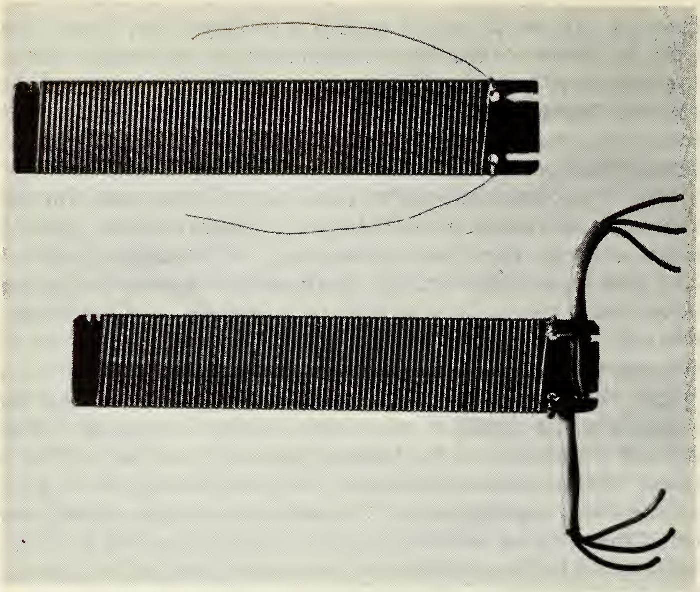


Fig. 5-14. Thermometer resistance elements with and without 3-wire cable attached. After Tanner

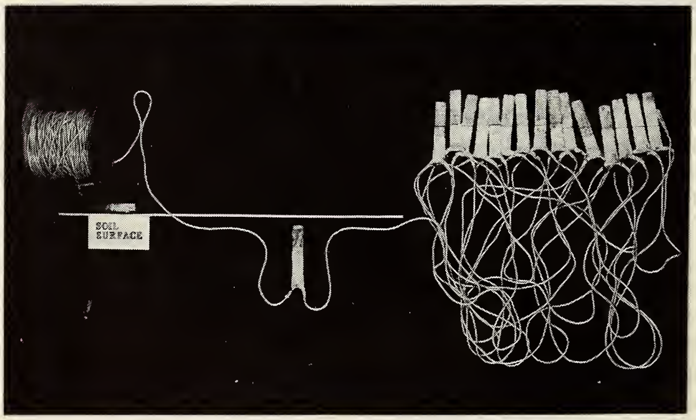


Fig. 5-15. Integrated resistance soil thermometer. After Tanner

(d) to maintain large geographical area observations. Although this technique is very expensive, the results would be highly valuable.

5.3.2 *Soil temperature*

In measurement of soil temperature, almost all types of thermometers are used, except for the sonic thermometer. These measurements aim at two kinds of information: soil temperature, and soil heat transfer (Buettner, 1955; Deacon, 1952), and these two should be measured simultaneously. Problems involved in soil temperature determination are: (1) sampling technique, both vertical and horizontal, due to the heterogeneity of soil constituents; (2) heating effects on ambient soil moisture of the sensor, due to the heat conducted from the exposed portion above ground; and (3) differential heating between soil and sensing element, involving heat flow from soil to sensing element or vice versa. The electrical resistance devices, such as the platinum resistance element, thermocouple, and thermistor, are ideal sensors for this purpose, because they are low in heat capacity and small in size.

Suomi (1957a) and Tanner (1958) have made use of the resistance of nickel wire for soil temperature measurement. Suomi's soil temperature integrator has been further improved by Tanner in the Wheatstone bridge recording device and temperature sensing elements. These elements are well insulated against soil moisture. The average soil temperature of several locations at either a single depth or a range of depths may be determined by a single reading, for example, a recording on a strip-chart potentiometer. Fig. 5-14 shows the thermometer resistance elements with and without 3-wire cable attached. Fig. 5-15 indicates the 15-element thermometer with one element placed in the soil. The elements have a desirable thermal capacity and a low thermal conductivity so that they do not affect the temperature of adjacent soil. It permits better sampling and reduces instrumental heating effects to a great extent, and thus is highly recommended for soil temperature measurement.

The Palmer dial thermometer (Fig. 5-16), a light portable instrument, measures the maximum and minimum soil temperatures in the range of -40° to +120°F with an accuracy to the degree. The steel sensing element is 13" long and 5/16" in diameter. It is small enough not to disturb the natural soil profile, and long enough to give space integration. Two indicators at the dial show the maximum and minimum temperatures and can be easily reset. This instrument is recommended for general use because of its simplicity and fair degree of accuracy.

5.3.3 *Water temperature*

The measurement of water temperature in reservoirs, rice paddy fields, wells, fish ponds, rivers, and even oceans, is directly and

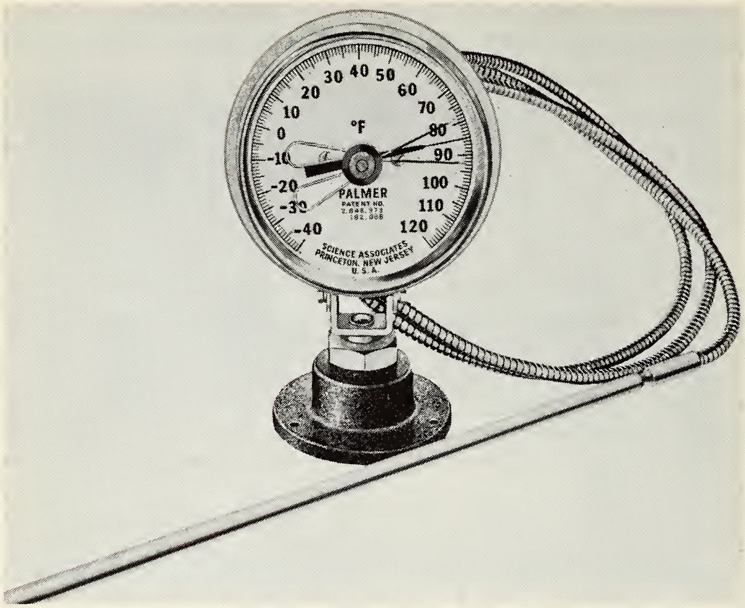


Fig. 5-16. Palmer dial soil thermometer.
(Courtesy of Palmer Thermometers, Inc., Cincinnati, Ohio)

indirectly related to agriculture. The measurement of rainwater is another aspect of agricultural importance. Nevertheless, most instruments for water temperature measurement have been designed by the oceanographer. In classical oceanographic work, three types of thermometers are employed: (a) ordinary thermometer; (b) reversing thermometer; and (c) thermograph.

(a) An ordinary thermometer is used to measure sample water temperature, either from surface or from deep water. The sample water can be obtained by a Nansen bottle, which is a reversing bottle filled with two plug valves, one on each end of the brass cylinder, operated synchronously by means of a connecting rod. The rod is fastened to the clamp securing the bottle to the wire rope. When the bottle is lowered, this clamp is at the lower end, and the valves are open to admit the water. The reversing position (180 degree turning) is made possible by sending a messenger weight down the rope. This weight strikes the release and shuts the valves. A number of bottles can be attached to the same wire rope. The sampling water can also be obtained by using an Ekman bottle or even a bucket; the latter is for sampling water near the surface only. (b) A reversing thermometer is employed to measure water temperature at the sub-surface or deep water level. This thermometer is sometimes used in association with Nansen bottles, as has been described above. It is a mercury-in-glass thermometer which records temperature upon being inverted and thereafter retains its reading until returned to the first position. It consists of a conventional bulb connected to a capillary in which a constriction is placed so that upon reversal, the mercury column breaks off in a reproducible manner. For details, the reader may refer to any book on oceanography or Processing Oceanographic Data.[2] (c) A thermograph is employed at shore stations and/or on board vessels, for recording water temperature at fixed levels. Thermocouples and thermistors, particularly the latter, have also been employed for measuring water temperature (Platt & Wolf, 1950). Like soil temperature measurements, the most difficult is the water surface temperature measurement. It is obvious that a three-dimensional sensing device is not appropriate for the direct measurement of a two-dimensional surface. Therefore, an indirect method, similar to the energy balance approach (See Section 4.1.1), can be used. Hammecke & Kappler (1953) developed a new device to evaluate water temperature pyrometrically with an accuracy of 0.05°C, through radiation from the surface. The true water surface temperature thus computed by the energy balance method is representative of about a 0.0001 mm layer of water. Studies on the measurement of rain temperature have been done by Novák (1932) and Byers et al. (1949). Studies on effects of water temperature in the paddy field in relation to yield of rice plants have been done by a number of Japanese microclimatologists such as Yoshida (1951), Tanaka (1953, 1954), etc.

5.4 HYDROFIELD

The presence of water in any state surrounding a plant or animal is defined as the hydrofield of its environment. The various states of water may be expressed as solid form (snow, hailstone, and frost), liquid form (rain, dew, and soil moisture), and gas (humidity and vapor pressure). Determination of the amount of water at different states is necessary. Other measurements, such as runoff, percolation, capillary action, water table, and various condensation-sorption processes, are also important but they belong to the realm of soil physics and hydrology.

Moisture in the air and soil is hard to measure, due to its uneven distribution in space and fluctuation with time. In meteorology, the conventional parameters for the description of moisture are precipitation and condensation, soil moisture, evaporation and evapotranspiration, and humidity in the air. Various instrumental designs for their measurement are described below.

[2]E. C. Lafond, 1951, Processing oceanographic data. U. S. Navy Hydrographic Office, Washington, D. C., H. O. Publ. No. 614. 114 pp.

5.4.1 *Precipitation*

In the measurement of precipitation, intensity, duration, and amount are three major considerations. The ordinary rain gauge, such as the 5-inch gauge of the Meteorological Office, London, the 3.57-inch standard gauge of the Canadian Meteorological Division, and the 8-inch standard gauge of the U. S. Weather Bureau, gives only the total amount of precipitation, and not intensity and duration. It would be impractical, also, to make hourly observations with ordinary rain gauges, if the total precipitation in 24 hours is small. The diameter of the receiver of an ordinary gauge has lesser effect on total amount of precipitation collected than does depth. For example, the shallow rim (U. S. Weather Bureau type) may lose rain by splashing out, and the deeper rim (the M. O. type gauge) on the other hand may collect water that does not belong in it. This is a problem of the diameter-depth ratio. Perhaps a gauge as large as 40 sq. ft. could be considered for calibration purposes, provided the evaporation is under control. In fact, the amount of rainfall measured by a rain gauge is influenced not only by the rate of evaporation, but also by wind speed and direction, and intensity of rainfall, which in turn affect the amount of splashing.

There are many kinds of recording rain gauges. According to the mechanism of construction, the major types may be classified into (a) the float type, e.g., Negretti & Zambra "Hyetograph," the Dines tilting-siphon, and the natural-siphon rain gauge; (b) the weighing or balance type, such as the Fergusson weighing rain or snow gauge; (c) the tipping-bucket type; and (d) the Nilsson rain gauge, or combination of the tipping-bucket and weighing types. The main advantage in the use of the recording rain gauge over that of the ordinary rain gauge is that it measures the duration, intensity, and amount of rainfall automatically and simultaneously. Hence the beginning and end of rainfall can be determined. With regard to the float type, advantages of the hyetograph are the absence of cumulative error and its simplicity of mechanism. Its disadvantage is that the float can be irreparably damaged by frost. In fact, all float types suffer the same disadvantage. The siphon gauge has the benefit of continuous recording of very light rain. As for the weighing type, the Fergusson weighing rain and snow gauge can measure precipitation in any form, and is recommended for use in cold climates. Its disadvantage is that wind will cause oscillation of the balance. The tipping-bucket gauge has the advantage of continuous remote recording. Its limitations are that no record is made for less than 0.01 inch accumulation of rain in the bucket, that it takes some 0.2 seconds to tip the bucket, and that serious error will thus appear if the rate of rainfall is at or above 2 inches per hour. Moreover, it cannot be used in freezing weather.

The U. S. Weather Bureau standard weighing-type precipitation gauge (Fig. 5-17) consists of a receiver of exactly eight inches inside diameter through which rainfall is funneled into a bucket mounted on a weighing mechanism. The rate of rainfall is recorded by a clock-driven strip chart, and expressed in inches at a specific time.

The tipping-bucket gauge has a triangular-shaped bucket which is divided into two compartments. The bucket is balanced on an axis so that the rainfall accumulation reaching 0.01" will tip the bucket, emptying it, making an electrical contact, and exposing the other compartment of the bucket to the rain. These contacts are recorded electronically at any distance. Fig. 5-18a indicates the general view of a tipping-bucket rain gauge, and Fig. 5-18b, the diagrammatic illustration of a similar instrument.

Various attempts have been made to improve the recording rain gauge. Yajima (1953, 1955) recognized that an improvement in the construction of the tipping-bucket rain gauge could be achieved by having the angle of the watershed, α, and the inclination of the bucket, θ, in the following relationship: $\theta = \frac{1}{2}(90 - \alpha)$. Frère (1958) found that the recording siphon rain gauge could be provided a maximum hydrostatic thrust sufficient to overcome the friction resistance by increasing the volume of the buoy and reducing its weight. Ponomarev (1957) indicated that accelerating the rise in the precipitation level in the float chamber will hasten the filling of the curved part of the siphon tube with water, in the siphon-type rain gauge. He also found means of reducing friction of the pen or ribbon, and hermetical sealing of the siphon attachment.

The newly developed radar technique for measuring rainfall intensity, duration, and amount is highly recommended (Wexler & Swingle, 1947; Byers, 1948; Spilhaus, 1948a; and Kodaira, 1955). It gives the best sampling in a short time and covers a large geographical area, whereas the rain gauge gives only point-source information and is not representative of the area, particularly during sporadic rainfall in summer. The measurement of the fall-velocity of water drops and raindrips has been studied by Laws (1947), and the study of raindrop size, shape, and falling speed has been conducted by Spilhaus (1948b).

Two devices are generally used for the determination of snow depth: the depth marker (or snow board) for shallow snow, and the depth indicator (or snow stake) for deep snow. The former is a 16" × 16" thin metal board which is placed on top of snow surfaces. The latter is a white-painted three-fourths-inch square stake of appropriate length, with a division every two inches. It is rather difficult to convert snow depth to actual amount of water; therefore, snow-water is measured. This can be done by using ordinary rain gauges with the removal of receiver and measuring tube. In other words, an overflow can is used to collect snow and then the amount of melted snow is measured. The

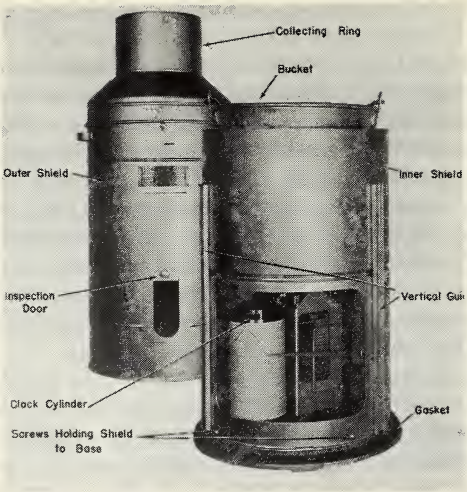


Fig. 5-17. U. S. Weather Bureau standard weighing-type precipitation gauge. (Courtesy of U. S. Department of Commerce Weather Bureau)

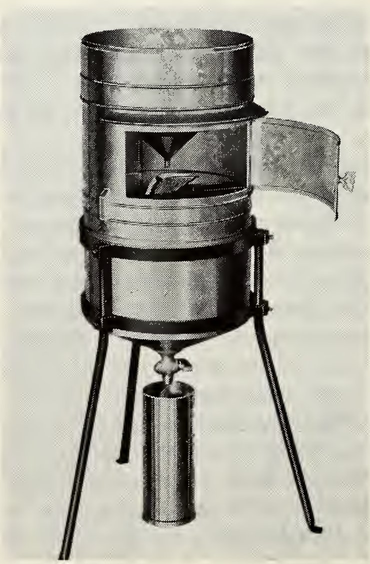


Fig. 5-18a. Tipping bucket rain gauge. (Courtesy of Belfort Instrument Company, Baltimore, Md.)

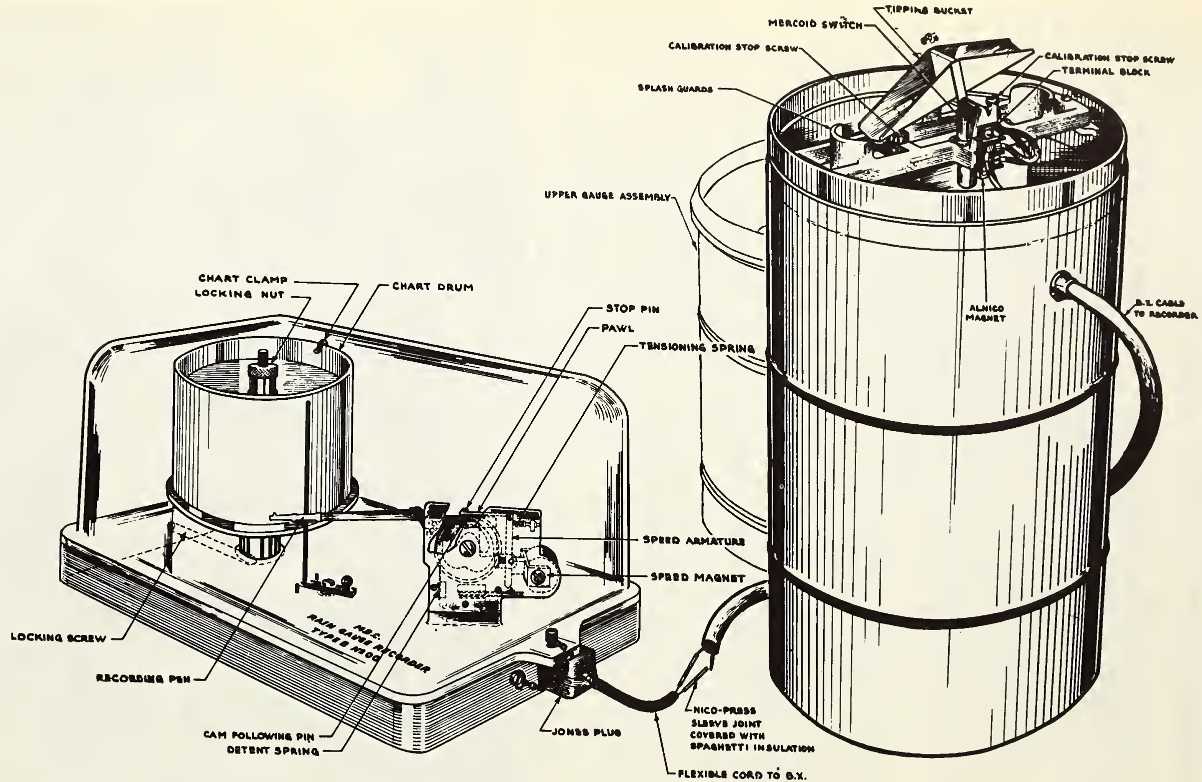


Fig. 5-18b. Diagram of tipping bucket rain gauge indicating various parts.
(Courtesy of Canada Department of Transport, Toronto)

weighing recording gauge can also be used for snow measurement by replacing the funnel at the bottom of the collector by a snow ring. An anti-freeze solution is placed in the bucket to melt the snow falling into it and to prevent damage of the gauge from freezing. Itagaki (1959) developed a new type of radio snow gauge; its main features are (a) a Geiger-Müller counter buried under the snow layer, to eliminate the effect of temperature on the counter; (b) use of Morse codes to send information obtained; (c) a linear relationship between the snow-water equivalent and the number of Morse codes; and (d) the simultaneous obtaining of information on temperature and humidity.

5.4.2 *Evaporation*

Evaporation is here referred to as the amount of water transformed into vapor from free water surfaces; evapotranspiration is that from soil and plant surfaces. The sampling technique for determining evaporation is much simpler in comparison to that for determining evapotranspiration. For example, when evaporation is being measured from a reservoir, a large evaporation tank would give representative measurements, provided that temperatures of the tank and of the reservoir do not differ. Differences in temperature, if any, can be corrected, if the temperature records in both tank and reservoir are known. When the sampling technique is applied to measure evapotranspiration, it is almost impossible to use a small area surface, such as the surface area of a lysimeter, to represent a large heterogeneous area. For both evaporation and evapotranspiration measurements, the "island effect," the difference in the surface of the instrument and that of the area surrounding it, should be considered.

Instruments for determining evaporation are generally classified under the term atmometer, but sometimes under evaporimeter, evaporation pan, and atmidometer. There are four main classes of atmometers which may be differentiated as (a) large evaporation pan; (b) small evaporation pan; (c) porous porcelain body; and (d) porous paper wick device. Presently, only the large evaporation pan and the porous porcelain body types are commonly used.

The large evaporation pan of the U.S. Weather Bureau type is made of galvanized iron or an alloy similar to monel metal, of cylindrical design. It is four feet in diameter and 10 inches in depth, filled with water. A cylindrical well, shown in Fig. 5-19, provides an undisturbed water surface around the hook gauge and, in addition, provides a support for the gauge. The gauge consists of a hook at the end of the stem that is graduated in tenths of an inch, over a range of several inches. A thermometer is placed in the water for the water temperature measurement.

The modified Bellani atmometer is one of the porous porcelain body type. The black Bellani plate serves as the evaporating surface and

Fig. 5-19. U.S. Weather Bureau-type evaporation pan.
(Courtesy of U.S. Department of Commerce Weather Bureau)

is connected by rubber tubing to the reservoir, i.e., the glass cylinder. Through a siphon mechanism, the water is sucked up to the plate for evaporation. This atmometer has a mercury-wool valve in the center tube, acting as a check valve to retard the reverse flow of water from the Bellani plate. The top plastic cover is used for protection from rain and birds.

The Steven-Roberts evaporimeter is shown in Fig. 5-20. It is essentially a weighing-type rain gauge and can measure the water loss, by weight, from a 25.3-inch-diameter pan which includes the outside area of the overflow pipe intake. Thus the rate of evaporation is automatically recorded. It is so designed that each 0.1 inch of evaporation corresponds to 1.0 inch of the record, and the record can be visually resolved to about 0.0025 inch of evaporation. The weight of the pan is balanced by a cam and counterweight mechanism. The maximum recording capacity is 0.6 inch of evaporation. Each minor division of the chart corresponds to 0.01 inch of evaporation.

For determining evapotranspiration, lysimeters are widely adopted as research tools (Harrold & Dreibelbis, 1953; Makkink, 1953; King et al., 1956; Visser & Bloemen, 1960). They give a continuous record of evapotranspiration; in turn, the soil moisture can be determined. The Hawaiian Pineapple Plantation makes extensive use of the tube-type lysimeters equipped with a liquid level recorder for determining

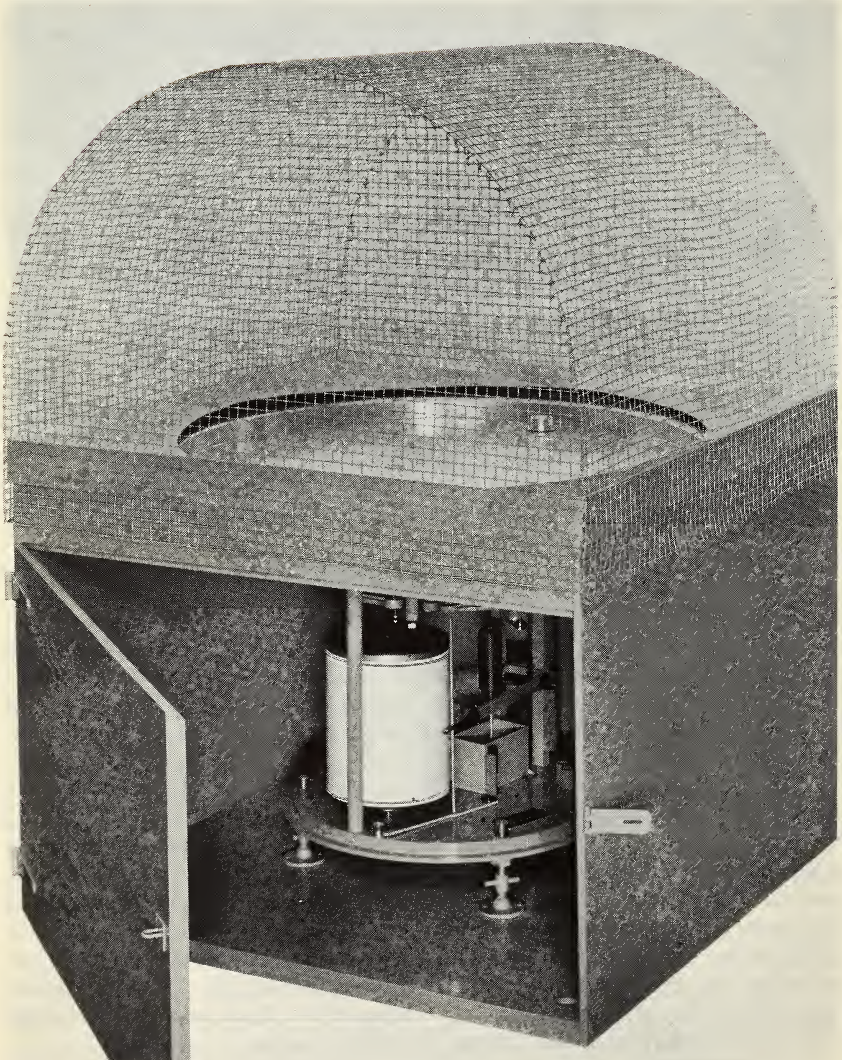


Fig. 5-20. Stevens - Roberts evaporimeter assembled with marine plywood housing and bronze screen.
(Courtesy of Leupold & Stevens Instruments, Inc., Portland, Ore.)

both evapotranspiration and soil moisture of the entire pineapple field. Advantages of this type of lysimeter include simplicity, continuous recording of a fixed locality, and low cost. The lysimeter method is recommended for a large uniform field, particularly in humid areas. In semi-humid areas or deserts, lysimeter measurements are often misleading, due to the "oasis effect" or "island effect." For any area usage, lysimeters large enough to give accurate results are bulky and expensive to install and operate.

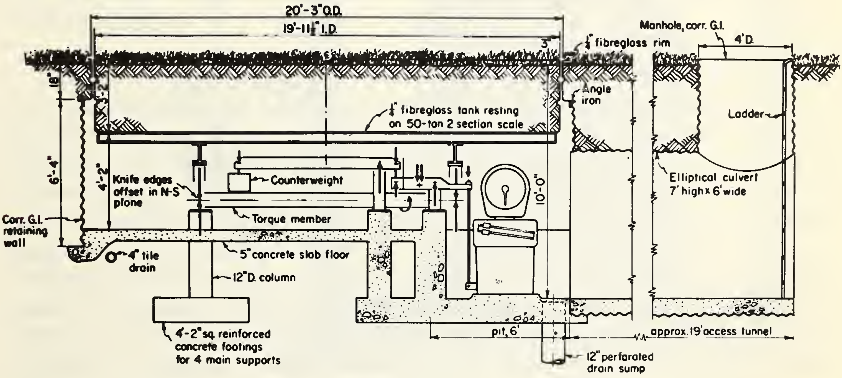


Fig. 5-21. Weighing lysimeter. After Pruitt

The weighing lysimeter installed at the University of California, Davis, California, is one of the standard lysimeters for research purposes (Fig. 5-21). It is a tank approximately 20 feet in diameter and 38" in depth, with a capacity of 50 tons of soil and water. It is used to determine evapotranspiration of an ideal spot, and also serves as standard for the calibration of other types of lysimeters. It has a high sensitivity of ± 0.0012" evapotranspiration. Common problems involved in the construction of various lysimeters, such as "island effect," "lysimeter wall effect," and "disturbed soil effect," have been solved in this type of lysimeter (Pruitt & Angus, 1960).

The floating-type lysimeter (Fig. 5-22), originally designed by Suomi in 1953 and modified by King et al. (1956), employs the Archimedes principle. It consists of a tank with a diameter of five feet and depth of six feet, which floats in a larger reservoir tank. The water stage recorder in a stilling well is connected to the reservoir tank by a plastic pipe, and the evapotranspiration is recorded at a 10-to-1 ratio. It is claimed that the sensitivity of this type of lysimeter is better than ± 0.002" of evaporation. The advantages of this type of lysimeter are simplicity and economy. Its limitation is that the air chamber in the lysimeter not only occupies the volume in the

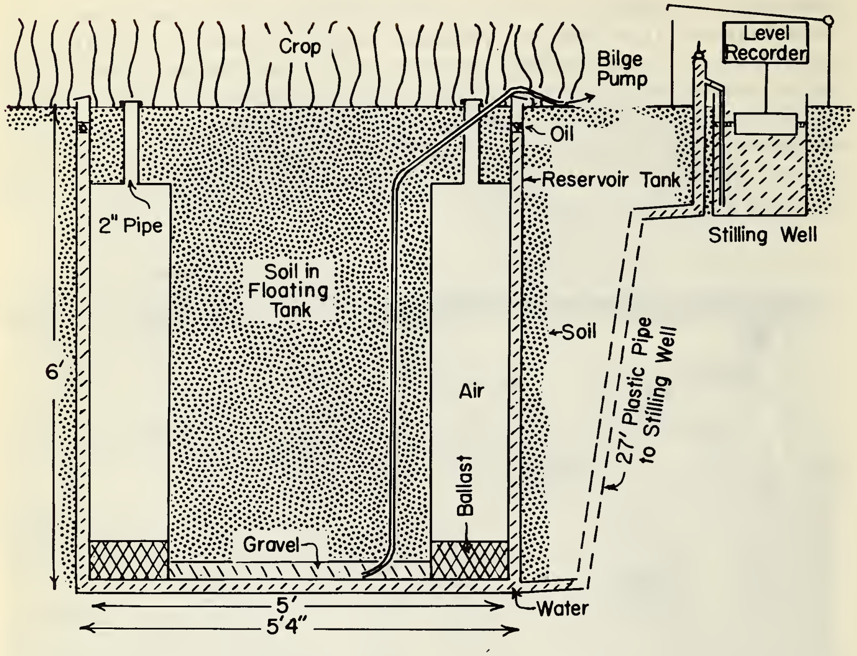


Fig. 5-22. Floating-type lysimeter. After King, Tanner, & Suomi

lower portion of the floating tank, but also gives a narrow non-cropped border area. Above all, this type of lysimeter is subject to wind effect.

The modified evapotranspirometer, designed by Thornthwaite & Mather, consists of a 55 cm diameter and 47 cm depth oil drum with an outlet for water drainage at the bottom of the container, connected by 1" piping to the overflow drum, which is housed in a cylinder with a cover. The difference between the amount of water put in the oil drum and that accumulated in the overflow drum determines the evapotranspiration. The main advantage of this instrument is that it is one of the simplest in design, and therefore inexpensive to install. On the other hand, it requires that the soil be kept in its field capacity or that the soil be constantly saturated in order to secure reliable readings; hence, only potential evapotranspiration can be measured. Moreover, it provides only the interval record, and not a continuous record.

The effective performance of any lysimeter, simple or complicated, depends on its size, construction, type of plant material used, and the location being studied. It is desirable to have minimum disturbance due to the lysimeter itself and maximum representation of the area being sampled. An ideal lysimeter, therefore, should be large enough to ensure a fully reliable sampling of the plant community, deep enough for unrestricted root growth throughout the season, and heavy enough to reduce wind effect. In addition, heat conduction and drainage problems should also be considered. These problems can be solved partially by the use of thin walls of poorly conducting material, by regulating the temperature in a space below the soil container, and by extracting moisture from the lowest layer of soil with porous tube or other material.

5.4.3 *Humidity*

The physical mechanisms utilized for the construction of air moisture instruments are: (a) the evaporation and condensation of water; (b) the hygroscopic nature of substances; (c) the absorption of substances; (d) the diffusion of substances; and (e) the penetration of infrared light. Among these, the infrared absorption hygrometer which senses the atmospheric moisture at a distance is the most ideal instrument, but it is costly. The dewcel utilizing the relation between resistance of lithium chloride film and the relative humidity was developed to indicate the presence of moisture in the air. It is not as expensive as the infrared hygrometer, is easy to operate, and gives an accurate indication when the air is saturated and at a freezing point; thus it is superior to the psychrometer.

The psychrometer consists of a pair of ordinary thermometers, a dry bulb and a wet bulb (wrapped with wet muslin or a thin piece of cloth), placed side by side. At usual atmospheric conditions, when evaporation takes place, the wet bulb indicates a lower temperature than the dry bulb. When the air is saturated, the two thermometers give the same temperature readings. The relative humidity is determined according to readings from these two thermometers. Occasionally, when the air is relatively moist at temperatures near the freezing point, the condensation heat will cause the wet bulb temperature to rise higher than the dry bulb; thus it fails to register the true humidity.

The dewpoint temperature measurements at two levels, together with the wind velocity or net radiation measurement, can be used for estimating heat balance near the ground (Suomi & Tanner, 1958). The daily maximum and minimum dewpoint observations can be made by using a maximum-minimum dewpoint hygrometer designed by Tanner & Suomi (1958). This instrument is a conjunction of the Foxboro lithium chloride dewcel and a maximum-minimum thermometer calibrated directly in degrees dewpoint. The advantage of this hygrometer is its simplicity and accuracy; however, the use of this instrument is limited to regions in which the relative humidity is above 15% at an air temperature greater than freezing. For air temperature at -25°F, the relative humidity is limited to 30%, and for -45°F, it is 75%.

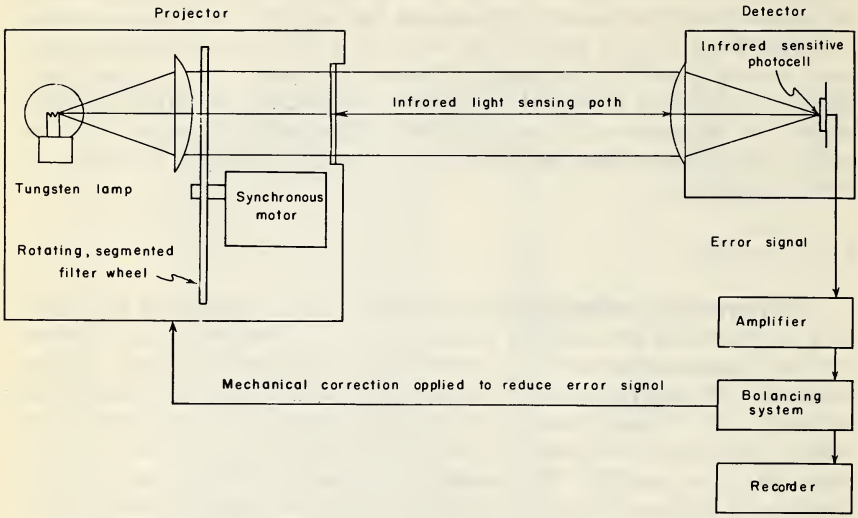


Fig. 5-23. Schematic diagram of improved absorption spectra hygrometer.

The improved infrared absorption spectra hygrometer, which employs a light beam as the principal sensing element (Wood, 1958), provides a unique and ingenious technique of measuring water vapor in the air. A schematic diagram is given in Fig. 5-23. This instrument can detect 1 mg of water vapor per cubic meter, or approximately one part per million by volume. The mechanism utilizes two narrow bands of infrared radiation for determining the water vapor content of a 12-inch path. One band, centered near the wavelength of 2.60 μ, is subject to attenuation by water vapor; the other, located near 2.45 μ, is free from attenuation. The ratio of transmitted band energies is sensitive to the concentration of water vapor in the path. Through the use of the servo-system, the ratio is effectively maintained at unity. The servo-operated glass wedge which consists essentially of a Brown "electronik" amplifier and servo-motor, moves to compensate for the energy imbalance caused by changes in the absorption of vapor. Wedge position is given electrical significance through the use of an appropriate transducer, calibrated in terms of vapor density, grams per cubic meter. This instrument is still in the experimental stage and not yet widely adopted. Advantages in the use of the infrared absorption spectra hygrometer are (a) its potential capacity in sensing a distance of a few inches to thousands of feet to integrate the absolute value of humidity in that path; (b) its high sensitivity at low vapor concentrations, where other techniques fail; (c) its high sensitivity in detecting rapid changes in humidity; and (d) its constancy in sampling concentration. Thus, the continuous monitoring of short-term atmospheric variations, ice fog determination, and evaporation measurement over a reservoir or farming area surface can be successfully accomplished through the infrared hygrometer. Its disadvantages are its less accurate recording at or below freezing temperatures (above dewpoint of 32°F, the error is $\pm$0.5°F; however, at -20°F, it is $\pm$1.0°F, and at -50°F, it is $\pm$2°F), its cost, and the high degree of skill required in its use.

Special mention should be made of the "hair hygrometer," because of its popularity. It was assumed that the changes in length and weight of a normal or flattened hair vary with relative humidity, and various types of instruments based on this principle have been designed. Such instruments are easy to construct and are inexpensive. Unfortunately, they have serious shortcomings. First, there is the hysteresis effect, by which the rate of hair elongation with humidity increase differs from that of hair shrinkage with humidity decrease (Sonntag, 1957b). Secondly, the changes in length and weight of hair vary with different temperatures (Sonntag, 1957a). More seriously, the individual hygrometer has its own scale, which complicates calibration (Sonntag, 1957c). Methods of mounting are another source of error (Maksic, 1955). MacHattie (1958) found that the average deviation per reading between hygrograph and psychrometer is $\pm$4.5% relative humidity and allowing for psychrometric error, an estimate of $\pm$3.5% relative humidity is obtained as the average error per hygrograph reading. He added that individual hygrograph errors were occasionally as large as 15% relative humidity, and points out that the dependence of hygrograph readings on previous as well as current humidity appears to be the chief cause of the large errors. Pápai (1958) further noted that hygroscopicity of the hairs used in hygrometers is caused by atmospheric pressure and the air in the hairs. Considering all such defects, it is suggested that the use of such instruments be abandoned unless the flattened hair has been well treated and is used for a short period of time, with careful calibration.

5.4.4 *Soil moisture*

The essential in soil moisture measurement is the technique of sampling. Three sampling methods are generally used, namely, point, line, and volume.

The point sampling enables the measurement of the rate of change of moisture at a fixed point, as employed by such tools as the tensiometer and nylon block (Buoyoucos, 1956). This method is relatively quick and measurements may be repeated at the same place. A brief description of a new modified nylon block and its mechanism is as follows: a nylon unit which is encased in plaster-of-Paris and buried at any desired depth in the soil, absorbs soil moisture and tends to be in equilibrium with that of the soil. A modified Wheatstone bridge, such as a soil moisture bridge and a moisture meter, is used to measure the change of electrical resistance in the nylon unit. The higher the moisture content of the unit, the lower the resistance, and vice versa. The advantages of the nylon electrical resistance method are its marked sensitivity at high soil moisture (i. e., the ability to measure soil moisture near the saturation range), durability, and recording of continuous data at a fixed point without disturbing the natural soil profile greatly. Disadvantages are inaccuracy at low soil moisture content, and difficulties in calibration. It has been reported that the nylon block works well in some soil types of high water-holding capacity, and conversely, in low moisture holding soil it does not work at all.

The soil moisture tensiometer is another common tool for the determination of soil moisture (Haise & Kelley, 1950; Sedgley & Millington, 1957; Richards & Hagan, 1958). The mechanism is based on the principle that the tension with which water is held in the soil increases with decreasing moisture content. Various types of tensiometers have been designed, measuring soil moisture changes from values near the moisture equivalent to capillary saturation. When the soil moisture tension exceeds one atmosphere, the tensiometer is no longer operative. Richards' (1952) membrane apparatus, which determines the soil moisture content of soil samples, measures moisture tension from one to 15 atmospheres.

Line sampling is usually used for measuring absolute soil moisture content at a fixed vertical line. Augers and Veihmeyer tubes (Veihmeyer & Hendrickson, 1949) are used for this sampling method. An auger takes soil samples from any depth as desired, the samples then being oven dried (standard procedure) or treated by calcium carbide (quick procedure). The disadvantages of the line sampling method are excessive disturbance of the soil profile, and the effect of variability in the physical properties of soil in different holes on the reading. This is particularly true with the Veihmeyer tubes. A soil boring tool can also be used for frost depth determination (Goodell, 1939). Another method for the determination of frost is the use of electric resistance (Rowland et al., 1955) in freezing soil.

Volume sampling is the most ideal method, particularly when the nuclear method is used. The use of neutron scattering devices for the measurement of soil moisture percentage has achieved wide recognition in the past decade (Belcher, 1952; Gardner & Kirkham, 1952; Brocard, 1954; Underwood et al., 1954; Danilin, 1955; Stone et al., 1955; Mortier & De Boodt, 1956; Stewart & Taylor, 1957; Holmes & Turner, 1958). It gives a better sampling of soil moisture, both vertically and horizontally, without introducing much disturbance of the natural soil profile. Its operation is based on the mechanism of a probe consisting of a source of fast neutrons in proximity to a detector of slow neutrons. The fast neutrons are slowed down by hydrogen atoms in soil water, and those slow neutrons returning to the detector are counted. Thus the number of slow neutrons detected per unit time is taken as a measure of soil moisture.

The portable neutron scattering moisture meter, designed by Stone et al. (1955) is suitable for field use (Fig. 5-24). The main features of the equipment are (a) a fast neutron source in the form of an annulus inserted in about the center of a slow neutron detecting tube; (b) glow transfer tubes, used for absolute neutron count determination; and (c) a calibrating volume of paraffin incorporated as a part of the source-detector carrying case, for simple field checking and standardization of the device. The disadvantages of any nuclear method are the complication in periodic maintenance of the electronic equipment, and the high cost.

Another volume sampling technique is a lysimeter method. This consists of weighing a mass of soil in the field by a suitable, permanently installed apparatus. Lysimeters can also be used for measuring evaporation and evapotranspiration, as was previously described.

5.4.5 *Dew*

Duration, amount, and intensity are the three common concerns in the determination of dew. The classical instruments for weighing dew deposits on a suitably exposed plate are known as drosometers.

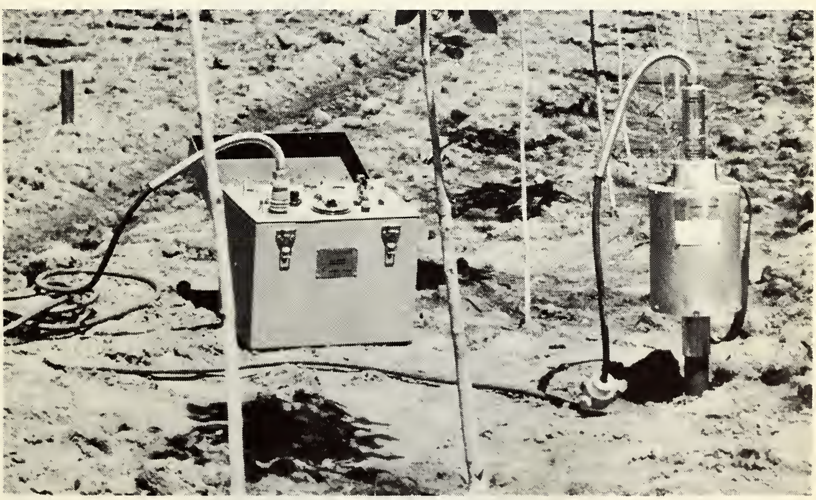


Fig. 5-24a. Portable neutron scattering soil moisture gauge in field operation. (Courtesy of Nuclear-Chicago Corporation, Des Plaines, Ill.)

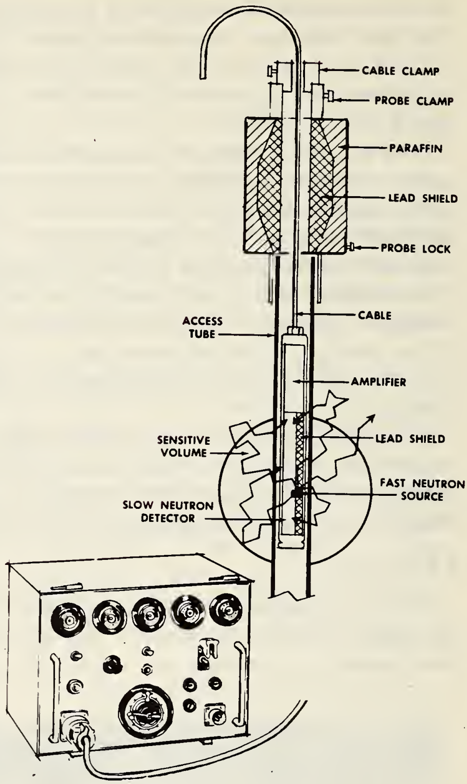


Fig. 5-24b. A close-up view of soil moisture gauge probe.

Fig. 5-24c. A diagrammatic view of soil moisture gauge probe.

(Courtesy of Nuclear-Chicago Corporation, Des Plaines, Ill.)

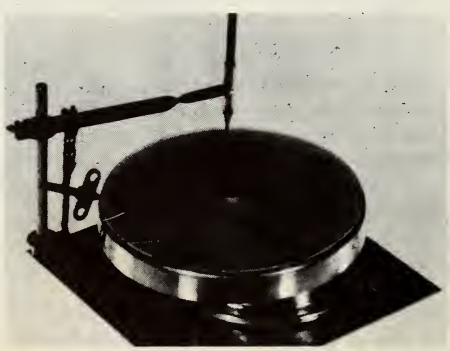


Fig. 5-25. The Taylor dew meter. After Taylor

Serious errors may be introduced by the differential characteristics between the plate surface and the ground surface under investigation. Moreover, it gives neither intensity nor duration of the dew deposit. The Taylor (1956) dew meter is designed for recording the duration of dew deposits and the starting time (Fig. 5-25). The depositing surface is made of a ground glass disc, 8" in diameter, with an emissivity value of approximately 0.9 in the infrared zone. It rests on a turntable, rotating once daily by a stem-wound clock mechanism. Dew deposition on the disc is comparable to that on foliage under similar placement. An indelible pencil touches the disc and makes a conspicuous line only when the glass is wet. This instrument has proved to be dependable and durable under field conditions.

Measurement of the rate of dew deposition describes the intensity as well as the total amount of deposition per unit time. The Craddock apparatus for measuring dewfall (Craddock, 1951) has been further developed by Jennings & Monteith (1954), and is known as the "sensitive recording dew-balance" (see schematic diagram as shown in Fig. 5-26). The 8" soil pan with a natural grass surface serves as the exposing surface. The soil pan is made of Paxolin, 11" in depth and 20 Kg in weight, inserted in a metal cylinder with a detachable base holding the soil's core. With the combination of mechanical and optical systems, an amount of 2 mg of dewfall per square centimeter can be detected by a photographic paper in a camera. During the day, the moisture is liable to condense on the colder parts of the balance, and

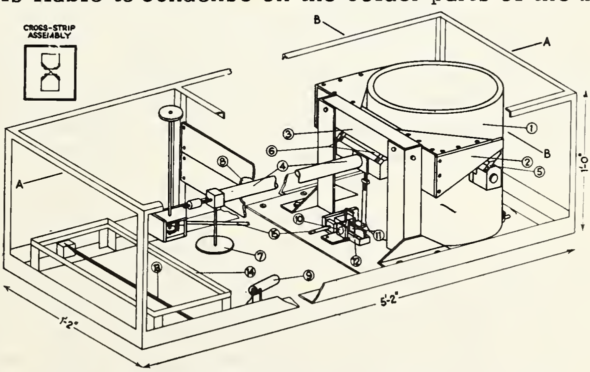


Fig. 5-26. A sensitive recording dew balance.

(1) soil-pan, (2) saddle, (3) bridge, (4) beam, (5) cross-springs for soil-pan suspension, (6) cross-springs suspended from bridge to support assembly of beam and soil-pan suspension, (7) platform for counterweight, (8) gate controlling light beam, (9) lamp, (10) lens, (11) rotatable mirror to receive slit-image from lens, (12) dash-pot for mirror, (13) mirror in camera section reflects light upwards, (14) camera box, (15) control to rotate suspended mirror for placement of light spot.

After Jennings & Monteith. Reproduced with permission of the Quarterly Journal of the Royal Meteorological Society.

care must be taken to remove the condensed moisture before operation. At night, however, the balance is warmer than the surface air and there is no condensation deposit on the balance, except on the surface of the soil pan. The advantages of this instrument are that it measures dew on the natural surface, it has high sensitivity, and it provides a continuous record of condensation or evapotranspiration, depending upon the synoptic conditions. Its high price, and the skill required in handling are considered as disadvantages.

Morris' weighing machine for evapotranspiration and dewfall is somewhat similar to Jennings & Monteith's "sensitive recording dew-balance," but much larger in size (Morris, 1959). It is self-balancing and produces a continuous record of small changes in a large quantity of soil (up to 2600 Kg), with alternative chart range of 1, $5\frac{1}{2}$, and 10 Kg, and an accuracy of 5 g. The soil container is 20" deep and permits the planting of several horticultural crops other than shallow-rooted grass used for the sensitive dew-balance.

Some valuable contributions to dew measurement other than those mentioned above are Duvdevani's (1947) design on optical dew gauges, Masson's (1948) atmospheric condensation measurement, and Gelbke's (1952) investigation on the electric dew recorder.

5.4.6 *Hail*

In view of their economic importance, measurements of hailstorm and hailstone are worth mentioning. Hail forecasting is considered in Section 9.3.3, and protection against hail is discussed in Section 12.4.1. A balance is used for measuring the weight, and a caliper for size and shape. The density (or intensity) of hail is generally estimated by actual count of the number of hailstones per unit area, and is sometimes estimated by the degree of damage to crops and by means of radar echoing. An improved method for measuring hail intensity has been designed by Schleusener & Jennings (1960), the instrument being known as the hail indicator. It was developed to estimate hail energy input per unit area by means of dent size and number of dents per unit area on the indicator; in turn, an objective measure of hail intensity is secured. The indicator, as shown in Fig. 5-27, consists of a packet of light foil (i.e., heavy-duty household aluminum foil), heavy foil (i.e., QQ-A-561B, 2 SO aluminum coil sheet, mill finish), and styrofoam. A 6" × 6" × $\frac{1}{2}$" piece of styrofoam is used as the base of the indicator, over which a 2" × 6" piece of heavy foil is placed at one edge of the styrofoam. The two pieces are then covered and wrapped by a 10" square of the light aluminum foil. Several packets are placed on stands fastened to fence posts and protected from the wind by a masonite and wood cover having a 5" × 5" opening on top.

Such structures have been tested in the laboratory under three major assumptions: (a) that the hailstones are spherical, (b) that they have a density of 0.9 grams per square centimeter, and (c) that they are

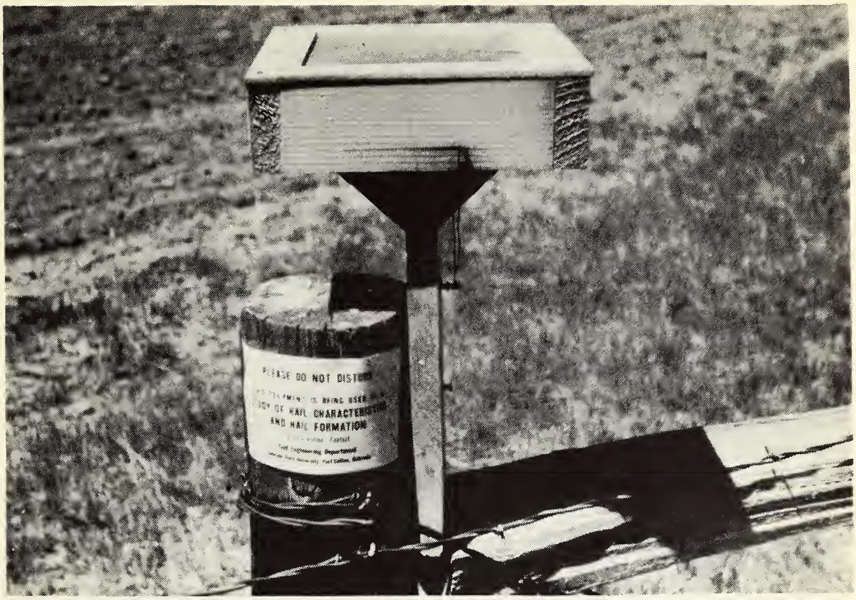


Fig. 5-27. Hail indicator. After Schleusener & Jennings

hard enough not to disintegrate upon impact. It is estimated that although the absolute error in estimating hail energy input may exceed 300%, the error in comparative measurements of hail energy input by this equipment is approximately 50%. Of course, this indicator is far from ideal and much improvement should be made. Nevertheless, it is simple and inexpensive to construct and maintain. It gives hail intensity values within acceptable limits of accuracy.

5.5 WIND FIELD

Wind and atmospheric pressure, the two most closely related factors, are dependent on one another. Of the two, measurements of air pressure at various levels are imperative in synoptic meteorology, and are one of the most discussed subjects in meteorological instrumentation. Three types of pressure instruments are generally used for the determination of atmospheric pressure: the mercury barometer, the elastic (or aneroid) barometer, and the hypsometer. In agrometeorology, this subject has been accorded little attention. Aside from the indirect relationship that pressure change has on weather, only a few applications have been made to plant growth (Shuck, 1931; Smith, 1906).

The problems in plant growth as related to low pressure at high altitudes are difficult to reconcile, because in such an environment the solar intensity usually is high, particularly the ultraviolet. The moisture and temperature are low, and the wind severe. The pressure-plant relationship is concealed and, therefore, this relationship can be investigated only in a completely controlled environment.

In view of the relative unimportance of the measurement of pressure in agrometeorology, no attempts are made here to describe such instruments. The reader may refer to Middleton & Spilhaus' textbook (1953) for further information.

5.5.1 *Horizontal wind*

The transfer of the air, including aerosols, depends upon the velocity of air movements through processes of diffusion, turbulence, and eddy transfer. The total movement of air during daylight and darkness influences insect flight, and is often a contributing factor in spreading spores and pathogens. Moreover, in estimating evapotranspiration by aerodynamic methods in the energy balance approach, a knowledge of wind profiles is necessary. Usually, several heights above ground are selected for the measurement of horizontal wind; they are 1, 2, 4, and 8 meters in height. The horizontal component of wind is customarily measured by various types of wind vanes for direction and by anemometers for speed. Usually, a sensitive wind vane can measure wind direction much more accurately than an anemometer can measure wind speed, particularly the low wind near the surface of the earth. It is a well-known fact that a rotation anemometer, such as the cup-anemometer (propeller or windmill anemometer), accelerates more rapidly than it will decelerate. Consequently, in fluctuating wind, it will indicate a velocity higher than the true value. This error will depend upon both aerodynamic characteristics and internal friction of the anemometer, and will vary from one instrument to another. This is particularly true with low level and weak wind. Various attempts at improvement have been made, including Thornthwaite's modified SCS cup-anemometer, Halstead's semi-cylindrical anemometer, the Sheppard type anemometer, Kassander's ping-pong ball anemometer, McGregor's (1960) transistor cup-anemometer, and Rider's (1960) sensitive cup-anemometer.

The Beckman & Whitley wind speed and direction recorder, shown in Fig. 5-28, is designed particularly for the study of the microclimatic environment, and displays an accuracy of $\pm 3\%$ for wind speed and $\pm 3°$ for wind direction. Two ranges of wind velocity can be selected for full scale on a six-inch-wide strip chart: 0 to 12 mph, and 0 to 30 mph. The time required for the recording pen to give a reading is approximately 1.25 seconds (or transient time upward), and 2.25 seconds (downward). When an extremely low-mass wind vane and a three-cup anemometer with a drag-free electronic transducer are used, the wind speed threshold becomes as low as 0.75 mph. This instrument can be operated on either AC or DC current.

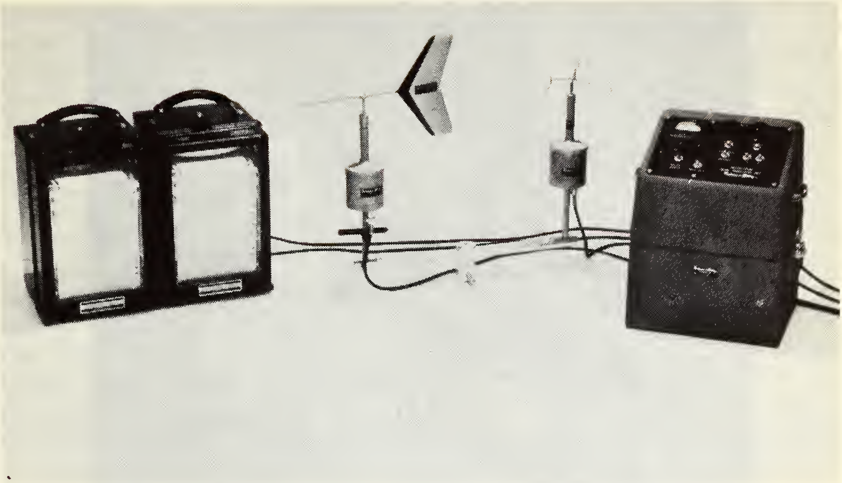


Fig. 5-28. Beckman & Whitley wind speed and direction recorder. (Courtesy of Beckman & Whitley, Inc., San Carlos, California)

5.5.2 *Vertical wind*

Although the vertical wind is important in microclimatology, in practice it is rarely measured. Suomi's sonic anemometer is designed to measure vertical wind according to the principle that sound traveling with the vertical air movement goes faster than against it. The transmitting and receiving head of the sonic anemometer are located 1.5 cm from each other, and the acoustic array of the path length is one meter. This is a delay type sonic anemometer, and the instrumental error is made as small as 0.002 meter per second. At present, it is largely restricted to laboratory use, and its adaptation for field operation is highly to be desired.

Following are some selected citations on wind instruments, as guides to the reader. In 1953, Ripken made a survey of measuring instruments for low-velocity wind. Suomi (1957b) and Thornthwaite et al. (1959) have made special contributions to the measurement of vertical wind. A fast-response anemometer for microclimatic studies was designed by Gill (1954). Walker & Westenberg (1956) made an absolute low-speed anemometer. Examples of anemometers making use of the cooling power of the air are Benseman & Hart's (1955) thermocouple anemometer, Deacon & Samuel's (1957) hot-wire anemometer, and Nottage's (1950) heated-thermocouple anemometer. In 1961, Henry et al. used a smoke-trail method for obtaining a detailed measurement of the vertical wind profile on a large scale. They measured photogrammetrically the successive positions of the trail of an ascending rocket.

Fig. 5-29. Illustration of laminar and turbulent flow.
(Photograph by Werner Wolff — Black Star)

5.5.3 *Turbulence*

The orderly flow of a fluid is known as "laminar flow," while the disorderly or complex random motion is called "turbulence," the latter characterized by irregularity and eddies. As shown in Fig. 5-29, the buoyant convection of cigarette smoke is laminar for some distance and becomes turbulent as a result of external disturbances. The turbulent process which governs horizontal and vertical heat, water-vapor, carbon dioxide, and momentum transfer explains various phenomena in the microenvironment. The degree of turbulence depends upon wind speed, thermal instability, and roughness of the earth's surface. Measurements of profile (wind, temperature, humidity, air composition, and aerosol) and fluctuations (temperature and wind) of the air, thermal flux, moisture content of the soil, and boundary stress of the ground are important to turbulence studies. Instruments such as the sonic anemometer (Suomi, 1957b), drag meter (Halstead & Ono, 1957), and modified SCS cup-anemometer (Thornthwaite & Halstead, 1957) have been used in the Great Plains Turbulence Field Program in O'Neill, Nebraska. For details, the reader may refer to ***Exploring the Atmosphere's First Mile***, Vol. I, ***Instrumentation and Data Evaluation***, by Lettau & Davidson (1957). Other turbulence instruments of interest are the turbulence recorder (Bunker & McCasland, 1954), shear stress meter (Vehrencamp, 1952), turbulence measuring equipment (Kovasznay, 1954), volumetric device on measurement of speed and turbulent pulsations (Ismailov & Shvartsman, 1958), and many others. Experimental basic research in turbulence has been projected by Corrsin (1961) as follows:

(a) The nature of laminar flow instability and the transition to turbulent flow;
(b) Energy spectra at higher Reynolds numbers;
(c) Direct determination of the spectral transfer function;
(d) Eulerian correlation functions for velocities at points separated in both space and time;
(e) Details on the effects of turbulent motion in homogeneous mixing in dispersion and in sound scattering.

These researches cover not only instrumentation, but also considerable theoretical background. For details on the theoretical approach, the reader may refer to ***Micrometeorology*** by Sutton (1953).

The implications of turbulence in the field of agriculture are many. One of the important field operations is spraying and dusting of chemicals. The dissemination of spores and pollen, the investigation of air pollution, the evaluation of soil moisture and evaporation, etc., are all dependent upon better knowledge of turbulent flow in the lower atmosphere. Since turbulence study is in the realm of micrometeorology, no attempts are made for further discussion here.

5.6 AIR, WATER, AND SOIL MEASUREMENTS

The horizontal and vertical distributions of air composition (or quality) which depend upon air movement, are of paramount importance to agriculture. Carbon dioxide and oxygen in the air and soil are the commonly measured components of air; however, the results of such observations have not been satisfactory. The conventional volumetric determination of carbon dioxide, for example, measures most of the gas from the pore space of the soil, but not much from the root zone.

To the best of our knowledge, the rate of carbon dioxide change in the root zone, which is overshadowed by the large quantity of carbon dioxide from the pore space, has not been measured. Other gases of agricultural significance are ammonia, nitric oxide, nitrous oxide, ozone, methane, etc. These gases, even in small amounts, have pathogenic effects on the growth and development of plants.

The quality of air is determined by the amount of foreign matter or aerosol in the atmosphere. Examples of foreign matter are smog, smoke, wind-blown dust, oceanic dust, meteoric dust, factory fumes, pollen, spores, and so forth.

The chemistry of air, soil, and water — and their measurements — are of paramount importance to agrometeorology. Since chemical properties of soil and water have been extensively discussed elsewhere by soil chemists, attention is placed on the discussion of air chemistry in this section. Moreover, the measurements of air are conducted mostly by special research experiments, and not in standard agrometeorological stations (see Section 5.8.2). Therefore, only a brief discussion of the subject will be presented.

5.6.1 *Carbon dioxide and other gases*

The infrared gas analyzer is designed for continuous measurement of carbon dioxide and other atmospheric gases with accuracy of about 0.3 parts per million. This instrument is highly effective for the study of carbon dioxide concentration at all levels above the ground, and thus is a valuable tool in agrometeorological research. In general, carbon dioxide in the air has been more successfully measured than that in the soil. Common techniques in determining the rate of carbon dioxide change consist mainly of pumping gases out of the pore space of soil. At present, there is no instrument for effective measurement of the rate of carbon dioxide change in the root zone.

For measuring the ozone concentration profile, the automatic chemical detector may be used. An early device which makes use of aqueous solutions of chemicals (Bowen & Regener, 1951) operates as follows: Ozone liberates free iodine from the 2% potassium iodide solution in distilled water to which a small amount of sodium thiosulfate has previously been added. This iodine is at first quickly bound by the sodium thiosulfate. As soon as the sodium thiosulfate is consumed, the free iodine appears in the chamber. It has a depolarizing effect upon the cathode of a small electrolytic cell consisting of two platinum wires at the top of the reaction chamber. When the free iodine appears in the solution, a current of 10^{-9} amp passes through the cell. Ozone density is taken in terms of 10^{-3} cm per Km as a function of time at four levels.

Recently, Regener developed a simpler and more effective "Chemiluminescent method" (1960). The device makes use of the luminescence of a dry substance in the presence of ozone. It not only determines the presence of ozone automatically and quantitatively, but is also capable of detecting minute concentrations of atmospheric ozone. It possesses very high sensitivity and instantaneous response. Since there are no liquid chemicals, this method can be used at extreme heights in the atmosphere, and is equally applicable to the continuous monitoring of ozone near the earth's surface. More recently, Regener has introduced Rhodamine B for ozone measurement, following a similar method with considerable changes in mechanism. Nevertheless, no publication is as yet available on this new development.

Some references on the measurement of carbon dioxide and other gases are Lehmann's (1931) measurements of carbon dioxide at several bioclimatic stations in the Lunz region, Thomas' (1933) automatic apparatus for continuous determination of CO_2 in the air, Huber's (1950) study of CO_2 gradient by means of infrared absorption recorder, Stott's (1957) sonic gas analyzer for measuring CO_2 in expired air. Fedotov (1956) used chemical means to determine the presence of nitrogen dioxide in the air. Gisclard et al. (1953) designed a simple device for air analysis. Turli͡un (1952) developed new instruments for the investigation of gas exchange in soils. Uhlíř & Kešner (1953) constructed a portable instrument for carbon dioxide measurement which used a titration technique and was suitable for field sampling.

5.6.2 *Water*

Almost all physical properties measured for air are observed for water also. In addition, surface water temperature, salinity, evaporation, water color, freezing and melting of ice, surface tension, and several other properties are measured. The techniques in measurement of physical properties of water are quite different from those for air. The reversing thermometer (see Section 5.3.3) is a good example. Chemical properties of water are much more easily and more accurately determined than those of air. In agricultural practice, the chemistry of irrigation water is a major concern. Other measurements are the physical and chemical properties in the water table and wells. In this respect, much work has been done in the Netherlands. Readers may refer to textbooks of oceanography for necessary information on such instrumentation.

5.6.3 *Soil*

The physical, chemical, and microbiological properties of soil have been listed in Section 2.1.1b. The measurements of soil temperature and moisture have been described in Sections 5.3.2 and 5.4.4. Other measurements such as soil erosion, runoff, penetration, pH values, etc., have been studied by soil physicists and chemists. These measurements are of importance to agrometeorologists.

5.6.4 *Air pollutants*

Various instruments have been devised for measuring air pollution. The deposit gauge, which is somewhat similar to the rain gauge, was designed by Owens as early as 1918. Since then, more refined deposit gauges have been designed, but their accuracies are questionable, due to the effects of wind, turbulence, and rainfall. Another instrument, the smoke filter, samples solid particles from the air by drawing a known volume of air through a filter paper by means of a pump; then the stained filter paper is examined by photometric methods. Other methods, such as the Ringelmann chart, sulfur dioxide apparatus, and ultraviolet daylight integrator, are also used for determining air pollutants.

There are enormous amounts of literature published on instrumentation for the study of atmospheric pollution. Davidson & Master (1941) designed automatic dust sampling and analyzing instruments. First & Silverman (1953) studied air sampling with membrane filters. May (1945) made the "cascade impactor" for sampling coarse aerosols, which was further improved by Brunetti, Magill & Sawer (1952). Zingg (1951) designed a portable wind tunnel and dust collector to evaluate erodibility of field surfaces. Adams, Dana & Koppe (1957) constructed a "universal" air pollutant analyzer, a sensitive, automatic, and integrated device which is desirable for field use. Dvorak & Chase (1951) designed a simple air-borne smoke densitometer.

5.7 PLANT AND ANIMAL MEASUREMENTS

Some descriptions of biological instruments are given here, under the headings (a) Plants, (b) Farm Animals, and (c) Insects and Diseases. In plants, measurements of physical properties, growth, and quality of organs are treated separately. Not much has been done in instrumentation for measuring plant organs under natural growing conditions, and subjective methods such as visual observation have been used for most measurements. Instruments for the measurement of quality of plant and animal organs have mostly been designed for food technology. Farm animal measurements belong to the field of animal physiology. Measurements on insects and diseases are done by entomologists and pathologists. Among various instruments employed in these areas, those which provide continuous records of living animal organs are of importance to agrometeorologists.

5.7.1 ***Plants***

(a) Measurement of the physical properties of plants. Among all available physical properties, the temperature and albedo of plants have been the most commonly observed. In the classical method, a grass-minimum thermometer (a spirit thermometer) is placed horizontally over the grassy area with its bulb just touching tops of grass blades. It is assumed that the thermometer has the same emissive property for temperature radiation as the grass. To obtain comparable results, it should be exposed near the middle of a large lawn. As far as convection, conduction, and radiation are concerned, the recordings thus obtained can be taken as the temperature of the grass blades, except for the occurrence of cooling by transpiration. When the thermometer is exposed at night, the record is fairly reliable.

Thermocouples, thermistors, and resistance thermometers which are very small in size are often used for measuring temperature of leaves, stems, roots, buds, and many other organs of plants, by inserting the sensing element into the organ. This will cause some minor injury to the plant organ and may affect the temperature observed. Instead of insertion, a close contact of the sensing element to the shaded portion of the plant organ may be a better way of measurement, depending upon the intension of the researcher: Is he interested in the plant surface temperature, or is he interested in measuring the temperature inside the plant body? The Albrecht resistance thermometer, for example, has been used by Mäde (1939) to measure surface temperatures by keeping the soldered junction of the thermocouple pressed against the leaf. This instrument is an automatic recording device, and an accuracy of 0.2°C can be obtained. For the determination of inside temperature, the utilization of isotopes may give satisfactory results without causing unnecessary injury to the plant. Much research is needed in this area.

Measuring the spectral distribution of light emitted by the crowns of plants appears to be an ideal method for securing average crown temperatues of a field. Improvements should also be made in this direction. The fluctuation of plant temperature is affected not only by techniques of measurement, but also by sensitivity of the particular sensing elements employed. It would be advisable to take the ambient air temperature of the plant at the same time the plant temperature is taken, for comparison.

As has been mentioned previously, the beam reflector would be a suitable tool for measuring reflected light, particularly when the instrument is placed above the crown of plants. Caution must be taken with regard to the shading effect of the beam reflector, and therefore the reflector should be placed at an appropriate distance above the crown. Kuhn & Suomi (1958) have made observations by placing this instrument on the wind of an airplane. Other measurements on physical properties of plants, such as transpiration of leaves, water movement, and content of plants, have been made by plant physiologists and botanists.

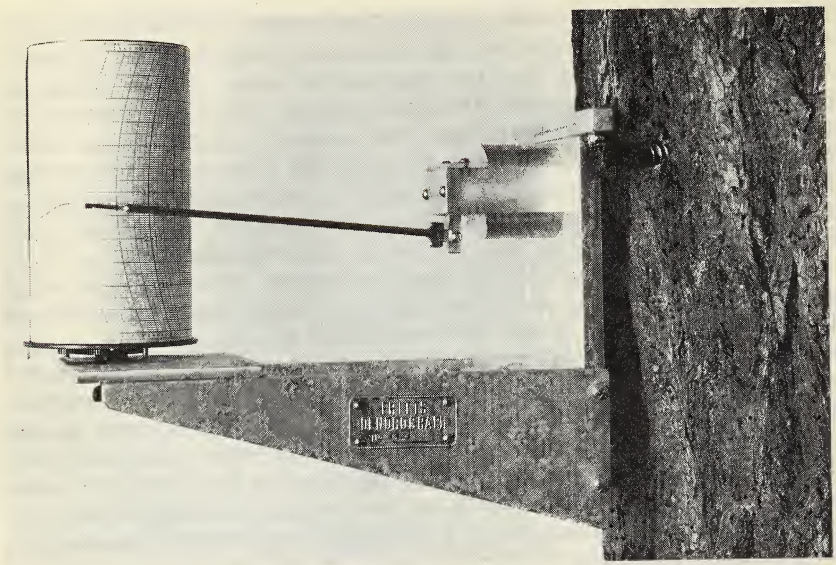


Fig. 5-30. Fritts dendograph. (Courtesy of M. A. Stokes, Laboratory of Tree Ring Research, Tucson, Arizona)

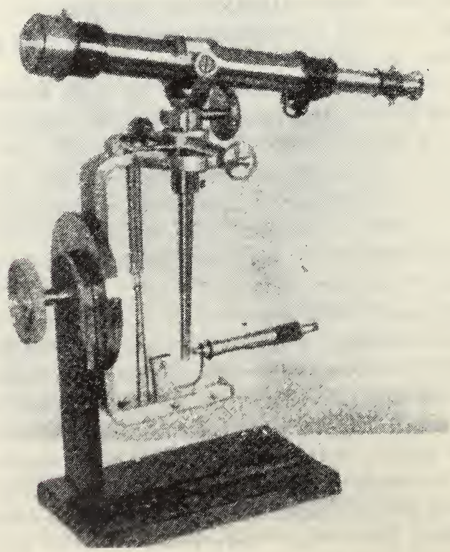


Fig. 5-31. Modified phenometer: After Kaempfert

(b) Measurement of growing plants. The measurement of plant parts or organs under natural growing conditions is most essential in agrometeorological instrumentation.

The diameter growth of a tree can be measured by calipers, tapes, or increment bars for the crude determination of growth. For measuring small amounts of growth over short time intervals, dendrometers and dendrographs are used. Among various types of dendrometers, the tree-ring band type is a useful one. It consists of an aluminum band which encircles the tree and is held firmly in place by a coil spring. The band is graduated in tenths of an inch and incorporates a vernier which permits readings of changes in circumference. The dendrometer is an inexpensive instrument with a fairly satisfactory degree of accuracy, and can be used to determine the growth of a large number of trees throughout the season. Its limitation is that one reading may not represent the true diameter growth of the tree (diameter increases may not be the same in different radii of the trunk). Therefore, when dendrometers are used, several radii should be selected at the same height above the ground to obtain the average value. Moreover, it provides growth data only at the time of observation.

The essential feature of the dendrograph is that the supporting frame is mounted by three screws driven into the xylem of the tree which serves as the reference for measurement, and the variations in the distance between the points of contact are magnified and recorded on a clock-driven drum. The early dendrograph was developed by MacDougal (1921), and several attempts at improvement have been made since. The new dendrograph, which is capable of detecting changes as small as 0.0001", was introduced by Fritts & Fritts (1955); see Fig. 5-30. The advantage of the dendrograph over the dendrometer is that it provides continuous and more precise records of tree growth; therefore, it is especially useful for microenvironmental studies. But it is much more expensive than the dendrometer.

Phenometry, the study of the measurement of growth as well as development of a plant or a specific phase of a plant, has been extensively pursued by German botanists. The instrument known as the phenometer, which is similar to a surveyor's transit, performs the measurement of plant parts when placed in the proper position. The modified phenometer designed by Kaempfert (1948) is shown in Fig. 5-31. It is able to measure the thickness of an object, e.g., a fruit in its natural condition. A long brass lever arm is set up vertically on its optical axis by a telescope of great light intensity. The end of the lever is placed in the clamp arm of a movable vise. The entire apparatus, including telescope and micrometer, can be rotated along the horizontal axis. The sight of the telescope through the cross-wire is adjusted so as to be tangent to one side of the object at a time. Thus, from the dial readings of the micrometer screw and the known distance of the lever arm as well as the distance between object and instrument, the thickness of the object can be determined accurately. This simple instrument is far better than a micrometer caliper or a vernier caliper, because it does not touch the object being measured. The German Weather Service at Trier has used phenometers for measuring the growth of rye, wheat, corn, flax, and several other agronomic crops.

For continuous registering of fruit size, both for enlargement and for shrinkage without interfering with the growth of the fruit itself, an ideal instrument known as the "Auxanograph" has been designed by Stenz (1962). The mechanism is somewhat similar to a thermograph equipped with a pen and drum for recording strip charts. The measuring vise consists of a poor heat conducting material. The jaws of the vise are firmly fastened to the bottom part of the instrument while the top is loosely fastened with a strip of light metal and is movable. Thus the growing fruits receive only a small amount of pressure and heat from the vise. This instrument can measure a fruit of any size up to five inches in diameter, with an accuracy of 0.02 mm. Harley & Masure (1938) also have made similar devices for measuring growing Winesap apples.

Various devices have been designed by horticulturists for the continuous measuring of potato tuber enlargement, the growth of cauliflower heads, and the like. Nevertheless, devices for the measurement of growing plants are far from sufficient and satisfactory at the present stage of development. Thus visual observation of phenological events with the aid of simple instruments (e.g., meterstick, caliper, weighing scale, etc.) is required. Examples of such observation are given in Tables 8-1 and 8-2. The reader may refer to Wang's (1962) Observational Manual of Vegetable Phenology, and to references in Chapter 6 for other crops.

(c) Measurement of the quality of plant organs. Quality measurements of crops are of importance to food technology in determining grades and standards of raw, canned, frozen, and dried products. The percentage of trash, defects, and maturity scores, for example, are determined by sampling techniques with the use of proper instrumentation. In agrometeorology, this information is useful in making a decision on field design (instrumentation and observation), studying crop response, forecasting crop quality, and controlling cultural practices for quality improvement. Consequently, the choice of significant elements and significant periods as well as the type of instruments is based upon the quality test. The word "quality" is a broad term, the specific meaning of which can only be defined by the user. It describes such characteristics of crops as colors, flavors, odors, textures, nutritive values, radiation preservation, and what-not. Only a few illustrations on the measurement of crop quality will be given here.

The tenderometer, designed in 1937, has been in use solely for the purpose of measuring tenderness of raw peas. It measures the combination of hardness and shearing force of the fresh seeds. A series of bars shears through a given mass of peas, and the resistance exerted by the peas is measured in terms of pounds per square inch. Various attempts have been made to use this instrument for other vegetables, but results have not been very satisfactory. A simpler and less expensive device for testing pea hardness in the field is known as the texturemeter, which is less accurate than the tenderometer. Operating on a puncture principle, it records the resistance on a hydraulic gauge. It has been found that the tenderometer gives a little over 1% error, while the expected error with the texturemeter is usually between 5 and 7%. The maturometer, designed by Lynch & Mitchell (1950) and used in Australia, is another instrument for the physical measurement of pea quality. The fibrometer (Wilder, 1948) has been used for measuring fibrousness of asparagus, and the succulometer (Kramer & Smith, 1946) for measuring maturity of raw and canned whole kernels of corn.

As far as physical means are concerned, the shear-press, designed by Kramer et al. in 1949 (Fig. 5-32) is a multiple-purpose instrument.

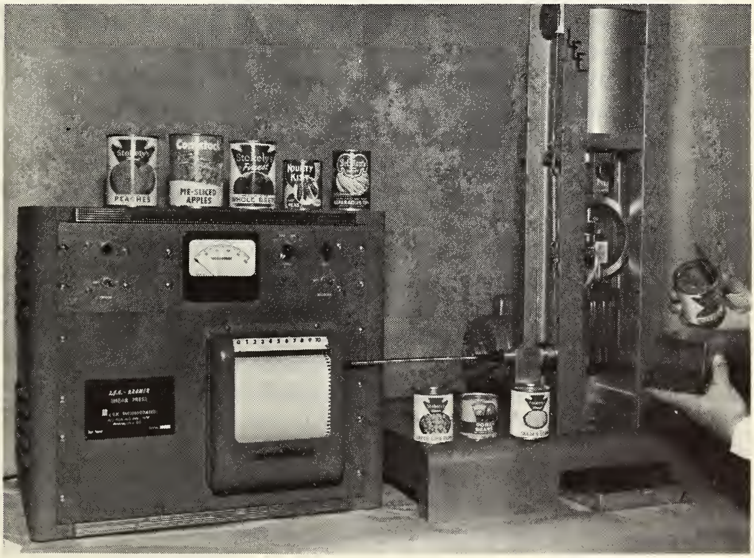


Fig. 5-32. Shear press.
(Courtesy of L. E. E. Incorporated, Washington, D. C.)

It consists of a test cell, a test cylinder, a power cylinder, a control valve, and an electrically operated pump as a source of hydraulic power. Different methods of applying force can be achieved by assembling the test cell differently. The force required to compress and shear the sample is measured by the compression of an appropriate proving ring dynamometer. A very good agreement has been found between maximum force values and the total work as measured by integrating the area under a time-force curve (Kramer, 1961; Decker et al., 1957). The shear-press, in spite of its cost, is also useful for determining the quality of a number of other vegetable crops by modifying the standard compression cell, e.g., for the measurement of firmness of onion bulbs (Ang et al., 1960), hardness of peas (Kramer & Aamlid, 1953), fibrousness of asparagus, juiciness of sweet corn and apples (Kramer & Smith, 1946), succulence of corn, and firmness of apples. Also, various modifications of the shear-press cell have been used commercially for maturity measurement of lima beans, green beans, beets, rice, peaches, tomatoes, asparagus, and other crops. Furthermore, it measures firmness and hardness of some meat and seafood, such as chicken, beef, and shrimp.

Aside from physical quality measurement, combinations of chemical and physical tests are used for determining such qualities as color, flavor, odor, and texture. As far as color is concerned, chemical treatment of products (such as extracting pigments from plants and then testing the color of extracts) followed by an optical test, has been employed. Nickerson (1946) made use of the Munsell color scale in grading a number of agricultural products, and Hunter (1952) has introduced the photoelectric tri-stimulus colorimeter with three filters for differentiating colors. Instruments such as the colorimeter, color-difference-meter, reflectometer, and glossmeter, have been used in grading raw cotton, tobacco leaves, etc. Applications of pure chemical testing are numerous. Alcoholic insoluble solid (AIS) is a good example in testing pea quality. Various analytic techniques in food chemistry, particularly in the area of biochemistry, have been introduced for determining composition of products. There is no end in listing all of the currently employed techniques. It should be pointed out that ease of handling and quick determination are essential features in instrumentation for quality testing.

5.7.2 *Farm animals*

Most available instruments for the measurement of animal organs and behavior under living conditions are used in shelters or stables. Some instruments are designed for the measurement of characteristics of the stable itself.

For determining the thermofield of poultry houses and stables, the resistance thermometer, thermocouple, and thermistor are again useful sensing devices to consider. For example, Williams & Thompson (1948) used a disc thermistor in a moulded plastic holder in order to obtain a continuous record of body temperature in man from the external auditory canal. Benjamin & Horvath (1949) mounted a 0.4 mm-diameter thermistor head, inserted in catheters through 19 hypodermic needles, for continuous measurement of temperature in human joints, or for the direct observation of intracardiac and intravascular temperatures. Drummeter & Fastie (1947) developed a field instrument for intravenous measurement of animal blood temperature in the vicinity of the heart, using a 1 mm-diameter thermistor head mounted on the end of a 5-French catheter. Kelly et al. (1949) used a butt-welded copper-constantan thermocouple of 30-gauge wires, with two 2-inch-long concentric shields having an inner diameter of ½'' and an outer diameter of 1'' for measuring air temperature of the stable at the animal level. The fine-wire thermocouple leads need to be only a few inches long, and can be soldered to larger wires to cut down the electrical resistance of the circuit. The inner shield should maintain a minimum of ½'' diameter because a small shield would slow down air flow and, in turn, reduce the rate of heat transfer by convection between the thermocouple and the air.

Cooling power (a measure of the cooling effect of the air upon an animal body) is determined by the amount of heat required by an instrument to maintain a constant temperature, usually 34°C. Instruments for the measurement of cooling power include the frigorimeter, katathermometer, and coolometer. The frigorimeter is often used to measure the physiological cooling power in milligram-calories. It consists of a black copper sphere with a diameter of 7.5 cm, the surface of which is electrically maintained at 33°C against heat losses from change in climate of the stable. One type of katathermometer, known as the liquid-in-glass thermometer, has two calibration markers on the surface of the thermometer stem corresponding to 38°C and 35°C. The thermometer is heated to 40°C and the time required for the column to fall from 38°C to 35°C is measured by a stop watch. It is suitable for use in a stable where the wind speed is low. With high wind speed, the temperature change will be too fast for an accurate time reading. The mechanism of this instrument is based on the principle that the time constant of the thermometer is a function of wind speed or ventilation. The hot-wire anemometer is another type of katathermometer, operating on the principle that the heat transfer to air from the heated object is a function of wind speed. The coolometer functions on the same principle as the hot-wire anemometer. These instruments would be more useful if they were designed to provide a continuous record.

Instruments for animal shelter research have been suggested and used by Kelly et al. (1949) as follows: thermocouple and heat flow meter (for measuring air temperature); flat-plate radiometer and globe thermometer (for measuring radiation as determined by surface color and structure of the stable); Hardy dermal radiometer (for measuring surface emissive power); and thermoelectric psychrometer (for measuring air humidity). Their suggestions on instrumentation for animal shelter are significant.

5.7.3 *Insects and diseases*

Essentially, this area of study belongs to the realm of entomology and plant and animal pathology. The majority of available instruments for the study of insects and diseases are samplers or catchers. The blacklight fluorescent insect trap is a good example of the insect catcher, and the portable volumetric spore trap is a disease sampler.

Blacklight insect traps of different designs are commonly used by entomologists to trap adults of many responsive night-flying species. The range of wavelength adopted for this type of instrument varies from 3200 to 4000 Å. Trapping objectives may, in part, influence trap design, but blacklight fluorescent tube-type lamps (Fig. 5-33), with their holders, starters, and ballasts, are basic to design. It induces

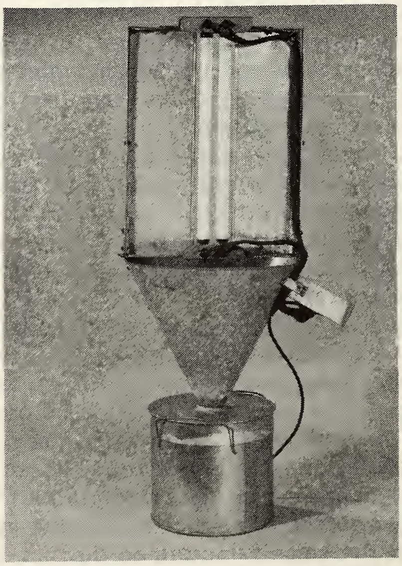


Fig. 5-33. Blacklight fluorescent tube-type insect trap.
(Courtesy of J. W. Apple, Dept. of Entomology, University of Wisconsin, Madison)

satisfactory insect response to the blacklight spectrum, and the fluorescent lamps serve as most efficient sources of sensitive light for insects. Simple and effective trap designs have lamps mounted vertically in the center of a baffle. A large number of insects flying to the blacklight hit a baffle and then drop into a funnel around the base of the lamp. A container beneath the funnel serves as an insect collector. In the collector, an inverted funnel screened over its largest diameter allows rain to pass through while the insects are retained. With canopies over the traps, the expense of a rain funnel can be avoided. Traps with lamps of the greatest wattages, nonreflective surfaces, and without top canopies have the largest insect catches. Considerable catches can be obtained from a 15-watt blacklight trap with a top canopy, but a 6-watt trap provides comparable results. Catches in blacklight insect traps are excellent for correlating biological events with weather. There is no ideal insect trap which will indicate the natural distribution of the insect population of a specific locality. This also holds true for blacklight insect traps. Their specific limitations are: they do not catch those insects not responding to this type of radiation; they are used only at night; and the amount of the catch is affected by the direction, location, and height of the trap.

A coprometer is used to collect frass ejected by insects through a given interval of time. Usually, hourly collections are made. A new type of coprometer for both laboratory and field uses was designed by Green & Henson (1953), and has been further modified by Green & Defreitas (1955). This is shown in Fig. 5-34. On the basis of several years of observation, it was proved that their apparatus gave an excellent service. The information obtained from the use of this instrument will determine the relationship between the feeding rates and the weather condition, and in turn, an estimate of insect population can be made. This is a highly reliable instrument, with timing error of 1 minute per 12 hours of frass collection, but should there be rain, it fails to function.

5.8 AGROMETEOROLOGICAL STATION

Some essential requirements for establishing an agrometeorological station or agricultural weather station, particularly for the study of crops, are: (a) that the site be representative of general crop climatic conditions; (b) that the choice of instruments be made carefully in order to obtain useful information (this involves the size of the station); (c) that the instruments on the site be correctly placed, so as to secure a good exposure (this includes methods of instrument installation); (d) that maintenance of the station be properly founded (this includes the ability of the observer and the technique of observation);

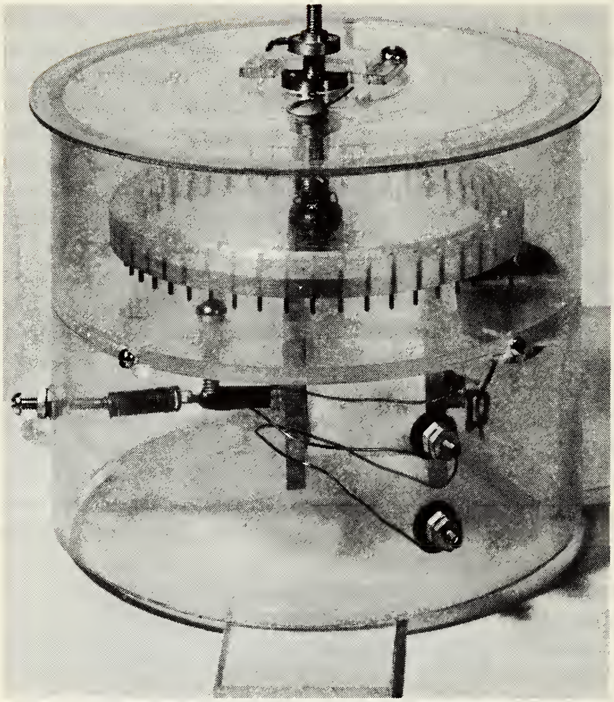


Fig. 5-34. A new type of coprometer. After Green & Defreitas

and (e) that the communication be well established to maintain an accurate and efficient data collection and processing (this includes recording, transmission, telemetering, teletyping or shortwave radio, and electronic computation).

The classical rules in observational site selection for climatological purposes can be summarized as follows: the observational plot should be located on a level grass lawn away from any obstructions (trees, fences, buildings, etc.); the plot should be at a distance at least twice (preferably four times) the height of any obstruction. Thus. the plot will receive an unobstructed flow of air, unintercepted rainfall, and not much shaded sunshine. These criteria might be applicable to operational uses in agrometeorology, depending upon the purpose. The ideal site for an agrometeorological station is that which represents the crop area under investigation. Therefore, it can be over a paddy rice field, in and above a sugar cane plantation, or within a pea patch. It does not matter whether the plot is located on a steep slope or flat ground. It depends solely upon the specific purpose of investigation.

The installation or placement of instruments on the site can be on a mast, in a weather shelter, on or beneath the ground surface. The height of the instrument above or below the ground, and the direction or orientation of the sensing element should be specified according to the type of instrument and the purpose of investigation. This is essentially a problem of exposure, and some of it has been covered in previous sections, in connection with each individual type of instrument.

At the present time, most of the weather service stations are not suited for agricultural purposes. Some are inadequately equipped in number and type of instruments, while others are located at improper sites. For example, the U. S. Weather Bureau's Cooperative Stations are installed with maximum and minimum thermometers and a USWB standard rain gauge; hence the type of observation (one level of temperature and three daily readings[3]) does not provide satisfactory data for agrometeorological purposes. Also, some stations are equipped with instruments suited only for the investigation of the upper air. The first class Weather Bureau stations are usually located at airports with most of the instruments exposed on the roof of the building. The cement roof does not represent the crop field, and the results of such observations are of little significance to the agrometeorologist. Moreover, many upper air instruments, such as the radiosonde, pilot balloon, and ceilometer, have little direct use in agrometeorology.

According to the class and size of an agricultural weather station, instrument packages for physical measurements can be classified into three categories: (1) the minimum requirement; (2) the standard requirement; and (3) the optimal requirement. This classification is based mainly upon the economy of both instrument installation and maintenance. The minimum requirement is the most economical, and does not require extensively trained observers. The standard requirement involves much more expense, and professional observers are needed. It is recommended for most agrometeorological research. The optimal requirement is the "ideal" up to date, and used only for basic research in agrometeorology. The type of station for each of the above categories may be called cooperative, standard, and experimental research stations, respectively. A list of instruments recommended for each station is given in the following section.

5.8.1 *Cooperative stations*

In the cooperative station, a set of instruments is used as a supplement to, or in reference to an agrometeorological network, or in

[3]The maximum, minimum, and current temperature at time of observation.

preliminary research for a first approximation. The instruments recommended are: (a) U.S. Weather Bureau standard maximum and minimum thermometers, (b) Max-Min dew-point hygrometer, (c) U. S. Weather Bureau standard rain gauge, (d) Palmer maximum and minimum soil thermometer, (e) U. S. Weather Bureau standard evaporation pan, (f) Bellani atmometer, (g) Campbell-Stokes sunshine recorder, and (h) U.S. Weather Bureau standard weather shelter. The above instruments are observed visually once daily. The wind velocity recorder is excluded from the above list because measurements taken at nearby regular weather stations can be used without introducing objectionable error for the study of large geographical areas. Items (a) and (b) should be used at two levels, one located next to the ground, the other at the top of the crown of the crop. The height of these instruments depends upon the type of crop under investigation.

5.8.2 *Standard stations*

In a standard station, the package is designed for recording most environmental elements automatically and continuously, without the use of visual observation. The recommended instruments are: (a) blacklight insect trap, (b) Taylor's dew meter, (c) Beckman & Whitley net-exchange radiometer, (d) thermocouple (thermistors) sensors at two levels, (e) Max-Min dew-point hygrometer at two levels, (f) Suomi & Tanner's soil temperature integrator, (g) tube weighing lysimeter, (h) Beckman & Whitley wind speed and direction recorder, and (i) recording rain and snow gauge (USWB type). Over half of the above instruments are electronically transmitted.

5.8.3 *Experimental research station*

The package in this station is designed for an ideal and basic research program in agrometeorology. The choice of instruments is, of course, dependent upon the purpose of the research; however, some recommendations are: (a) Taylor's dew meter, (b) sensitive recording dew-balance, (c) Beckman & Whitley net-exchange radiometer, (d) Beckman & Whitley total-hemispherical thermal radiometer, (e) thermocouple (thermistors) sensors at three levels, (f) infrared hygrometer, (g) neutron moisture meter, (h) tube weighing lysimeter, (i) Thornthwaite cup-anemometer, (j) recording rain and snow gauge (USWB type), (k) blacklight insect trap, (l) infrared gas analyzer, (m) Suomi & Tanner's soil temperature integrator, (n) spectrobolometer, and (o) others (aerosols, radiational fallout, ozone, etc.). Electronic transmitting devices are used for the above instruments, with the exception of items (j) and (k). Also, the use of the magnetic tape recorder is advised. In other words, the whole system, from input (sensing device) to output (computer), must eliminate human error as much as possible.

5.8.4 *Communication*

The word "communication" may here be defined as the transformation of sensor output into numerical data of a desirable form, including collection and compilation of widely dispersed observations over a large geographic area. In general, the electronic signal from the sensor is not suitable for transmission by wire or radio. The use of teletype involves several procedures in order to reach the final desired form: signals→strip chart→numerical interpretation→codes→teletype. This type of communication system is not very satisfactory because it contains drawbacks such as the possibility of bias introduced by the human factor, inefficiency, and the expense involved. For a large network with a great deal of data, for remote sensing, and for continuous data processing, various automatic computors have been introduced. Detailed descriptions of various systems are beyond the scope of this text. Some references on the subject are given at the end of the chapter, including Bellamy (1957, 1961), Ridenour (1955), Cook Research Laboratories, and Suomi & Parent (1961).

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CHAPTER 6

Phenology and Seasonal Changes

6.1 SCOPE OF PHENOLOGICAL STUDIES

Phenology is the science which relates climate to periodic events in plant and animal life. In other words, it is the study of recurrent phenomena of life and their relations to weather and climate that constitutes the science of phenology. A periodic event refers to a detectable or undetectable (latent) pattern of the life-cycle, unique to a specific plant or animal. Detectable events refer to those which can be seen by the eye or measured by instruments without causing injury to individual organs. They are, for example, budding, leafing, flowering, setting, and ripening of fruits, and coloring and falling of leaves of trees. Also, such events as breeding, grazing, migration, hibernation, and lactation are detectable in the life-cycles of animals. For insects, they are first larva, first appearance, first attack, and hibernation. Latent events are those which can be neither observed by the naked eye, nor measured directly by instruments, but may be detected by anatomical and biochemical means. Subterranean ears and the formative stage of sweet corn, germination, floral primordia, grand vegetative growth stage, and root development of plants as well as puberty and insemination of animals are examples of undetectable events. In short, phenology, known as the science of appearance[1], deals with the sequence of significant seasonal events in the biosphere and the atmosphere. In observing these events, emphasis is placed on the date of occurrence, such as the arrival date of birds, the earliness of blossoming, and the time of maturation of the crop.

When phenology is applied to the study of birds, it is called ***aviphenology***; of insects, ***insect phenology***; of animals, ***zoo-*** or ***animal phenology***; of plants, ***phytophenology***; of tropical plants, ***tropical phenology***; of climatology, ***regional-*** or ***climatological phenology***;

[1]The word "phenology" was first defined by Charles Morren in 1853, though the concept was brought forth by Karl von Linné in 1751.

and in studying the blossoming date of plants, ***floral phenology***. In relation to agriculture it is called ***agrophenology***, which we emphasize in this chapter.

The first description of phenological events was recorded in the Old Testament of the Bible[2] about 1014 B.C. Man has since frequently recorded phenological phenomena in mythology, weather-lore, poetry, songs, and literature. The search for the order, meaning, and application of these seasonal events was already under way in ancient civilization. Recognizing the relation of plant life events in agriculture to astronomical phenomena, Athenian astronomers correlated such phenomena with weather changes and constructed the phenological calendar.[3] In China, the phenological calendar was introduced during the Han Dynasty, about 2500 years ago, and has been widely adopted by farmers throughout that country.[4] Also, in Rome, Caesar (100-44 B.C.) is said to have issued a calendar of phenological events which was used by farmers.

Phenological study in the modern scientific sense is a fairly recent development. The methods and purpose of phenological observations were first set forth by a Swedish naturalist, Karl von Linné, the author of the well-known book ***Philosophia Botanica***, 1751. In his book, he suggested the construction of a local phenological calendar based upon the observation of various seasonal events of plants so that the variation of geographical areas could be distinguished. Between 1750 and 1752 he established a network of 18 stations in Sweden. His regional phenological investigations, together with his calendar, established the basis of modern phenological studies.[5]

In 1780, the first international phenological network was established in Europe by the Meteorological Society of Mannheim in Germany, and their data were published between 1781 and 1792. The Belgian phenologist Quetelet (1839) issued instructions for phenological observations which were regularly used in 80 areas throughout Belgium, the Netherlands, Italy, France, England, and Switzerland. During the period 1841 to 1872, he collected all the results of the observations. Since then, phenological observations have gained world-wide recognition, largely on a regional basis. The standardi-

[2]See Solomon, Chapter 2, verses 11-13. Also, there are many weather prophecies recorded in the Book of Job in the Old Testament.

[3]S. Günther, 1895, ***Die Phaenologie*** (Phenology).

[4]Cochin Chu, 1937, About the phenological new calendar, ***Science***, China, 15 (3) : 334-339. The calendar was written by the first emperor of the Han Dynasty.

[5]Although the world's first phenological station was set up by the Kraków Academy of Poland in 1490 and observations were carried out for several years afterward, Linné is generally recognized as the earliest authority of modern phenology.

zation of universal phenological observations began at the first International Conference of Phenology in 1935 in Danzig under the auspices of the Commission for Agricultural Meteorology of the International Meteorological Organization (IMO), which is presently called the World Meteorological Organization (WMO) of the United Nations. The second conference was held in Toronto, Canada, in 1947, and the third in Paris in 1953. These conferences led to the establishment of more stations and the achievement of greater uniformity in observations.

A brief review of the development of phenology in various countries is in order.

(1) Germany. In 1853, Karl Fritsch made significant contributions by introducing *An Instruction for Vegetative Observation*, and by encouraging European countries to develop phenological organizations and research. Martius and von Schübler also contributed to phenological observations of the early days.

During the period 1882 to 1941, Hoffmann, and later his student Ihne, made various phenological maps for Central Europe. They analyzed the occurrence of first leafing, first blossoming, first fruit-ripening and foliage color of over 30 types of plants in more than 100 stations in Europe. Their work on the phenology of plant form and of plant protection, particularly Ihne's work on regional phenology, is recognized as a highly valuable service to agricultural management.

The Federal Phenological Service in Germany started a phenological network in 1922. This network was enlarged steadily, and by 1939 about 10,000 workers were engaged in this work throughout Germany. Their research embraces the phenology of native and cultivated plants, such as fruits, vines, and weeds, as well as plant pathological studies. Between 1945 and 1952, a phenological service was established in West Germany under the German Weather Service. The *Instructions for Phenological Observations* prepared by the Weather Service in 1952 covers events of 240 plants and about 30 birds, insects, and other animals. Since 1953 a separate phenological service in East Germany has been organized. The phenological data are published every year in the *Meteorological Yearbook* . To date, they have fairly unified phenological observations for both West and Central Germany.

In 1955, Schnelle published a book entitled *Plant Phenology* . This is one of the most comprehensive and systematic treatises on plant phenology available. An attempt is made to present the subject in a manner that stresses precision of observations and their amenability to quantitative treatment. One of the best references on phenological history of Germany is that by Morgen.[6]

[6]A. Morgen, 1951, *Beiträge zur Geschichte der Phänologie zum zweihundertsten Jahr ihrer Begründung* (Contributions to the history of phenology on the 200th year of its beginning), Angew. Meteorol., Berlin, 1 (2): 36-43.

(2) Poland. In this predominantly agricultural country, the establishment of the first European phenological station in the vicinity of Kraków in 1490 for observations on the date of blossoming and fruit-setting of a few selected plants marks the beginning of Polish phenology. The observations at this station were discontinued after a number of years. From the year 1865 on, the Warsaw Botanical Gardens conducted studies on bird migration, wild plants, and forests. Between 1892 and 1924, Polish phenologists such as Wierzba and Wierdak contributed much to the observations of both native and cultivated plants. In 1924, the first phenological research was organized by the Union of Agricultural Research Centers. In 1931, this organization, in collaboration with the Minister of Agriculture, sponsored a publication entitled *Instruction for Making Phenological Observations*. Since 1949, Poland has maintained 2,000 cooperative stations for observations on the blossoming of native plants during spring and autumn. In the last decade, Molga has contributed much to agrophenological research. A pocket phenological atlas was put out by the Polish Panstwowýa Instytut Hydrologicno-Meteorologiczny in 1950, containing a list of 23 plants and 6 birds as indicators for observations. This atlas fulfills one of the recommendations made by the Commission of Agricultural Meteorology of the International Meteorological Organization. In 1955, with more items for observation, a teletype phenological code was introduced for ease of communication among some 700 phenological stations. From 1958 on, Polish phenologists have made some improvement on crop forecasting and instrumentation, especially with an emphasis on agricultural applications. In 1960, Borowski reported some phenological observations from Bialowieza.

(3) Scandinavian Countries. (a) In Finland, the Finnish Academy of Science has been publishing phenological data since 1896. Recently, Johansson (1951-1954) put out a series of papers, covering 200 years (1750-1950) of Finnish phenological observations, where a complete history of the development of phenology in Finland is cited and all important successions of observations and their results are included. Discussion on the recent microclimatological and comparative local phenological observations as well as the relationships between phenological and meteorological factors are included in this series. Lehtoranta (1951) presented a valuable study on the spring characteristics of starlings in Finland for the period 1785 to 1930. Erkamo's work (1951) on synphenological observations[7] has brought some progress in floral phenology.

(b) In Sweden, Linné, as was mentioned earlier, directed the first network of 18 phenological stations for the period 1750 to 1752. With

[7]The recurrence of events in the study of an individual and a group of plants is synphenology.

this as a precedent, all subsequent phenological programs in many countries for the first 25 years of the nineteenth century developed. However, regular phenological observations began in 1873 under the leadership of Hildebrandson. From 1881 on, the observations were conducted by the Central Meteorological Institute of Stockholm. Beazeley (1880) studied some phenological events with the turn of the seasons. Arnell et al. in 1930 presented a paper on the yearly course of vegetable development in Sweden.

(c) Norwegian phenological observations had been conducted and reported as early as 1843 by Printz and later by Schübeler in Oslo and vicinity. The lengthy observations concerning the dates of flowering for native and garden plants at Stavanger for the years 1897 to 1926 were published by Moe in 1928. Since 1950, a special network organized by Lauscher has been leading the country to a more extensive phenological observation and reporting service. Recently, two volumes on the *Phenology of Norway* were presented by Lauscher & Printz, including numerous tables of carefully evaluated data for a dense station network and discussions of phenological seasons, along with comparisons between Scandinavian and Alpine phenology.

(4) Great Britain. This country has a long history of phenological observations. An early contribution to British phenology is found in the outstanding continuous records made by the Marsham family for the period of 190 years up to 1925. Their observation is still continued to date. The observations were initiated in 1736 by F. R. S. Marsham and carried through five generations in the vicinity of Norwich. Phenological events recorded in the reports are: Flowering of snowdrop, wood anemone, hawthorn, and turnip; leafing of hawthorn, sycamore, birch, elm, mountain ash, oak, beech, horse-chestnut, hornbeam, ash, lime, and maple; migration of swallows, cuckoos, nightingales; appearance of yellow butterflies; croaking of frogs and toads; singing of thrushes; cooing of ring-doves; and nest-building of rooks. This long record was summarized in Margary's report in 1926.

Other continuous phenological observations are those conducted by the Royal Meteorological Society from 1875 to 1948, of which the results from observations of various wild plants in the British Isles have been regularly published in the Quarterly Journal of the Society. This journal continued to grow in volume until 1940, with the maximum increase observed between 1930 and 1939.

Of the British scientists in the field of phenology, the names of J. E. Clark, C. J. P. Cave, H. B. Adams, R. H. Hooker, R. Marshall, E. Mawley, H. C. Gunton, and I. D. Margary appear as responsible personnel on the phenological reports in the Royal Meteorological Society's Journal. In 1926, Clark presented a report concerning the importance of establishing an international phenological network for collaboration between all countries. Also, his study on phenology and extreme weather conditions was reported in 1932. And in 1936, he reported a historical survey of British phenology for the period 1875-1935.

In 1919 and 1920, comparative studies on crop-cycles in the United Kingdom, the United States, and France were made by H. L. Moore. H.C. Gunton had been responsible for findings of phenological observations between 1935 and 1940. In 1938, H.F. Smith presented a valuable statistical study of the correlation between phenological plants, and temperature, rainfall, etc.

In addition to the observations conducted by the Royal Meteorological Society, individual phenological investigations for recent years have been concerned with ovservations on various farm crops, hay-fever plants, potato blight, woodlands, locusts and grasshoppers, soaring birds and dragonflies, and bird migrations. In summary, excellent continuous records rather than research have been the contribution of Great Britain.

(5) Other European Countries. European countries other than those mentioned earlier are Austria, Czechoslovakia, the Netherlands, Belgium, France, Spain, Switzerland, Italy, Yugoslavia, Hungary, Greece, etc. Among them, Italy, the Netherlands, and Austria have done comparatively more in phenological studies.

(a) In the Netherlands, a few observations on native plants have been conducted since 1855. More comprehensive, better organized observations were initiated in the years 1879-1880, as shown in the Dutch Meteorological Yearbook. Köppen in 1890 put out a paper called "The Regular Calendar for Plants and Animals for the Netherlands." The Dutch Phenological Society operated a small observation network and their results were published annually. Woudenberg's (1953) paper on "Rapport on Progress in Agricultural Meteorology in the Netherlands for the Period 1947-1952" included various phenological activities. Around 1955, the Dutch Society for Agricultural Science established a Department of Ecology and Phenology, and the Royal Netherlands Meteorological Institute in De Bilt has considerably expanded the program of phenological observations. Native plants, fruit trees, cultivated plants, animals, birds, and insects have been observed regularly. Various forms for phenological observations have been issued and the following phenological events observed: For bird migration, such as swallows, the number of nests, the first seen, and the birds' singing are recorded. Observations of plants include rye, wheat, oats, corn, peas, beans, flax, and seed cabbage, and such items as first fruit setting, dates of planting, emergence, tasseling, flowering, ripening, and harvesting; type of ripening and its uniformity are covered accordingly. Other recent observations on apples, plums, cherries, strawberries, and pears are mainly on the various phases of leaf and floral development. Bijhouwer's findings on the periodicity of apple blossoms were published in 1924. Observations on woody perennials, herbaceous native plants, and fruit trees in various seasons include leafing, curvature of leaves, and flowering. An increasing amount of detail is being made on the farming calendar and disease incidence in connection with wireless weather forecast and broadcasting of farming advice.

(b) In Italy, Minio (1926) published phenological data collected from several stations since 1922. Contributions to the phenological study of grapevines in Italy were made by De Gasperi (1934). In recent years, Marcello, a synphenologist, presented a large number of phenological reports concerning the phenological rhythmic pattern of the whole plant world (1947, 1954). Azzi (1956), an agricultural ecologist, made observations for years on many kinds of crops and discussed their application in agricultural operations. Zanon's twenty years' record of observations on pomegranates and seven years' observations on English yew were introduced in 1952.

(c) In Austria, after the initiation of phenological studies by the famous phenologist Karl von Fritschen (1827–1881), Rosenkranz (1940, 1953) has done almost all of the compilation and research work in this field. Werneck, in 1937, published the first phenological report for the period 1926–1930. In 1928, the National Phenological Service collaborated with the Central Institute of Meteorology and Geodynamics in Vienna. Rosenkranz's first report was a result of the first ten years' observations (1928–1937). After the war, he presented several phenological reports and research. In 1951, he published a book entitled *Outline of Phenology*, in which a special treatment was given to phenological characteristics in Austria. His research covers both native and cultivated plants, such as snowdrop, anemone, and summer oats.

(d) In Yugoslavia, phenological observations were started in Croatia in 1946. In 1951, a network was organized by the Agrometeorological Service and extensive phenological reports, on both a nationwide and provincial basis, have been published.

(e) In Greece, phenological observations have been made only on native plants and fruit crops of the Mediterranean type.

(f) Switzerland, in 1951, established an observational network under the Central Meteorological Institute in Zürich. In 1940 Bider published meteorological observations for the period 1936–1938.

(g) In Spain, the climatological section of the National Meteorological Service established a well organized phenological service in 1942, and regular reports have been issued since then. The early reports were compiled by Compmany (1936), and later reports by Diaz (1942). Blázquez (1950) analyzed isophenes and isolines in Spain. In 1958, the Climatology Division of the National Meteorological

Service put out a *Meteorological-Phenological Calendar* as a handbook for observers. In it, the role and goal of phenology, instructions for making observations, and lists of plants (both native and cultivated) and animals (birds and insects) adopted for observations in Spain are given, in addition to graphs and maps containing information on various weather elements during the agricultural seasons of 1956 and 1957.

(h) In Czechoslovakia, a well organized phenological service was started in 1925. Between 1923 and 1938, Novák & Šimek compiled a *Phenological Yearbook* particularly for Silesia and Moravia. Czechoslovakian phenologists displayed strong interests in agrophenology and aviphenology. Some more recent publications include Minář's study (1944) on the length of the vegetative period for 33 stations in the protectorate of Bohemia and Moravia, emphasizing altitudinal influences on vegetative periods, Rudkovskij's study (1950) of the importance of birds in their natural surroundings, Brablec's determination of environmental requirements of rice at various phasic developments with special attention to frost damage. In Brablec's work, areas suitable for rice cultivation were explored and the possibility of growing cotton was suggested. Kurpelová (1960) summarized phenological observations in Slovakia during 1924-1958. Phenological reports for the years 1938-1951 were published in the *Phenological Yearbook* put out by the Hydrometeorological Office between 1953 and 1959.

(i) In Belgium, phenological observations outside Brussels were begun only recently, although Quetelet (1841-1872) had once led European observations. From 1947 on, Lardinois prepared reports for a number of years. In 1950, he reported observations on the flowering dates of trees at Uccle for the period 1901 to 1930.

(j) In France, the first phenological report from various stations was published by the Central Meteorological Bureau in 1880. Angot studied the phenology of vegetation and migration of birds between 1880 and 1890, and the results of his study were published annually by the Bureau from 1882 to 1892. In 1942, France's observation program was made more extensive. Fleckinger (1945) made graphical presentations of the floral bud development of pear trees. In 1947, Sanson compiled some French phenological observations, the discussion of which appeared in a published report. Attention was paid to disease phenology and techniques of observation on fruits.

(k) In Hungary, Szönyi (1950) reported observation of 18 different kinds of deciduous trees for the period 1936 to 1938. The study covered the relationships between the growing period of trees and the water table level. A phenological survey covering 66 species of lilacs was reported by Mándy in 1949, and a critical study of Mándy's paper was done by Berényi (1950). In 1950, Szöke wrote on observations of natural vegetation. He described observations of six different phenological events among 22 trees and 12 species of shrubs. A five-year phenological program was set up in 1950, and a proposal for the establishment of 500 agrometeorological stations was made. Berényi & Justýak reported their surveys on mountain vineyards in 1956.

(6) Japan and Other Asiatic Countries. (a) Japan has a long history of phenological observations. Modern scientific investigations were undertaken in 1886 when the first nationally organized program of phenological observations was established. Since then, phenological investigations have been drawn from various weather stations. After 1930, when a division of agricultural meteorology was founded in the Central Meteorological Observatory, systematic and successful programming of the observational data has been conducted by the Observatory and the results published in the monthly journal.

By 1940, Japanese phenological observations had become quite extensive, covering over 50 types of plants and animals. In addition to the service of the Observatory, various phenological observations have been made by both public and private groups. Among Japanese phenologists, Daigo, Suzuki, and Nakahara are well known for their prominent contributions to the field. Particularly, Daigo & Suzuki's book, ***Phenology in Japan*** (1947), and Nakahara's ***Phenology*** (1948) deserve attention. In recent years, Daigo has written many essays on his extensive work in phenology.

In the area of plant phenology in Japan, such events as budding, leafing, blossoming, maturation, coloring, and falling of leaves are observed. The primary concern as found in many reports appears to be placed on the blossoming period of cherry trees and budding and leafing of mulberry trees. In 1951, Sekiguchi reported on the floral isophene of cherry blossoms. Besides cherries and mulberries, agricultural crops such as rice and fruits are also studied with regard to sowing, budding, earing, blossoming, maturation, and harvesting. The main items in animal phenology include first and last singing, first and last appearance, and hibernation of a variety of insects, birds, and reptiles. Observations of cicadas, swallows, and frogs are especially extensive. Fire-flies, locusts, shrikes, and snakes are also studied. Nakahara has contributed much in the area of animal phenology, particularly on birds in that country.

(b) In India, agrophenology has achieved great attention in the past 25 years. Agricultural crops observed are rice, wheat, cotton, tea, and tropical fruits and vegetables. Champion, in 1937, made suggestions on phenological observations in India. Ramdas & Mallik's paper on "Phenology in India," published in 1953, discusses the scope and history of phenological activities in India.

(c) In China, despite the fact that interest in phenological observations existed more than 2,500 years ago and that practical applications for various observations were widely adopted in the form of a phenological calendar, we find very few activities in the science of phenology in modern China before 1950. In 1937, Cochin Chu introduced the new phenological calendar based on analysis of the old calendar of the Han Dynasty. A collection of some 300 items of Chinese folklore concerning phenological events was summarized in 1943 by P.H. Chu. In 1942, Won's three-year phenological record in Nanking found relationships between various meteorological elements and phenological events.

Some studies were done by Japanese phenologists on both native and cultivated plants in Taiwan prior to 1945, and presently phenological observations in Taiwan are conducted by the Taiwan Weather Bureau. As to phenological studies in Communist China, no information is available at present.

(7) Southwestern Asia. Although little phenological work has been done in Turkey and Israel, wider attention is now being given to this field in these two countries. Phenological observation results in Turkey are published in the *Meteorological Yearbook.* In Israel, phenological stations have been initiated for the observation of peas by the Thornthwaite & Higgins method. Siev (1949) made an intensive study on the phenology of some wheat varieties in Palestine. The results of his study indicate that photoperiodism is not the only determining factor in the heading of wheat. *The Bioclimatic Atlas of Israel,* prepared by Ashbel in 1950, may be considered an encyclopedia in the form of a diagram.

(8) Latin American Countries. (a) Of the various Latin American countries, Argentina has contributed most to the field of phenology. Particularly in recent times, Argentina has made tremendous strides in phenological studies. A comprehensive phenological program is maintained within the Agrometeorological Division of the National Meteorological Service. Observations are made mainly in various parks of the urban areas, with the Botanical Gardens in Buenos Aires as the central observational post for the study of native plants. Also, experimental stations have been set up to conduct phenological research on cultivated plants and fruit trees. About 7,000 observers are maintained for this activity. The Boletin Fenologico annually publishes the results of observations on native plants, and valuable information has been derived from evaluation of phenological records.

Pascale's phenological chart (1952) for spring and winter wheat in La Pampa for 1947-1950 includes isophanes of sowing, earing, and harvesting of wheat. The phenological behavior of 50 varieties of peaches is reported by Néstor (1951). Huguerza investigated the regional phenology and genetics of pomology in Buenos Aires Province. Nine years of data concerning grafting, flowering, pollination, and ripening of a number of different kinds of fruit trees are analyzed in his report (1938). He found the possibility of improving unproductive varieties of fruits by better spacing of trees and by determining the factors of frost hazards. In 1945, De Fina reported on the relation of temperature and precipitation to phenological phases of various crops grown in Argentina.

(b) Although it appears that other Latin American countries are more interested in production and yield of crops, Brazil does have some phenological records on various fruit and vegetable crops. For instance, the Secretaria da Agricultura of Rio de Janeiro issue phenological maps for sweet potatoes, beans, avocados, oranges, lemons, mangoes, tomatoes, tangerines, and bananas in 1960. In the Boletin Técnico do Instituto Agronómico do Sul (1957) can be found the blossoming dates for different varieties of apples, peaches, and plums, including graphs showing temperature relationships. Planting information was made available in 1959 in Campinas, Brazil (Instituto Agronómico) for peaches, watermelons, sweet corn, beans, apples, asparagus, artichoke, onions, lettuce, and other crops.

(c) For countries other than Argentina and Brazil there are data available at the Agronomy Department, University of Guayaquil in Ecuador on the dates of planting, germination, blossoming, and harvesting on the following: squash, pumpkin, sweet potatoes, onions, cabbages, beans, corn, peanuts, melons, beets, tomatoes, and lettuce. In Quito, Ecuador, information concerning planting and harvesting dates for garlic, peas, cabbage, lettuce, radishes, and tomatoes is available. In Lima, Peru, the Ministero de Agricultura, in their publication *Informe No. 113* have blossoming period data on Peruvian potato varieties. And in Montevideo, Uruguay, data are available on planting, germination, and harvesting dates in 1950 for peas.

(9) Australia. The importance of phenological observations was stressed as early as 1924 by Maiden. In West Australia, a private program of phenological observations was promoted by Gentilli. In 1949, the Meteorological Service established a program for these observations. Phenological reports that have been gathered and published are scant; nevertheless, a recent study by Gentilli should not be overlooked.[8]

(10) Soviet Union. A review of the limited information on phenology in the USSR indicates that an interest in phenological observations was recognized in the middle of the nineteenth century. The development of Russian phenological activities is attributable to the pioneering work of Kaigorodov. Also, other famous phenologists such as Swatzkiĭ, Smirnov, Podol'skiĭ, Schulz, Schamraovski, Schigelieff, Rudenko, Popov, Selishchenskaia͡, and Godnieff are noted for their contributions.

[8] J. Gentilli, 1949, A new field for Australian naturalists, Western Australian Naturalist, 2(1): 15-20.

In the past half century, there has been a new development in phenological services in various areas of European Russia concerned primarily with observation of various agricultural crops. During 1932-1934, Poggenpohl published a 22-years' record of observations on cultivated and native plants for the period 1886-1907. After 1945, phenological predictions have been emphasized with regard to growth periods and harvesting problems. In 1946, Samoĭlov published a detailed report of the experimental selection of fruits and berries which could be cultivated on the mountain slopes of Primor'e. In 1951, Rudenko wrote a book, ***Methodological Instructions and the Program of Fundamental Phenological Observations.*** In this, he presented a comprehensive outline of the procedure and objectives of phenological observations in the USSR. Concerning the historical development of Russian phenology, Surkov presented a 75-years' historical account of phenological work in the USSR in 1949. Also, a survey of the history of phenological observations in Russia from the time of Peter the Great was written by Rudenko in 1951.

The conduct of observations is now under the supervision of the Hydrometeorological Service, USSR. The results of phenological research are available from various agricultural and botanical stations. Collaborating with scientific investigations are the Phenological Commission of the Geographical Society and the Soviet Academy of Science. Both phenological and meteorological observations are used by the Hydrometeorological Service for application to cultivated plants in various areas. According to Davitaya,[9] there are some 10,000 phenological stations associated with meteorological stations in the USSR, and several stations maintain over 100 years of phenological records. Intensive research is directed particularly toward crop prediction and geobotanical studies.

(11) United States. Phenological activities in the USA were begun in the nineteenth century. In the 1880's, Merriam began his work on plant distributions in North America, which led to the formulation of his life zone theory.[10] In 1896, an introductory text on phenological observations was written by Bailey. Thoreau (1906), known as the Father of Phenology in this country, made phenological records for a period of 12 years from 1850 to 1861.[11] Around 1851, the Wisconsin State Agricultural Society published a number of years' phenological data for eight localities in Wisconsin. With the cooperation of various

[9]Based on a verbal communication during his visit to the University of Wisconsin on July 11, 1961. Davitaya is the Deputy Director of the Hydrometeorological Service in the USSR.

[10]C. H. Merriam, 1898, Life zones and crop zones of the United States, Division of Biological Survey, Bull. No. 10, U. S. Department of Agriculture.

[11]H. D. Thoreau, 1906, *Journal*, Vols. 7-20, Bradford Torrey, ed., Houghton-Mifflin Co., N. Y.

public and private institutes and individual phenologists, the Smithsonian Institution initiated a nation-wide survey of observations on periodical phenomena of certain trees, herbaceous plants, and animals between 1851 and 1854.[12] Lengthy phenological records have been kept by several private individuals in the US. Phenological records on both native and domestic plants kept by Mikesell from 1873 to 1912 in Ohio were reported by Smith in 1915. Another similar continuous record on the spring flowering of native plants was kept by Deam from 1920 to 1952 in Indiana, as summarized by Lindsey & Newman in 1956.[13]

Greater progress in American phenology was made after 1900. Among various works contributing to the development of American phenology, Hopkins' research on periodic responses of plants and animals to climatic factors is perhaps the most significant. His studies resulted in his famous Bioclimatic Law in 1918, which he expanded in 1938. This law and Hopkins' extensive application of it to all continental areas of the world appeared to represent a new direction for bioclimatical and phenological research. In 1947, Leopold & Jones presented comprehensive studies on the earliness of native plants in two adjacent localities of Wisconsin for the periods 1881-1885 and 1935-1945.[14] The results of their investigations indicated a considerable deviation from Hopkins' Law, and led to the conclusion that this law, derived from a few plants and insects in many localities, has been oversimplified.

Use of phenological observations in crop production is evidenced by various research. Studies on corn phenology have been particularly emphasized since Magoon & Culpepper used an intensive phenological approach in their research on the response of sweet corn to varying temperature in 1932.[15] The Iowa State University has made many contributions in the area of corn phenology as found in theses and reports. Their emphasis is placed on yield prediction as well as moisture and temperature requirements at various stages of development. Also in Iowa, the crop-weather yield project was set up by the Agricultural Marketing Service of the U. S. Department of Agriculture in cooperation with state agricultural experiment stations in 1938.

Phenological investigations of The Johns Hopkins University have been directed primarily to peas since 1952. Intensive studies on pasture grasses have been conducted at Purdue University. The phenology

[12] See U.S. Patent Office Report, *Agriculture, 1854*, pp. 436-448, published by the U. S. Government Printing Office, Washington, D.C., 1855.

[13] A. A. Lindsey & J. E. Newman, 1956, Use of official weather data in spring time-temperature analysis of an Indiana phenological record, *Ecology*, 37(4): 812-823.

[14] A. Leopold & S.E. Jones, 1947, A phenological record for Sauk and Dane Counties, Wisconsin, 1935-1945, *Ecological Monographs* 17(1): 81-122.

[15] C.A. Magoon & C.W. Culpepper, 1932, Response of sweet corn to varying temteratures from time of planting to canning maturity, U.S.D.A. Tech. Bull. 312.

of various vegetable crops is being widely studied in Wisconsin, and lilac studies are noted at Montana State College. The University of California contributes much on the phenology of fruit trees. The American Institute of Crop Ecology, under the leadership of Nuttonson, has made intensive studies of wheat, rye, barley, and other agronomic crops and fruits in the U. S. A. and in European and Asiatic countries since 1947. The Crop Reporting Board of the Agricultural Marketing Service, U.S. Department of Agriculture, has issued a series of publications since 1947 on the usual planting and harvesting dates as well as blooming date on commercial vegetables, fruits, and nuts. These publications are specified by states and are further divided by areas or districts in each state. The Crop Reporting Board dispatched agents to 15 operational states in 1961 to count and measure fruits and crops in sampling fields for the purpose of crop forecasting. It should also be pointed out that the Phenological Society of Wisconsin was organized in 1959, the first statewide organization in the country, with over 600 cooperative observers and with investigations covering alfalfa, crocus, lilacs, tobacco, and a number of observations on native plants, birds, and insects.

The preceding is by no means an exhaustive list, and there are other countries not mentioned here which also maintain official or private phenological programs. The above survey of roughly 200 years' history in the phenology of the world reveals that phenological research begins with individual localized observations at a few localities and tends to become a universally standardized establishment. Since phenology is a horizontal science, modern achievements in the physical and biological sciences are important assets to the development of modern phenology. The number of species and events of observations was very large around the 1930's and has since been reduced greatly, with more emphasis on simple but accurate observations through a better choice of indicators. Visual observations have long been employed, but they are subjective; the development of objective approaches by virtue of modern achievements in biochemistry, physics, and morphology is a task to be achieved in the near future. In this respect, the present era is a more or less transitional period, moving away from less accurate subjective visual observations to more accurate, objective instrumentation.

Studies on native plants, wild birds, and animals have dominated the field during the past centuries, but a trend toward more studies on cultivated plants and domestic fowl is emerging.

Publications of the various nations in recent years have substantially improved in quality. By and large, Germany and the Soviet Union have contributed much toward modern phenology. As mentioned above, Rudenko's paper on methodological instructions and the program of fundamental phenological observations is a comprehensive outline of the procedure and objectives of phenological observation in the USSR.[16] In his paper, the time of making phenological observations, criteria for assessing the stage of harvest, and the intensity of flowering and formation of ovaries are described. Also, the various phases of development in trees, shrubs, grasses, and crops, and a list of plants and animals (birds, fish, insects, etc.) upon which observations are to be made, are given, along with a sample of phenological form.

Since 1945, increasing emphasis has been placed on applications of phenological techniques to farm operations, site selection, and cultural practices. In other words, the study of phenology in relation to agriculture has entered the realm of micrometeorological application. The use of electronic computation and the recent development of nonparametric statistical analysis will benefit and in turn further research in phenology. It is hoped that plants may be used as a measuring stick or an integrator, representing the integrated weather, so that more accurate crop prediction will eventually become possible.

6.2 PHENOLOGICAL RESEARCH IN AGRICULTURE

It is beyond doubt that phenological approaches have an indispensable relation to agriculture. Various aspects of phenology which are applicable to agriculture will be discussed in this section.

6.2.1 *Native and cultivated plants*

When phenology is merged with botany, bioclimatology, autecology, and the agricultural sciences such as agronomy, horticulture, and forestry, it becomes plant phenology or simply phytophenology.

Historically, plant phenologists have devoted themselves to the study of native plants rather than to cultivated plants. They have spent most of their time in improving techniques of observation, collection, presentation, and interpretation of data, but little in application. Nevertheless, plants of domestic species have been emphasized in the past 30 years, and more scientific approaches are under way. In fact, any contribution made in the study of native plants would be of use to cultivated plant studies. Native plants commonly observed among several European countries and the Soviet Union are: Common lilacs (*Syringa vulgaris*), snowdrop (*Galanthus nivalis*), wood anemone (*Anemone nemorosa*), Norway maple (*Acer platanoides*), horsechestnut (*Aesculus hippocastanum*), birch (*Betula verrucosa*), beech (*Fagus sylvatica*), basswood (*Tilia grandifolia*), ash (*Fraxinus excelsior*), oak (*Quercus penduncula͏ta* black locust (*Robinia pseudoacacia*), elder of Europe (*Sambucus nigra*), coltsfoot (*Tussilago*

[16]Published in 1951 by the Vsesoinznoe Geograficheskoe Obshestvo, USSR, Izvestiia, 83 (4) : 395-411.

farfara), chrysanthemums of different varieties, and many others. The most popular phenological events or indicators observed for the above species are the first blossoming and full blossoming dates. Also, the unfolding of leaves, second blossoming, end of blossoming, ripening of fruit, coloring of foliage, and falling of leaves are sometimes observed. In Great Britain, observation of some 33 native species has been reported without interruption since 1891 by the Royal Meteorological Society for the first blossoming of 28 flowering plants and for first leafing and first blossoming, color change, fruit ripening, and leaflessness of five native trees. In Poland, since 1949, an annual report of 2,000 stations has been made on the marsh-marigold (*Caltha palustris*), coltsfoot, and hazel tree (*Corylus avellana*) for spring flowering, and of birch and horse-chestnut for their autumnal flowering. In Japan, a variety of cherries, weeping willows, mountain lilies, maples, dandelions, and several others have been observed for first blooming, full blooming, and coloring of foliage. The blossoming of the cherry tree (*Prunnus subhirtella*) is their specialty. For example, Koyano (1951) investigated the cherry blossom time in the Tokyo district. During the same year, Sekiguchi examined the 80% blossoming date of cherry trees at the Akaho Fan, Kami-ina, Nagano Prefecture, Japan.

For further information on native plants, the reader may refer to Schnelle's textbook on plant phenology, published in 1955. In this book, the topics of discussion are: the history of plant phenology in Germany and other countries, the procedure for making phenological observations in Germany and elsewhere, the nature of the observations and phenometry, the organization of the phenological service reporting phenological land surveys, phenological gardens, service, etc.; an evaluation of observations, including verification and quantitative analysis, graphical and tabular presentation, etc.; an interpretation of analyzed observations and their correlation in time and space; and the value and application of phenology in agricultural climatology, forestry, soil science, and even apiculture.

Phenological studies on cultivated plants may be termed "crop phenology" or "agrophenology." During the past 30 years, most of the research on crop phenology in the United States has been devoted to corn and a few other field and horticultural crops. In Japan, rice and mulberries are of particular interest. Olives and grapes are of greatest importance to Italian phenologists. Wheat and other small grains have been studied most in Germany. In Europe, events such as sowing, germination, emergence (shooting), blossoming (the first, the full, and the end of blooming), and harvesting have been observed for winter crops (e.g., winter barley, winter wheat, winter spelt, and winter rye, and several pasture grasses), summer crops (e.g., wheat, barley, rice, corn, and oats), vegetable crops (e.g., peas, snap beans, cucumbers, potatoes, beets, and broad beans), other crops (e.g., flax, rape, opium poppy, hemp, sunflower, cotton, hop, and tobacco), and pasture crops (e.g., alfalfa and crimson clover) and several other grasses. Most of the above crops have been observed in Germany and some in Yugoslavia and France. In the Netherlands, observations are made on corn, peas, and beans for visible plume and style. For potatoes, the shape of tubers at the time of harvest is observed. Phenological events for fruit trees generally observed in Germany and France are first flowering, full flowering, last flowering, fruit-ripening, and leaf-falling. Plants observed are almond, peach, apricot, cherry, plum, pear, apple, chestnut, grape, gooseberry, raspberry, blackberry, orange, fig, lemon, mulberry, quince, medlar, and others. Phenological observations in Yugoslavia are similar to those in Germany, but include two more items, leaf-unfolding and time for picking. In Czechoslovakia, only leaf-unfolding, flowering, and ripening are observed. The Polish are satisfied with blossoming observations for almost all fruit trees. In Finland, Sweden, and Spain, flowering and ripening of fruits are the major items observed. In Japan, the commonly observed events are first and full flowering, fruit-ripening, and sometimes the budding and coloring of leaves, for persimmon, pomegranate, grapefruit, tangerine, peach, apple, and pear. In Italy, date-palm, almond, apple, cacao, cherry, chestnut, coffee, fig, grape, pear, peach, olive, plum, raspberry, orange, and lemon are observed for events such as leafing, budding, floral initiation, fruit-setting, and harvesting. Italians have done a number of specific observations on fruits; for details, the reader may refer to Azzi's book *Agricultural Ecology* , published in 1956. In Austria, most observations are made on first blossoming and fruit-ripening, but additional events are noted for apples, namely the first and full blossoming and coloring and falling of leaves. In the Netherlands, the major items observed are the first, full, and end of blossoming, as well as the ripening of fruit for sweet cherry, plum, pear, apple, gooseberry, and raspberry.

Those items which are constantly observed may be considered as phenological indicators for fruits and trees. The period between two events may be called a phenological stage. In Italy, the grapevine, for example, is one of the major plants that has been observed for a period of about 40 years, and the phenological stages designated for the grapevine are: (a) budding to first flowering, (b) first flowering to fruit-setting, (c) fruit-setting to first fruit-ripening, (d) first fruit-ripening to full ripening, and (e) full ripening to the completion of harvesting. For olives, according to Briccoli (1928), phenological stages may be described as: (a) first flowering to first fruit-setting, (b) first fruit-setting to fruit-blackening, (c) fruit-blackening to full maturity, and (d) full maturity to the end of harvest. For chestnuts, they have been observed in Italy as: (a) first leafing to first flowering,

(b) first flowering to first fruit-setting, (c) first fruit-setting to first maturity, and (e) first maturity to the end of harvest. The above stages are all visually detectable. With regard to the latent (undetectable) stages, Marcucci (1948) performed a series of experiments on physio-morphological observations on the pre-budding and pre-flowering of olive trees. In this period of dormancy, he found that the undifferentiated buds which are not yet defined as floral or foliar are not completely dormant. This hidden period, or latent stage which is susceptible to changes of temperature and humidity, has been named the "cryptophase." Azzi (1956) indicated the latent stage of the almond, namely the maximum weight of the fruit, as essential for determining the yield. The maximum weight is considered as the latent stage, because weighing of fruits without their removal from the parent tree is impractical. In other words, there is an invisible phase existing in the long extended period between the first fruit-setting and the ripening of the almond.

The choice of appropriate indicators is a vital problem in agro-phenological research. In addition to those criteria for the selection of indicators mentioned in Section 3.2, the type and organ of the crop as well as the time of observation should also be considered. For fruit trees, blossoming and ripening dates of crops have generally been accepted as significant indicators. In the case of woody perennial fruit trees, the time of flowering or bud formation has long been recognized as one of the important stages of development. Random sampling of peaches on flower count (number of flowers for a few selected branches), on fruit count (number of fruit of a specific size for those branches used for the flower count), on fruit-diameter measurements (the suture, the cross, and the length diameters measured at weekly intervals, beginning two to three weeks before the start of pit-hardening), and on the weight of the fruit (weekly measurements starting at the time of the first diameter measurement to the end of harvest) are important indicators for yield estimates. The diameter measurement of peaches has been intensively used by Davis (1942, 1948, and 1951). According to him, the suture and cross diameters are better indicators for peach-yield prediction than are the leaf-area, leaf-fruit ratio, and fruit-diameter ratio measurements. He found a linear logarithmic relationship between the weight and the suture and cross diameter measurements on a weekly basis. Classically, the suture diameter is that diameter which is largest through the plane of the sutures, the cross diameter is that which is largest at right angles to the sutures, and the length diameter, the distance from the stem end to the base of the tip at the distal end. The suture and the cross diameters can be measured by a vernier caliper much more accurately than the length diameter. Thus, the relationships between the suture and cross diameters and weight are preferred to that between the length diameter and the weight. Westwood & Batjer (1958, 1959) made similar studies on both fruit weight and diameter on two arbitrary reference dates for harvest size prediction and determination of thinning time of Elberta and J.H. Hale peaches. They report that average harvest size so predicted proved to be satisfactory. They have also studied Delicious and Winesap apples by measuring the "box size" at 35 days from the full blossom and extending to the harvest for similar purposes.[17]

According to Lilleland (1936), the apricot, like the peach, shows three stages of fruit size development, namely a period of rapid growth, one of slow enlargement, and another of very rapid enlargement. In a study of the growth and development of flower buds of the Royal apricot, Brown & Kotob (1957) described a three-period growth, based on bud measurements, as: periods of slow growth, transition, and rapid bud development. It has been demonstrated that the boundary between periods can be clearly distinguished by the growth curve in terms of the dry weight of young flowers within the buds. In addition, a fourth period of bud development was designated by Brown (1960). Further divisions of the stage of development of the Royal apricot flower bud are indexed by Brown (1953) on a numerical scale of 0-9 (Table 6-1).

Table 6-1. Key to Stages of Development of Royal Apricot Flower Buds

Stage	Description
0	No evidence of differentiation.
1	Sepal and early petal initials evident.
2	Sepal and petal primordia more advanced than in stage 1; early stamen and pistil initials evident.
3	All floral parts readily distinguishable; anthers without evident sporogenous tissue.
4	All floral parts larger, more advanced than in stage 3; anthers with sporogenous initials evident.
5	Pistils with young ovules evident; anthers with early pollen mother cells.
6	Pistils and ovules large, more advanced than in stage 5; mature pollen mother cells in anthers.
7	Increased size of pistils and ovules; tetrads in anthers.
8	Well-developed ovules, at or just prior to formation of mega-gametophyte; mature pollen grains in anthers.
9	Open flowers.

After Brown, 1952

The development of fruit size or the flower buds of apricots has been employed in the study of temperature relationships and found useful to the harvest prediction of the French prune (Baker & Brooks, 1944), Bartlett pear (Brooks, 1945), sour cherry (Tukey, 1952), Gravenstein apple (Brown, 1954), and Royal apricot (Brown, 1953, 1955).

[17] "Box size" is the term applied to the standard method of expressing apple sizes in the state of Washington. It refers to the number of apples required to fill a standard northwest apple box.

Seeds and woody parts of the trunk of woody perennials are major economic items in agriculture. Thus, the studies of size, quality, maturity date, and yield of fruits are of paramount importance to the canning and brewing industries. For example, the apple grower's decision on whether apples should be sold for the fresh market or kept in storage depends on the determination of significant phenological indicators associated with certain physical parameters. The earlier indicator, such as flower count and fruit count, has a definite relation to the later performance, such as harvesting. This also holds true for the relationship of the date of budding and 50% blossoming to the date of first ripening.

Vegetables may be classified into three categories, according to Hill (1952). They are earth vegetables, herbage vegetables, and fruit vegetables, depending upon the nature of plant parts comprising the edible portions. The earth vegetables are those whose underground parts are consumed as food. Some are true roots, while others represent modified stems, such as rootstalks, tubers, corms, and bulbs. The true root vegetables are carrot, radish, parsnip, sweet potato, yam, oyster plant, cassava, beet, turnip, and rutabaga. The underground stems include potato, onion, garlic, leek, Jerusalem artichoke, taro, and dasheen. The herbage vegetables have nutrient materials stored in parts of the plant developed above the ground. Almost any part of the shoot system of the plant may be utilized as food storage. In spinach, cabbage, kale, and lettuce, leaves are consumed; stems are the essential parts in asparagus and kohlrabi. Buds are the most important parts in Brussels sprout; leafstalk in rhubarb and celery; and immature flowers and flowerstalks in cauliflower and broccoli. In fruit vegetables the nutrient materials are stored in parts of the fruit and seeds. Tomato, cucumber, eggplant, okra, pumpkin, and squash belong to this category. Peas, snap bean, lima bean, and soybean provide food in the form of seeds; these are known as legumes.

The classical indicators at the time of harvest for earth vegetables are appearance, size, and hardness of ground parts as well as growth conditions of the top part. Onions, for example, can be harvested when a bright, clean hardness with a dry skin appears (McGillivray, 1952), and when the neck tissue is softened, the root dead, the top weakened and fallen over in the region just above the small bulb (Shoemaker & Teskey, 1955). It appears that observations of the morphological and chemical changes in the top part in relation to the development of the ground part is a necessary step for the improvement of indicators. Also, the rate of enlargement of the ground part as related to various phenological events such as blossoming and leaf elongation apparently needs to be measured. For the herbage vegetables — lettuce, for example — Thompson (1939) indicated the harvest as that time after the leaves become large enough for use. Shoemaker & Teskey

(1959) assured the harvest date by good size and a well-formed and solid head. Brown & Hutchinson (1949) stated that the head is sufficiently solid for harvesting before any sign of seedstalk development is noted. McGillivray (1952) indicated the best quality is tender and fairly firm to hard, as criteria for harvest. The measurement of water content and turgidity of leaves are suggested as better indicators by Meyer & Anderson (1954). The determination of hardness as well as chemical composition would be another point to consider. Number and size of leaves, associated with height and diameter of head lettuce, are also important. The commercial seed catalogs sometimes list indicators for harvest, such as that found in ***Vegetable Description List for Canners and Freezers***, issued by Northrup, King & Company (1952) in Minneapolis. For more satisfactory indicators, it is desirable to note the stage of floral primordia in association with the number of leaves or the initiation of the floral head. The observation of the maturity of seeds and measurement of hardness, as well as the rate of size change, of the head will be another consideration on indications for harvest.

For fruit vegetables — watermelons, for example — Shoemaker & Teskey (1955) stated that the muffled and dull or dead sound produced when the fruit is tapped is an indication of ripeness. It has also been pointed out that the appearance of a yellow tint at the ground spot and the dried tendril at the place of attachment of the fruit stem and vine reveal harvestable fruit. Brown & Hutchinson (1949) designated three methods for testing harvestable watermelons as: (1) The Thumping Test — where a flat and dull sound indicates ripeness, and a sharp, ringing sound is a sign of immaturity; when the tendrils are dead, the melons are ripe, and if green, they are not ripe. (2) The Pressure Test — differentiates ripeness by the creaking sound when pressed against a solid surface. (3) The Plugging Test — the most reliable test of ripeness, but applicable only on fruit for immediate use. To bring about some improvement of the indicator, it should be recognized that the first lateral branching of the vine has much to do with the fruitification, as well as the relationship of the measurement of circumference to the final product. Azzi (1956) stated that the circumference of the melon doubles every five days until completion of maturity, when its increase becomes nil. Thus, measurements of the rate of circumference change as associated with the chemical components of the fruit become important. Concerning vegetable crops, the sharpness of phases as described in Section 3.2.3 is strongly recommended for the harvestable quality and the determination of harvesting date. Indicators of this sort have been studied by Wang (1958). The phenology of various vegetable crops has been given in Fig. 3-3.

In 1952, Higgins further divided the phenological phases of English garden peas between nodes into 10 subphases. He used figures, i.e., 1, 2, 3, 4, etc., such as the first, the second, and the third node, etc., for the nodal number, and decimal figures, i.e., 0.1, 0.2, 0.3, 0.4, etc., for tenths of a node. These decimal figures are explained by him as below:

0.1 — Bud begins to develop. It increases in size and the tendril unfolds between the first pair of leaflets.

0.2 — Second pair of leaflets, which are held closely together, begins to show between the first pair.

0.3 — Second pair of leaflets and tendril elongate.

0.4 — Second pair of leaflets separate. Elongation of these and the tendril takes place.

0.5 — Second pair of separated leaflets and tendril elongate.

0.6 — Second pair of leaflets begins to separate from the first pair.

0.7 — Second pair of leaflets becomes completely separated from the first pair.

0.8 — Second pair of leaflets begins to unfold and become further separated from the first pair. The first pair of leaflets remains tightly closed.

0.9 — Second pair of leaflets unfolds completely while the first pair begins to unfold.

1.0 — Both pairs of leaflets have fully expanded and between the first pair of leaflets is a tightly closed leaf bud. This is a completed node.

The above decimal figures are used for the vegetative development of peas and are better illustrated in Fig. 6-1. During the seedling stage, the first two nodes are underground and the third node is hard to observe; therefore, the fourth node is the first appearance to be recorded. For example, when seven-tenths of the fourth node has been developed, the record would be 4 plus 0.7 or 4.7, and so forth. Also, when the blossom appears at the time of the sixth node, it is recorded as B-6. Aside from the vegetative development, Higgins observed the planting date (also the time of day), emergence date, blossoming date, fruit-maturing date, and the date that growth stopped. His methods are well suited for English garden peas, as they possess recognizable subphases, grow fast, and thus can be readily observed.[18]

Since 1961, the Agrometeorological Pilot Stations network in Wisconsin and neighboring states has been making phenological observations on various types of peas, sweet corn, sugar beet, and snap

[18]Through personal communication, the author understands that the above description was Higgins' first approach. He has devoted 12 years to further expand his work on a dozen vegetable crops, field crops such as alfalfa, and chemurgic crops. A series of publications of Higgins' valuable research will be published some time within the next two years.

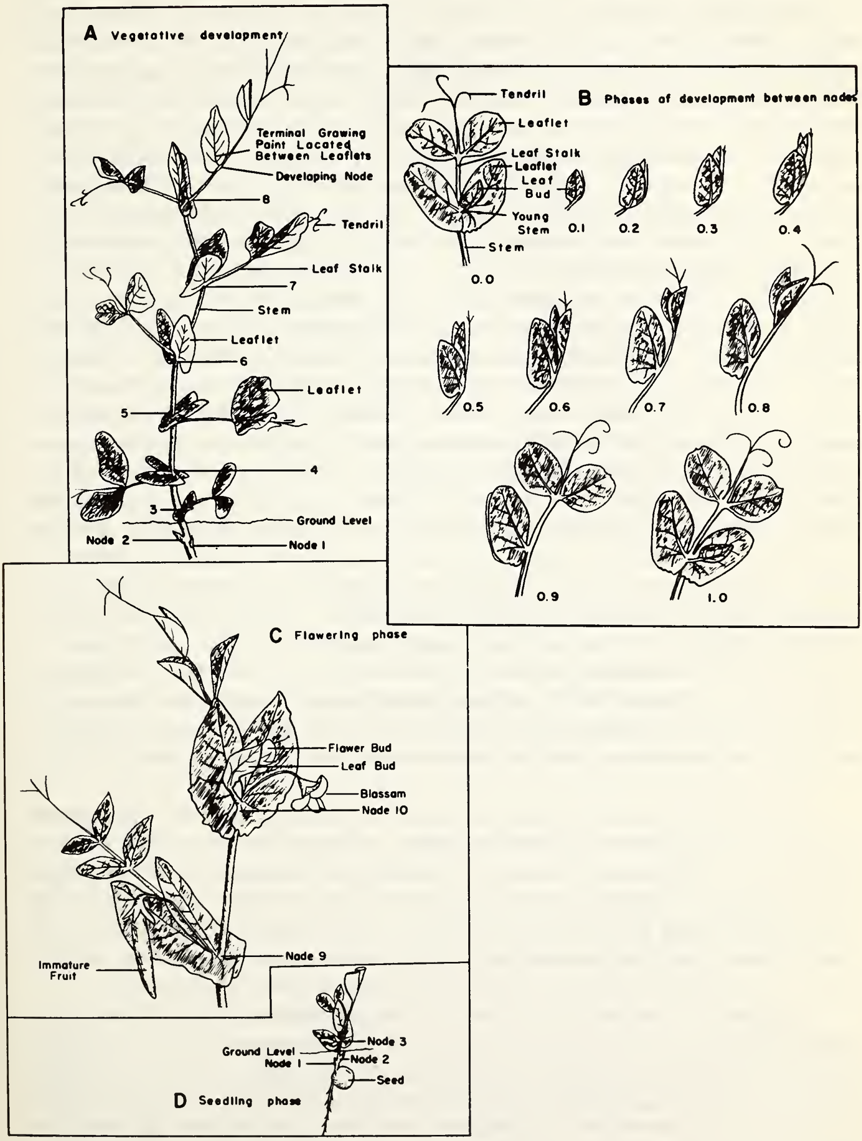


Fig. 6-1. Development of garden pea. After Higgins, 1952

bean. The observable events for peas include planting (P), emergence (E), stand count (seven days after emergence and also at the time of the first blossoming), plant height, which is the length of the stem (H_S), node count (N), 10% of the field flowering (B_1), 50% of the field flowering (B_2), harvestable pods (H_p), and the actual harvest (H). Similar observable events held for snap bean, except for the stand count, node count, and blossoming stage. For corn phenology, observations were made on planting (P), emergence (E), stand count (seven days after emergence and at the time of the first tassel emergence), plant height, which is the height with leaf extended (H_L), tassel emergence (T_1), tassel pollen shed (T_2), another plant height measurement which includes the tassel tip (H_T), first silking (S_1), 75% of the field silking (S_2), number of suckers per 10 plants (R), harvestable ears (H_E), and finally the harvest (H). (Symbols were used for convenience of tabulation, electronic communication, and as codes for communication and mapping.) For beet phenology, planting date and measurement, emergence date, stand count (seven days after emergence), height of plants with the leaf extended, and also the leaf spread measurement and root diameter, were recorded. Other general events observed for all crops concerned were: frost and storm damage, weeds, the weather report (such as the temperature gradient of the air and the soil), direct sunshine and sky radiation, infrared radiation, net radiation, atmometer readings, rainfall at the pilot station and on the field, cultural reports on seed treatment, fertilizer, insecticide, herbicide, and fungicide, and disease and insect reports (if any), with specifications as to the extent of damage done to the crops. The program for the future as planned will include phenological reports on other crops such as mushroom, cucumber, and tomato. The above-mentioned phenological events are minimum requirements for observations, but they are practical.

Presently, problems related to agrophenological research fall under the topics of growth and development, silking and pollen receptiveness, date of planting, maturity, harvest and production, forecasting and periodicity, phenological calendars, phytometers and indicators, bioclimatic laws and microclimatology, and regional phenology. In short, these may be grouped into three categories: (a) spatial distribution, (b) time variation, and (c) space and time relationship.

(a) Spatial distribution. Here, the geographical distributions — both horizontal and vertical — of a single phenological event at a fixed time are employed. In floral phenology, for example, a floral isophane analysis is made by drawing isolines through geographical points where the time of occurrence of flowering for the same flowering date for identical species is observed for a specific year. These isolines are known as isophenes or isophanes. The analysis of normal flowering dates for one locality, which determines the normal floral isophane map for that locality, is one of the regional phenological studies. Isakairs are another approach to spatial distribution, employing isolines indicating the same departure in days from the normal isophane for one specific year. For meteorological usage, if the "isophane" were equivalent to the "isotherm," then the "isakairs" would be equivalent to "temperature anomaly." Similarly, the "temperature gradient," both horizontal and vertical, will be equivalent to the "pheno-gradient." The isolines can be applied for all other phenological events, such as fruit-setting, fruit-ripening, and leaf-falling.[19]

(b) Time variation. In this study, the time sequence of the occurrence of one or more phenological events for a single species or a number of species is at a fixed geographical location or locations. The study of a single event for many years for one locality, such as the earliness of the apple blossoming related to the extreme temperature, is an example of time variation investigations. Another example is the study of phenological events for a certain area, such as a phenological calendar of a specific locality or area.

(c) Space and time relationships. Here, the time variation of a single event or events is investigated with respect to a large geographical area. A good example is the Bioclimatic Law of Hopkins (1918).[20] Further discussion of Hopkins' Bioclimatic Law will be found in Section 6.4.4a.

6.2.2 *Birds, insects, diseases, and others*

Seasonal behavior of many types of animals, ranging from birds and insects to mammals, has drawn the interest of phenologists. Zoologists, ornithologists, plant pathologists, and entomologists offer most contributions to this field. Aside from the studies on birds and insects, observations on reptiles, small animals, mammals, diseases, fish, poultry, and cattle are also made in some countries, but to a lesser extent.

The choice of species of animals as well as items of observation differ from one country or geographical area to another. For example,

[19]For seasonal migration of birds, the line of equal arrival date for a specific bird or group of birds over a large geographical area is known as the "migrant isophane" or "isochrone." The "migrant isakair" refers to the line of equal departure from the normal isophane value for a specific year's event. They are analogous to the isoline of the blossoming date of plants which are the "floral isophenes" and the "floral isakairs."

[20]A series of studies has been conducted by Hopkins since 1900. In 1918, Hopkins' law first appeared in the *Monthly Weather Review*, Supplement No.9, as "Periodical Events and the Natural Law as Guides to Agricultural Research and Practice." There are 42 pages with maps and charts for illustrations. Two years later, he published a paper in the *Journal of the Washington Academy of Science* entitled "The Bioclimatic Law," (see Vol. 10, pp. 34-40). In 1933, he published his paper with M.A. Murray in the *Acta Phaenologica*, Vol. 2, pp. 33-34, as "Natural Guides to the Beginning, Length, and Progress of the Seasons." In 1938, he revised his law, and it was published in the U. S. Department of Agriculture's Miscellaneous Publication No. 288 as "Bioclimatics: A Science of Life and Climate Relations" (188 pages).

in Japan, birds such as swallows, shrikes, and wild geese, and insects such as cicadas and fire-flies, have been commonly observed. Other animals such as frogs, snakes, and fish are also observed. For most species, Japanese phenologists are concerned mainly with first seen, first heard, last seen, and last heard. The British Royal Meteorological Society has been conducting observations of birds since 1891 on such items as first heard for song thrushes (*Turdus Musicus*) cuckoos (*Cuculus canorus*), and nightingales (*Daulias luscinia*); first seen for flycatchers (*Muscicapa grisola*); and first and last seen for swallows (*Hirundo rustica*). Their observations of insects include honeybees (*Apis mellifica*) on the flowers, and queen wasps (*Vespa vulgaris*) on the wing. In addition, the British have studied 20 different kinds of birds for the arrival of spring migrants (e.g., garden warbler, corncrake, wheatear, and house martin) and seven kinds for autumn migrants (e.g., the first redwing and the last swift). Additional records for the first-singing have been compiled on the lark, blackbird, missel thrush, and song thrush since 1915. The Marsham family is continuously providing reports for animal phenology in England. The commencement of egg laying, first eggs seen, and the number of eggs, for the robin, chaffinch, blackbird, and song thrush are observed. Also, butterflies and moths have been intensively observed for the first appearance, since 1920. Along with work on plant phenology, Great Britain is known also for having a long continuous record on animals.

Research on animal phenology may be discussed according to the species studied. Since more studies have been done on birds and insects, the bibliographies of these two items will be mentioned first.

In birds, a common item of observation is migration, such as the first arrival and last seen, in relation to temperature, light, and wind. Problems of temperature and bird migration depend upon (a) the effective height at which temperatures are observed; (b) the duration and fluctuation of temperature with time; and (c) temperature effect on the food supply for birds. The thermal aspect of soaring birds has been studied most intensively by Cone (1962). He proved his theory with observations and introduced some meteorological and aerodynamical views of the subject. This is the most valuable study to date. Some classical studies are listed below: Main presented a report in 1932 on the study of temperature as related to birds' migration. Hashimoto (1938) studied the migration of the eagle and temperature in the so-called "cold-dew season" in Japan. Another study on the eagle and temperature relationship was done by Nakahara in 1939 on the basis of a series of phenological surveys. Kumagaya (1920) presented a report concerning temperature effects on bird migration in southern Japan, and Kageyama (1938, 1940, 1941) discussed the relationship between the migratory wild goose as well as white birds and temperature. Von Haartman, in 1951, reported on the arrival time of the swift (*Apus apus*) and its relation to temperature. Migration in spring usually occurs with a rising temperature and in autumn with a falling temperature. In each case, the changing temperature seems to be a more potent factor than the absolute degree of temperature. Contrary to the common belief of observers that the arrival date of various species could be predicted by a study of the weather conditions, Lincoln (1950) indicates that the state of the weather has little effect on the time of arrival, since the temperatures at arrival time of several birds vary a great deal, ranging from near freezing to full summer weather. Nevertheless, the advance of the isoline of temperatures or isotherms is found to correspond closely with the northward movement of certain species. For example, the northward travel of the Canada goose is found to coincide with the advance of the 35°F isotherm. As shown in Fig. 6-2, the migrant isophane or isochronal line is parallel with the isotherms. But this so-called regular migration is performed by a very small percentage of species, the great majority choosing an exactly opposite course — to remain in their winter homes until spring is far advanced, and then reach their breeding grounds by a migration much more rapid than the northward advance of the season. A more comprehensive study on bird migration and weather was made by Robbins in 1949.[21] The longest period of survey on bird migration is found in the work of Lehtoranta (1951), in which he summarized the phenology of spring migration of the starling (*Sturnus vulgaris*) for the period 1785-1930 in Finland.

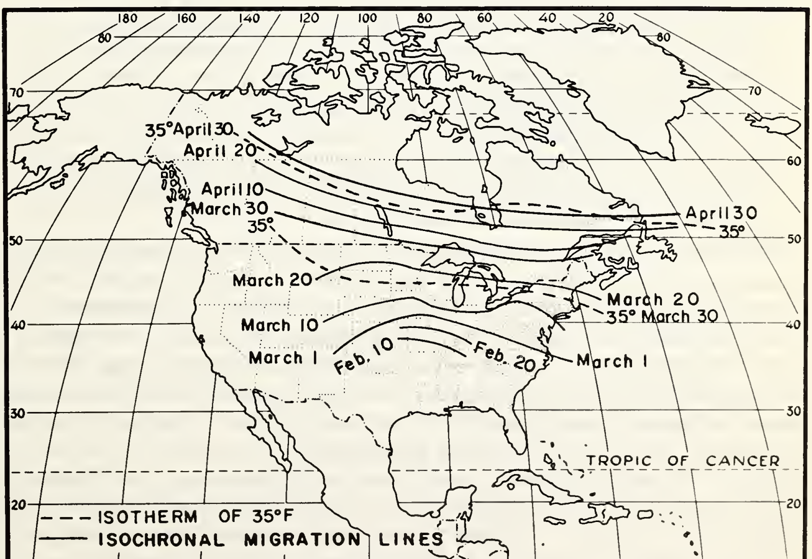


Fig. 6-2. Migration of the Canada goose.

[21]C.S. Robbins, 1949, Weather and bird migration, *The Wood Thrush*, 4(4): 130-144.

As to the wind effect on migratory birds, as early as 1910 Fujihara observed the influence of wind direction on birds' migration. Lincoln (1950) also indicated that headwinds are as unfavorable to migration as is rain or snow, as they greatly increase the labor of flight and cut down the speed of travel. A moderate tailwind appears to offer the best condition for the passage of migrants. In 1938, McMillan, too, emphasized the relation of birds and wind. Cooke (1936), on the contrary, states that the direction and force of the wind, except when associated with temperature, generally seem to have only a slight influence on migration. The correlative study of pressure patterns with migration of birds was reported by Landsberg in 1948.

As for studies on the relationships between bird migration and light, there are studies done by Rowan (1925) and Allard (1928). More recently, Scheer (1953) measured global and zenithal light intensities in connection with phenological observations on birds. His findings revealed a high correlation with zenithal and a comparatively low correlation with global light intensities. This was attributed to the dependence of the global light on horizontal obstruction, elevation, and contraction. In general, the duration, quality, and intensity of light seem to have some bearing on the migratory behavior of birds, though not much research has been done along this line. Cooke (1936) discussed various factors in birds' migration and emphasized bird physiology more than environmental factors.

> Some birds migrate by day, but most of them seek the cover of darkness. Day migrants include ducks and geese (which also migrate by night), hawks, swallows, the nighthawks, and the chimney swift. The night migrants include all the great family of warblers, the thrushes, flycatchers, vireos, orioles, tanagers, shore birds, and most of the sparrows . . . Most migratory birds desert the entire region occupied in summer for some other district adopted as a winter home. These two homes are separated by very variable distances . . . The different courses taken by the birds to get around or over the intervening inhospitable region are almost as numerous as the bird families that traverse them, and birds often seem eccentric in choice of route; many do not take the shortest line. The food is the principal factor in determining the migration route.[22]

Riabinin in 1950 made personal observations on the development of plants in the spring and the appearance of some singing birds in the park of Poznań, Poland. He concluded that the synchronization of the migration of song birds has a close relationship to phases of plant development. In the same year, Rudkovskij reached the same conclusion by relating the arrival and departure of birds with certain phases of plant development in Czechoslovakia. Similarly, Selishchenskaia͡, in his review of the phenological observations during the spring of 1950 at Leningrad, associated the blossoming of flowers and the appearance of insects and birds with the seasonal march of temperature and rainfall. These findings agree with Cooke's statement

[22]T. G. Pearson, & J. Burroughs, 1936, *Birds of America*, Garden City Publishing Co., Inc., Garden City, N.Y., pp. xxxi-xliv, under the title "Bird Migration," by Wells W. Cooke.

that "the food is the principal factor in determining the migration route."

In regard to species of birds, swallows appear to be most commonly observed. An extensive study on the migration of swallows is found in Japan, and a series of studies done by Nakahara.[23] Swallows seen in Japan are mainly of the *Hirundo rustica getturalis* variety, and the results of observations indicate that the first arrival date ranges from March to June, with the earlier dates in southern localities. Some authors, such as Okabe (1928), Azuma (1932), Ehara (1940), and Nakahara (1940a), have correlated the date of first arrival of swallows with temperature and wind. The nesting and wintering of swallows have been studied by Maki (1928) and Maruoka (1937). The main route of swallow migrations is through the South Pacific Islands to Taiwan or the China mainland, to the Ryukyu Islands or Korea, to Japan. In 1938, Kageyama reported his investigation of migratory wild ducks and the period of their hatching. The migration season of cranes was discussed by Maruoka in 1939. Bats and their habitat are another topic being covered by the Japanese phenologists Kishita (1928) and Moto (1932). The singing of the broad-billed roller (*Eurystomus orientalis*) in Hokkaido Province has been observed by Furuhata & Kuroiwa (1936). Other birds occasionally observed in Japan are nightingales, swans, wild geese, skylarks, wagtails, and various types of sea birds.

Aside from birds' migration, the study of plover eggs is noteworthy. Post in 1956 obtained 51-year data on the first egg of the plover in Friesland, the Netherlands. The day of laying and the day of finding the egg is approximately the same because the Frisian egg searchers sit and wait until the egg is laid. It has been found that most frequently the first egg is laid on or about March 21, the earliest date being March 9 (in 1912) and the latest date, March 29 (in 1917). Results indicate that the date of laying is influenced by the occurrence of high temperature in the first ten days of March. In other words, the higher the temperature, the earlier the egg will be laid. Post claims that by making observations on temperature, one would be able to predict the first laying date.

For observations of insects, the cicada is the most popular species of study in Japan, particularly in the 1930's. Asahina (1934) investigated the number of years that the larva of the cicada could subsist under the ground. The first sound made by the cicada in the spring has been studied by Kagei (1934), Minegishi (1936), Hirayama (1936), Hitomi (1936), and Nakabayashi (1936). Kato (1920) observed the relationship between the buzzing of the spring cicada and spring temperature. Maba (1936) also studied the buzz of this insect. The humming and life cycle of the cicada were studied by Matsumura (1936). Other contributors on the phenology of the cicada are Dohi (1936),

[23]In the past 25 years, Nakahara has published several series of surveys on Japanese bird phenology.

Hurd (1919), Ishikura (1936), Kato (1936), Kishita (1936), Kobayashi (1936), Kuroda (1935), and Miyashita (1936).

Concerning the musical behavior of insects other than the cicada, Allard (1929) concluded that light and temperature induced such sounds from meadow katydids. Bessey & Bessey (1898) called the cricket a "thermometer cricket." Matthews (1942) also found that the chirping of crickets is higher in warm weather and lower in cool. His presentation has later been slightly modified by Clarke (1954), and a simple formula presented as $T = N + 42$ for the relation of stridulation rate of the tree cricket (*Oecanthus*) to temperature in degrees Fahrenheit, N being the number of chirps in 13 seconds.

Much attention has been given to the locust, because of its severe injurious effect on crops, particularly in the desert. The appearance of locusts in Europe in the eighteenth and nineteenth centuries was described by the Russian Kulagin in 1921. The British Museum has organized the Anti-Locust Research Centers in London and issues the Anti-Locust Bulletin. Many British authors have engaged in the study of the locust. Burnett (1951) observed the behavior of the red locust (*Nomadacris septemfasciata*) in the solitary phase. Kennedy (1951) studied the theory of long-range migration of the desert locust and the behavior of swarms in Arabia, Iran, and Kenya for the period 1942-1944, and concluded that the surface wind profile — including speed, direction, and gustiness — as well as surface temperature, has a definite bearing on the flight of swarms. His findings indicate that the wind shearing effect on the swarm increases with height. A high air temperature induced resting of the swarm; a high air humidity over the field encouraged flight. Photographs and cartographical analyses indicate that flying locusts moved with the warm wind, but against the cold wind. During the cold wind period, they remained grounded. Also, a strong wind suppresses flight, while a light wind supports it. Rainey (1951) hypothesized a rainfall effect on the appearance of the locust in the breeding area. In 1958, he studied the relation of atmospheric turbulence in eastern Africa and the flying locust by comparing synoptic maps and movements of the locusts. Locusts first move downwind, reach the convergence zone, and finally come to the rainfall areas. This indicates a close association of swarm distribution and the inter-tropical convergence zones.[24] Stephenson (1953) also reported on a survey of locust control in eastern Africa. Japanese phenologists are also interested in the flying locust; papers were published on this subject by Iizuka (1935), Inao (1935), and Kishita (1936).

Mosquitoes and fireflies are other insects of interest. Bates (1945) related climatic factors and seasonal distribution of mosquitoes in

[24]The dividing line in the tropics between the southeast trades and the northeast trades of the Southern and Northern hemispheres, respectively. The inter-tropical convergence zone occurs only along the portion of the dividing line as has been observed.

eastern Columbia for a 30-year period. He claimed that rainfall, temperature, evaporation, and noon humidity between December and part of March apparently control the seasonal fluctuation in the biological phenomena of mosquito distributions. Hashimoto (1939) studied the relation between malaria and storms in terms of the phenology of mosquitoes. Penfound, Hall, & Hess (1945) studied malaria control in the light of the spring phenology of plants in and around the reservoirs of northern Alabama. The phenology of injurious insects was discussed by Filipjew in 1928. Daigo & Suzuki (1944) investigated the season of the mosquito and fire-fly in Japan. The life cycle of the fire-fly has been described by Hirose (1933). Kanda (1931) studied the phenological difference of two species of fire-flies in Japan. Koike (1939) investigated the fire-fly in relation to local weather. Other insects occasionally observed in Japan are butterflies, common flies, and dragonflies.

Insects listed above may have some indirect relationship to crops and farm animals. Aside from the locust, the most popular economic insect in the phenological literature is the olive fruit fly (*Dacus aleae*) of the coastal plain of Israel, which has been investigated by Avidov (1958). A method of phenological survey for forest insect studies was thoroughly discussed by Morris, Webb, & Bennett in 1956. The phenological events of the British Lepidoptera as related to sunshine, rainfall, and temperature were studied by Gunton (1935).

Research on bees and silkworms is another topic of agricultural importance. The effect of temperature on the heart rhythm of silkworms was studied by Crozier & Federighi (1925). Tsutsumi (1924) made a correlation study of weather and cocoon production in Nagano, Japan, for the period 1907-1919. In a study of phenology and apiculture, Rosenkranz (1953) suggested the usefulness of predicting the length of an interval between the middle of the sweet cherry blossoming period and that of the acacia blossoming period. His grouping of yearly interval data according to altitude (station above sea level in meters) and type of weather is shown in Table 6-2. According to Rosenkranz, by knowing the beginning of the sweet cherry blossoming period, the probable interval between the blossoming dates of cherry and acacia could be predicted through the observation of present weather condition. Warmth and moderate humidity combined with a preponderance of clear weather shortens the period; cold and exceptionally clear weather lengthens it. In extremely good and favorable weather, for example, at the height of 200 meters, the probable interval between the acacia and the cherry blossoming period is 27 days, and an increase of approximately three days per 100 meters altitude rise is observed in the length of interval periods. In the case of extremely bad weather, the difference is two days per 100 meters. These findings agree fairly well with Hopkins' Law.

Table 6-2. Interval Between Acacia and Cherry Blooming Period (in Days)

Altitude in Meters	In Extremely Good Weather	In Good Weather	In Normal Weather	In Bad Weather	In Extremely Bad Weather
200m	27	31	36	40	44
300m	30	35	38	42	46
400m	33	36	40	44	48
500m	36	39	42	46	50
600m	38	42	45	48	52

After Rosenkranz, 1953

Diseases are still another aspect of phenological studies. Tehon established methods and principles of interpreting the phenology of crop pests in 1928. He used the hythergraph instead of climograph to study the occurrence and severity of plant pests as affected by a combination of temperature and rainfall. The hythergraph is a rectangular graph with rainfall as ordinate and temperature as abscissa, while the climograph has relative humidity as one coordinate and temperature as the other. Isolines, known as thermohyets or thermohyetic lines, are drawn on the hythergraph to describe various degrees of attack by insects and diseases on plants. The pests studied by Tehon (1928) with the hythergraph were the late blight of potato, the bacterial wilt of melon, leafhopper, sugarbeet "curlytop," cucumber beetles, and wheat leaf rust. Since then, many plant pathologists have paid much attention to the seasonal phenological stages of plants and the development of diseases. Spore maturity and discharge are related to the leaf-unfolding stage and occurrence of leaf spots on fully developed young leaves, beginning with lesions on the leaves, followed by increases in the lesions, and ending with defoliation.

The bruzone disease of rice is caused by hydrogen sulphide development in the soil. Vámos' study (1954) on the relationship between weather and rice disease indicates that the weather influences the development of the disease in such a way that when winter is prolonged and followed by a cold spring, the decay of organic matter is hindered. In this condition, the reduction of sulphates from the soil to sulphites is decreased, and hence the development of the disease is retarded. On the other hand, a warm spring, together with a cool summer, would promote the outbreak of the bruzone disease. Since the solubility of gases (H_2S) is higher in cold water, more gases released from the sulphate into the irrigation- or rainfall-water would eventually drain down to the soil and cause the outbreak of the bruzone disease.

Potato blight (*Phytophthora infestans* —fungus disease) is one of the most significant plant diseases readily influenced by weather. The study of potato blight is a very common subject in the field of pathological phytoclimatology. Bourke has made studies on this topic for a number of years, 1952-1962. His report for the Potato Blight Warning Service in Ireland (1953) suggests the possibility of synoptic forecasting of the potato blight on the basis of the following weather patterns:

> Open waves of maritime tropical air which arrive over the northwest Europe area during the potato growing season is normally ideal for the development of potato blight. The weather condition is predominantly overcast sky accompanied by rain or drizzle. The air temperature range is from 12° to 16°C, and is saturated or near saturated . . . Stagnant or slow-moving depressions giving lengthy periods of wet overcast is another blight weather. The synoptic condition is that an ill-defined quasi-stationary front which is frequently associated with slow moving depressions and thunderstorms is always present.

The microenvironment of the potato crop is just as important as synoptic conditions. Penman & Long (1949) and Broadbent (1949, 1950) have measured temperature, humidity, and wind in and above potato crops to determine the environment of aphids, the potato virus disease carrier. Results of their studies showed that weather among plants was often favorable for the activity of aphids when the weather outside or the general weather situation was unfavorable. In 1953, Hirst, Long, & Penman made additional observations of dew by means of dew balance and other weather elements at six heights between 10 and 320 centimeters in relation to the potato blight, and found similar results. In 1916, Erwin found that the late potato blight epidemics in Iowa were a result of excess of rainfall. However, in 1921, Johnson indicated that the late potato blight was affected by air temperature. The autumn migration of aphids, as a phenological phenomenon, was studied by Riabinin (1951). In England, in 1957, the mild preceding winter and dry spring were found to be most favorable to the aphids which spread the disease of sugarbeets known as virus yellows, and as a result, the crop suffered the worst outbreak since sugarbeets became a principal crop in England. Since weather affects the host plant as well as the life cycle of fungus and insect pests, the population level and activities of vector insects are also greatly influenced. Increasing interest in this area has developed in the past decade.

In addition to viruses and fungi, studies are made on such topics as soil temperature influences on the activities of the white grub (McCulloch & Hayes, 1923), the effect of a cold spring upon some marine animals in the oyster beds in the Thames Estuary of England (Orton, 1932), and the habitat of lizards in view of the phenological development and seasonal effect (Namba, 1929). The meteorological influence on the phenology of hibernation was studied by Nakahara in 1941. Menges (1952) made graphical presentations on the beginning and the end of hibernation of indigenous German amphibia and reptiles and the times of croaking of indigenous frogs. Kiba (1935) observed the forest blue frog in Japan. In the same year, Kumano studied the relationship between coastal temperature and the Tonosama frog. Also in Japan, Nakazawa (1921) investigated the spring migration of frogs in relation to sexual differentiation, and Mori (1915) explained the relationship of the rain frog and precipitation.

The phenology of farm animals has rarely been studied in the past, although — as was mentioned in Section 3.3 — some laboratory experiments on the phenological phenomena of some such animals have been conducted under controlled conditions. Some important phenological events desired for the observations of farm animals are, besides the birth of the young and death of the old: growth rate (e.g., weight gain and hair production), puberty, breeding, insemination, and lactation. The major items of observation differ, depending upon the species of animals and the nature of utilization. In the case of dairy cattle, the main concern is on milk production; for the beef cow and swine, meat production is of greater significance. From the standpoint of animal physiology, observations of respiration rates, growth rates, body temperature, blood pressure, etc., would be most significant. Grazing migrations and hibernation are other items observed in some animals. In relation to animal disease, the spleen weight (size or enlargement) should be observed, for a virus infection will usually cause its enlargement. Observations on lung and air sacs, as well as sedimentation of the blood, are good indicators of health condition. For fowl, the growth rate (sometimes in terms of water or food consumption), egg production, and hatching are necessary items of observation. In addition, the chemical composition of the feces, as well as their physical aspects such as firmness, wateriness, and quantity, may be taken as indicators of the general state of health.

6.3 SEASONAL CHANGES AND CALENDARS

The treatment of seasonal change differs, depending upon whether one is engaged in the science of astronomy, climatology, or phenology. Accordingly, these are designated as the astronomical, climatological, and phenological seasons.

6.3.1 *Astronomical season*

By observing the relative position of the sun and earth, astronomers found that the revolution of the earth is associated with seasonal changes. The mechanism which causes seasonal variation is the inclination of the plane of the equator at an angle of $23\frac{1}{2}°$ from the plane of the earth's orbit. In other words, the axis of the earth is inclined at an angle of $23\frac{1}{2}°$ from a perpendicular line against the plane of the orbit. If one assumes the earth as stationary in space, then the sun is viewed as rotating around it. Thus, the plane of the sun's orbit, known as the ecliptic plane, is the plane of the earth's orbit. It follows, therefore, that the ecliptic plane is inclined at an angle of $23\frac{1}{2}°$ to the earth's equatorial plane. The equinoxes[25] occur at the

[25] The date at which the sun passes directly above the equator, where the day and the night are equally divided. In spring, it is the vernal equinox; in fall, the autumnal equinox.

intersection of the two planes. The vernal equinox is found where the sun in its apparent motion crosses the earth's equator going northward and the autumnal equinox is at the intersection as the sun is going southward. The solstices[26] are the positions where the inclination of the earth's axis is toward the sun. The winter solstice, when the sun is farthest south with respect to the earth, occurs just a few days before perihelion.[27] At that time, the sun is directly overhead at noon in latitude $23\frac{1}{2}°$S. Similarly, the summer solstice, when the sun is farthest north, occurs just a few days before aphelion. At that time, the sun is directly overhead at noon in latitude $23\frac{1}{2}°$N. Hence, a year is nearly equally divided into four seasons, with the events of the vernal equinox, the summer solstice, the autumnal equinox, and the winter solstice marking the beginning of spring, summer, autumn, and winter, respectively. These significant events correspond approximately to March 21, June 22, September 23, and December 22, except for leap year, where some variations are observed. The calendar constructed on the basis of astronomical seasons is known as the solar calendar. On the other hand, the construction of the lunar calendar is based on the observation of the phases of the moon, such as new, first quarter, full, and last quarter. In the lunar calendar system, the 15th of the month approximates full moon, and the new moon is observed about the first of the month. Since the rotation of the moon around the earth follows a $29\frac{1}{2}$-day cycle on the average, a lunar month consists of 29 and 30 days alternatively, but, unlike the solar calendar, the number of days for a specific month is not fixed. Also, unlike the solar calendar, a duplication of a certain month takes place in leap year. A lunar day, known as the tidal day, is the time required for the moon to rotate once with respect to the earth. Although the lunar calendar at present is not of much scientific use, its relation to amplitude and period of the oceanic tides as well as the atmospheric tides should be recognized. Occasionally, the lunar calendar is used by some biologists in their study of plant development in relation to the moonlight effect.

The astronomical expression of the climate is calculated in terms of temperature on a uniform solid surface of the earth resulting from intensity and duration of sunlight. It follows that the elevation of the sun, as it varies with seasons, determines the climatic zone known as the "solar climatic zone."[28] The solar climatic zones are, therefore,

[26]The date at which the sun is farthest north or south. In the northern hemisphere, the summer solstice falls on or about June 21, and the winter solstice on or about December 22. The reverse is true in the southern hemisphere.

[27]The point of the orbit of the earth which is nearest to the sun; aphelion, that farthest from the sun.

[28]According to climatic divisions on an astronomical basis, five "solar zones" are established. Between the Tropic of Capricorn (latitude 23.5° S) and the Tropic of Cancer (latitude 23.5° N) is the ***Equatorial Zone*.** In this zone, the sun is overhead twice during the year; its height at noon is never smaller than 43°, and its duration is never less than

parallel to the altitude lines. The "solar climate" may best be termed as the "mathematical climate"; it has scientific use which was initiated by climatologists in the early days and still holds its importance. In climatological and phenological studies, both solar and lunar calendars can be used only as references in regard to the seasonal changes.

6.3.2 *Climatological season*

In climatological studies, seasons are defined according to regional climatic elements such as temperature, wind, rainfall, cloudiness, and sunshine. In the tropics (Equatorial Zone), rainfall is generally considered the primary parameter due to negligible variations in daily and seasonal temperatures. Thus, the climatological seasons in such areas may be classified as "rainy season" and "dry season." In the tropical regions of southeast Asia, a "cold season," a "hot season," and a "monsoon season" are recognized. In these regions, wind, rainfall, and temperature are taken into account. Temperature is the major factor to be considered in the polar regions (Polar Zone), where a long cold winter season and a short mild summer season are identified. In the temperate zone, four seasons are generally adopted, in accordance with rainfall and temperature combinations.

In his classical studies, Wladimir Köppen (1900), a German climatologist,[29] used temperature and rainfall for the classification of five major and 24 minor climatic types. He emphasized the degree of dryness, coldness, warmness, and humidness for summer and winter as related to vegetation. Modifications of Köppen's classification are many, including Köppen's own. Among them, Thornthwaite's scheme has gained most general acceptance. In his presentation of the "precipitation effectiveness ratio" in 1931, he pointed out that the importance of precipitation for vegetation depends not only on its amount, but also on the intensity of evaporation; later, he introduced the "tem-

10.5 hours. Between the boundaries of the Equatorial Zone poleward, and the Arctic Circle (latitude 66.5° N) or the Antarctic Circle (latitude 66.5° S) respectively, are the *Temperate Zones*. At the Polar Circles, the sun has just reached the horizon on the shortest day, if the twilight time is disregarded. Beyond the Polar Circles are the *Polar Zones*. These zones are distinguished by the fact that the shortest day is 0 hours, and the longest is 24 hours.

[29]Köppen devised his first classification in 1900 by using vegetation zones of the World Vegetation Map of de Candolle, a French plant physiologist; in 1918, he revised it with greater attention to temperature, rainfall, and their seasonal characteristics. He summarized his temperature records in terms of the warmest or the coldest monthly mean temperatures, but his presentation of rainfall is only in a quantitative sense, such as "moist all season" and "dry winters." In 1936, Rudolf Geiger collaborated with Wladimir Köppen on further revising Köppen's classification. Their publication is entitled *Handbuch der Klimatologie*, Vol. 1C, Verlagsbuchhandlung, Gebrüder Borntraeger, Berlin (1936).

perature efficiency ratio."[30] Apparently, the importance of the daily mean temperature is too strongly emphasized in the preparation of both indices for climatic classifications. Both Köppen's and Thornthwaite's approaches are based on the conventional definition of seasons, and the blind application of their classifications in the study of significant local seasonal changes will produce inadequate results, for their aim is regional climatic classifications and not seasonal changes. An attempt to establish a more detailed classification was made by Hartshorne in 1938 by his definition of six standard seasons. Jefferson in 1938 also presented a discussion on the standard season. Newman & Wang in 1959 defined seasonal changes in the middle latitudes. Their approach adopted the weekly frequency of selected temperature levels in various areas of Wisconsin for the division of crop response periods into six agricultural seasons, namely, winter, early spring, late spring, summer, early autumn, and late autumn. In short, they classified the annual time table of climatic changes into natural agricultural seasons. The criteria for their classification are the responses of various field crops to the distribution of daily maximum and minimum temperatures within weekly periods. Ideally, the establishment of a satisfactory climatic season, from the standpoint of its practical application to agriculture, should take into consideration the physiological response of each individual crop to the integrated climate rather than to single climatic elements, so as to obtain a more reliable climatic calendar. This problem necessarily leads to the problem of phenological seasons, which is our next topic.

6.3.3 *Phenological season*

As far as farm management is concerned, an appropriate phenological calendar could furnish some useful information with regard to a group of plants or animals, and sometimes to a certain single species of plant or animal. Neither the astronomical calendar nor the climatological calendar is as useful as the phenological calendar in farm operations. For this reason, farmers and growers are advised to follow a phenological calendar instead of the usual calendar for plowing and sowing. When used for scheduling of planting or harvesting, it is the "planting calendar" or the "harvesting calendar"; when used for spraying of insecticides, fungicides, or herbicides, it is the "spraying calendar."

The observation of various phenological events, for the purpose of determining the timetable of seasonal changes, dates back to ancient Chinese civilization. About 500 B.C., Han Kao Chu, the first emperor of the Han Dynasty, divided the traditional lunar calendar of four seasons into 24 subseasons. Each subseason is further divided into three

[30]For further information, see C.W. Thornthwaite, 1931, The climates of North America according to a new classification, *Geograph. Rev.*, 21 : 633-655 (this is Thornthwaite's first classification); Thornthwaite, 1941, Atlas of climatic types in the United States, 1900-1939,

phenological periods, thus comprising a total of 72 phenological periods in a year, with five-day intervals. Seasons, subseasons, and phenological periods are all specified by the lunar calendar each year, but none of the phenological periods falls into the same calendar date from year to year. Each subseason consists of three phenological periods, and each period represents an event. Events indicating the arrival of spring, for example, are designated as "Thawing by the eastwind; the yellow birds first seen, and the fish come upon the ice." Events indicating the establishment of spring are "birds first nesting, cherries first blossoming, and thunders first thundering and so forth."[31] Along with the use of birds, fish, insects, turtles, trees, and the like for the description of various events, differentiations in altitude, latitude, and longitude were also considered to some extent. The earliest phenological calendar in Europe was prepared by Karl Von Linné in 1751, based upon the life cycle of plants.[32] The phenological events used are leafing, blossoming, fruiting, and leaf-falling, in association with the regional climate. Since then, phenological calendars suitable for different localities of Europe have been established, particularly in Germany. Schnelle (1949) has prepared a phenological calendar for the high altitude areas of south Germany by taking a 10-year mean value for each beginning date of the various phenological phases. He classified phenological dates according to three groups of plants: native, cultivated, and fruits. A total of 28 native plants, 30 cultivated plants, and 30 fruits were chosen and arranged by months from March to November. For March 4, it is hazel blooming; the 10th, snowdrop blooming; the 30th, oat sowing. For April 23, it is sweet cherry blooming, and for the 26th, potato sowing. For May 7, apple blooming is the indicator, and for the 13th, horse-chestnut blooming, and so on. Otto (1938) constructed 24 maps to illustrate the phenological calendar for Rhineland, 1934-35. The phenological characteristics of various fruits and grain crops have been described for vine, cultural, topographical, and forest areas.

In the United States, Bigelow (1818) observed more than $2\frac{1}{2}$ months' difference in the seasons between the northern and southern extremes of the country through his intensive investigation of the blossoming dates of certain plants between Montreal, Canada, and Fort Clairborne, Alabama. In 1900, Hopkins had come to the conclusion that for West Virginia, there was an average rate of variation of about four

U. S. D. A. Misc. Publ. 421; and Thornthwaite, 1948, An approach toward a rational classification of climate, *Geograph. Rev.*, 38 : 55-94 (this is Thornthwaite's final revision). See also Section 7.4.2 for details.

[31]These phenological events have been translated literally. The original events run in poems with rhymes. A modification of the ancient calendar was proposed by Cochin Chu in 1937, based upon phenological observation in Nanking, China. Unfortunately, the development of the phenological calendar in Communist China is not known to the western world.

[32]K. V. Linné, 1751, *Philosophia Botanica*, Stockholmiae, apud Godofr. Kiesewetter.

days to 1° of latitude and 400' of altitude, and in 1915 he added the variation of four days to 5° of longitude, earlier westward and later eastward from a median point in the continent. This was the early stage of his Bioclimatic Law. In 1916-1918, he had his first series of theoretical phenological calendars of wheat established on the basis of his law. He labeled his calendars the "Winter Wheat Seeding Map Calendar of the United States," the "Harvest Calendar for Spring Wheat for the United States," and so on. At the same time, he constructed his phenological disk calendar for the computation of dates and altitude limits from latitude, longitude, and altitude, and from isophane and altitude. The major limitation to his theoretical establishment is that it is based on only a small number of observations for a large geographical area. Lamb (1915) made a phenological calendar designated as "A Calendar of the Leafing, Flowering and Seeding of the Common Trees of Eastern United States," evidently the first such calendar based upon a satisfactory number of actual observations.

In recent years, phenological calendars have been made in countries all over the world. For example, Lastowski (1936) made his wall calendar in Poland. Hyde (1949), in his study of phenology of British hay-fever, gives a calendar of occurrence and concentration of air-borne pollen of different species in England and Wales with notes on their distribution and anti-germic properties. He points out the significance of this calendar to sufferers from allergy. In 1953, Thornthwaite established the climatic calendar for the growth of pea plants in Sea Brook Farm, New Jersey. In 1952, Billard made a climatic calendar as a guide to planting. In Bohemia, Brablec (1953) devised a phenological calendar of nature for his locality.

The phenological calendar date employs the system of year-day in place of the common usage of calendar date system such as January 15, March 2, etc. Like many others, Schnelle (1955) designates January 1st as 1, and the accumulated number to December 31st as 365 for the normal year and 366 for leap year. Accordingly, March 1st corresponds to the 60th day for the normal year, while it is the 61st day for leap year. Wang's calendar divides the climatological year into 52 weeks, where the eighth week (from January 1) is eight days instead of seven for the normal year, and the ninth week is also eight days for leap year.[33]

An ideal calendar which would be able to indicate seasonal changes and plant development should be based upon a long-term observation for the same species of the specific plant, together with a concise measurement of the microenvironment. Such observations should be reproduced for a large geographical area with consideration of latitude, longitude, altitude, and soil type. Standard plants, soils, and

[33] J. Y. Wang, & V. E. Suomi, 1957, The phyto-climate of Wisconsin, I. The growing season, Agr. Expt. Sta., Univ. of Wisc., Madison.

environments should be chosen, and techniques of observation should be carefully established. This was the idea for the establishment of the International Phenological Gardens, which will be discussed shortly. Native plants usually are better than cultivated plants, and their use as "guide plants" should be encouraged.

6.4 MULTIPLE TECHNIQUES IN PHYTOPHENOLOGY

The applications of phytophenology in agriculture are mostly directed to the fields of forestry, pomology, and agronomy. Lesser fields of application are floriculture and vegetable science. Application in these fields falls primarily in the following areas:

(1) Forecasting of crop production;
(2) Forecasting of seasonal operations;
(3) Management decisions;
(4) Selection of sites and appraisal of farming areas; and
(5) Improvement of cultural practices.

The intention of this present section is to describe methods of application of phenological techniques, particularly that of plant phenology, in agricultural crops.

Phenological methods, as applied to agriculture, uncover more meaningful relations between meteorological variables of the natural environment, both air and soils, and the associated biological responses of various crops. There are two schools of thought in the treatment of phenological material. The first group believes that a phenological record is an important supplement to the recording of traditional meteorological elements. Schmauss' discussion (1948) illustrates this type of approach by suggesting the possibility of making microclimatic observations through non-instrumental phenological means. Here, value is placed on the appearance of phenological events and their periodicity as affected by environmental factors. The second group, as opposed to the first, believes that a phenological record can be represented exactly by the sum of functions of various climatic elements. Berg (1952), in his study of the importance and limits of phenology for climatology, pointed out that phenological data represent their own climatic element. Sometimes in phenological studies, the physical environmental factors need not necessarily even be taken into consideration. But to be sure, methods in agrophenology are a portion of agrometeorological studies, and such studies require an intensive investigation of the physical environmental factors in association with the broad aspects of growth and development of crops, in both natural and controlled environments.

Five major techniques in agrophenological studies will be discussed: phenological events and weather elements, empirical formulation, experimental establishment, time sequences and area analysis, and periodicity and prediction.

6.4.1 *Phenological events and weather elements*

Since temperature and rainfall are critical to crop response and are commonly observed, these two elements are widely adopted in the study of the recurrence of phenological events. Solar intensity, relative humidity, evaporation, wind, and pressure are of less concern, though they are also important. In the study of solar radiation and phenological events, the daylength at various latitudes, insolation, cloudiness, sunspot, and even ultraviolet radiation have been investigated. With respect to the moisture of the air and soil, rainfall, relative humidity, evaporation, transpiration, evapotranspiration, irrigation, water level, soil moisture, flood, and drought are significant factors. For air movement, the speed and direction of the wind, convective current, convergence zone, air mass movement, weather pattern as related to cyclones and anticyclones, and others, are of concern. As an illustration, temperature effect, including sunspot, will be discussed as an element affecting phenological events. Factors other than temperature will be discussed in Sections 7.4 and 7.5.

When temperature is employed as a measure of environment, the mean and accumulated air temperatures are the most frequently used parameters. In addition, the vertical temperature gradient, temperature inversion, soil and grass temperatures, the extreme temperature, and also the occurrence of frost and freezing damage are sometimes adopted. In general, extreme temperature is a better indicator than accumulated temperature, and the vertical temperature gradient is likewise better than the point temperature measurement in the weather shelter. In short, any measurement that indicates the true air or soil temperature of the actual environment of a crop is better statistical material. The mean and accumulated temperatures are statistically identical and average out the singularity of the temperature changes affecting plant growth, unless a short (five to ten day) period's mean or accumulated temperature is employed. For example, Böer (1952) made correlative studies on a long period of phenological events of nine stations in Thüringia with a five-day mean air temperature of Jena. Factors under consideration were rainfall, temperature, weather types (e.g., the association of spring phenological events and anticyclonic weather patterns), and altitude effects. He found that temperature, especially the spring temperature, is the dominant factor and that rainfall is less important. He proved his statements by studying the relation between the spring temperature and the beginning phenological phases of snowdrop, horse-chestnut, lilac, elder, winter rye, and beech. Another study on the short-period temperature was done by Schnelle in 1952. As a result of observations on the daily mean and minimum temperatures before and after the date of autumn leaf-coloring in Geisenheim, Bamberg, and Hof, he was convinced that leaf-coloring is dependent on temperature. He found that the minimum temperature sinks to 7° C for a period of 10 to 18 days before the color change. However, many workers, including Schnelle, believe that the seasonal (or monthly) accumulated or mean temperature, and even the annual mean temperature, are adequate parameters for bioclimatic studies. In 1949, Lessmann claimed that the mean annual temperature is a sufficient index of the general bioclimate in southwest Germany. He found that the mean annual temperature shows a higher correlation with the onset of phenological periods and with later developmental phases than do precipitation and various climatic formulas (such as the aridity index of de Martonne, rain factor of Lang, etc. See Section 7.4.2). His equations expressing the relationship between mean annual temperature and onset of phenological periods are as follows:

$$\frac{F}{10} + T = 20.8\,, \quad \text{and} \quad \frac{S}{10} + T = 28.9\,, \qquad (6\text{-}1)$$

where F is the onset of spring, S is the onset of summer, and T is the annual mean temperature in degrees Centigrade. Following the same trend of thought but with minor modifications, Lessmann in 1952 used the accumulated hourly total temperatures below 0°C and over 0.5° and 10° C for study of the ecological climate in the vicinity of Freiburg. Notwithstanding the above statement, he also pointed out that the interruption of the blossoming of fruit trees is due to cold spells, based upon examination of the duration of the characteristic phases of the guide plants for the threshold temperatures of 5°, 10°, and 15°C during the vegetation seasons of 1947 to 1951 in the southern Upper Rhine Plain of Germany.

Schrödter (1952-54) emphasized the value of the threshold temperature in the use of accumulated temperature. He established the threshold temperatures for a number of arbitrary starting dates in the application of the temperature summation rule to the prediction of winter rye harvesting date. Thus, the mean temperature ($\bar{T}$) during the period above the lowest temperature for plant growth (C_1) is expressed as

$$\bar{T} = C_1 + \frac{C_2}{d}\,, \qquad (6\text{-}2)$$

where C_2 is the accumulated temperature, and d is the number of days between the beginning of growth and flowering. After examining the five years' data (1947-51) on several plants on various starting dates and their mean errors, he determined the values of the above equation for winter rye as

$$\bar{T} = 4.4 + \frac{303.5}{d}\,, \qquad (6\text{-}3)$$

for d starting on April 15, and

$$\bar{T} = 4.4 + \frac{379.8}{d}\,, \qquad (6\text{-}4)$$

where d is counted from March 15. For snowdrop, when d starts on March 15, it is

$$\bar{T} = 5.3 + \frac{411}{d} \tag{6-5}$$

Heutschel (1951) compared the blooming date of the snowdrop with the accumulated temperatures above 0°C with various starting dates: from January 1, from the last frost date, and from the date of disappearance of continuous snow cover. He found the period between the end of snow cover and the last frost date as the best representation and concluded that the flowering of the snowdrop represents development of a definite combination of climatic conditions. This holds true for other plants, e.g., gooseberry.

Researchers who employ cumulative temperature in the study of plant response are known as heat unit workers. Although this approach has been improved greatly, it has some limitations, as pointed out in Section 4.2.3. Nevertheless, the advantages of the heat unit approach are its simplicity and systematization. It may serve as a first approximation for practical purposes, provided it is correctly used.

Seasonal temperature effects on phenological events comprise another area of interest which utilizes various types of temperature such as the seasonal mean, monthly mean, and weekly mean temperatures. There are many subjects concerned. For example, the length of spring vegetative periods of lilacs is one Mandy, 1949), and the germination period of summer oats is another (Rosenkranz, 1951c). In 1950, Rosenkranz found that the length of the vegetation period in Austria for snowdrop, anemone, etc., which ranges from beyond 250 to less than 150 days, was an effect of the daily mean temperature below 5° C between pre-spring and autumn. However, Minář (1944), in his study of the vegetative period in the protectorates of Bohemia and Moravia, Czechoslovakia, defines the vegetation period as the number of consecutive days when the daily mean temperature is above 10°C.

For plant developmental studies, extreme temperature is a better measure of environment than mean or accumulated temperature. In 1918, Knörzer observed the effect of an extraordinarily hot April on the progress of phenological phenomena in East Russia. In Italy, Zanon (1952), in his study of the phytophenological peculiarities of 1951 for the bioclimate of Venice, found the significance of the extreme temperature by comparing the extreme and mean of 1951 with the long-period average between 1836 and 1935 on the flowering dates of English yew and pomegranate, which are determined by the critical temperature of 5°C minimum air temperature on the day immediately preceding flowering. In Germany, Witterstein (1952) made a detailed statistical study on the duration of 10 phenological periods which constitute the year. These periods were found to spread most in early spring and least in midsummer. Also, Schnelle (1950) performed a study on a long-period record for 1841-1939 and 1867-1947 and classified the yearly average and extremes of various phenological events into pre-spring to autumn, thus deriving the duration of different phenological seasons. Parallelism was shown in his study between 20 years' mean of snowdrop blossoming and mean temperature of February through March, with an association of higher temperature to earlier blossoming. Koyano (1951), in his study of the rate of opening of cherry flowers in the Tokyo district, recognized that high extreme temperatures resulted in earlier blossoming, by as much as five days. Many studies of this type are performed, particularly in floral phenology.

The application of the sunspot theory to the study of phenology has been controversial. It states that an increase in solar disturbance (solar storm) or sunspot numbers is an indication of cooler, wetter climate and greater stormy weather. Conversely, a decrease of sunspot numbers is generally accompanied by warmer, drier climate and fair weather. It follows that the phenological phenomena which usually relate with weather and climate are consequently governed by the solar activity. Willett (1953) studied the influences of solar disturbance on the general circulation of the atmosphere and recognized two types of solar disturbances: the ultraviolet and the corpuscular radiation types. Short bursts of ultraviolet radiation result in a heating of the lower latitudes and, in turn, cooling of the polar regions. The corpuscular bursts are associated with greater heating of the upper air over the polar regions than over the tropics, particularly during the winter. Stormy weather accompanied by extreme changes of temperature is generally caused by the corpuscular disturbance. In 1952, Yamamoto found a unique relationship between sunspot activity and climatic changes in Europe and Asia. He computed the mean full blossom date of cherry trees on both continents for the period 700 to 1700 A. D. in his paleoclimatological approach. He described changes of climate and phenological phenomena as following the variation of sunspot numbers. Schneider (1950), in his study on leaf-unfolding of horse-chestnuts as related to sunspot variations and air temperature in March, found that leafing is early near the sunspot maximum and late at the sunspot minimum.

When rainfall is used as a measure in the study of phenological events, the monthly mean, extreme rainfall, number of rainy days, and sometimes frequency and effectiveness are employed. However, rainfall is seldom studied independently of other environmental factors. Moreover, rainfall is not as effective as other environmental factors, so no attempt is made to review rainfall alone, but it has been and will be cited in conjunction with other environmental factors when necessary.

6.4.2 *Empirical formulation*

One of the elementary approaches in phenological studies is that of empirical formulation. It correlates phenological events and environmental factors by a certain mathematical formulation, simple or complex according to the nature of the research, most frequently in the form of equations. It is simple, because one needs only to substitute his data, both biotic and abiotic, into the given formula and determine the coefficients. It does not involve the initiation of the principle for the functional relationship of physical and physiological laws. With the given data and known equation, he can always reach a certain conclusion. Unavoidably, this approach could involve a certain degree of bias. First of all, the coefficients or constants so obtained may fit well to the historical data, but they may not be applicable to a new set of data. Secondly, an empirical formula so obtained is regional, pertaining to locally peculiar characteristics. Finally, some empirical formulas are dimensionally inconsistent, as will be explained shortly. Nevertheless, the usefulness of this type of approach on the regional level is recognized by many phenologists as an aid to research.

The following illustrations indicate the types of formulation, the kinds of application and their results, together with their limitations.

Bider (1946) examined the correlation coefficients between seasonal weather and cherry yield in Switzerland and found that a warm, dry, and sunny summer and early fall, cold, dry, and cloudy winter, and dry, warm, and sunny spring were associated with high yield. He demonstrated with a series of empirical equations that the yield is a function of precipitation, temperature, and duration of sunshine. His equations furnished a reliable calculation of the cherry harvest within 15 % of the actual yield, provided that extreme weather did not occur during the developmental and harvesting stages. Some of the equations are

$$E_1 = 4.7 - 0.128\,(N_1 - 99)\,, \qquad (6\text{-}6)$$

where E_1 is the yield, N_1 the number of rainy days with rainfall over 0.1 mm; and

$$E_2 = 4.7 - 0.088\,(N_2 - T + S - 118.0)\,, \qquad (6\text{-}7)$$

where N_2 is the number of rainy days in August, September, October, December, and January (precipitation > 0.1 mm) and the sum of the rainy days in April and May (precipitation > 0.1 but < 1.0 mm), T, the temperature of August minus that of June, and S, the duration of sunshine (hrs/10) in November and December.

The above empirical formulations, although claimed by Bider as satisfactory, are dimensionally inconsistent. For instance, the dimension of the last term of Equation (6-7) involves three different units: the rain factor expressed in days, the temperature in degrees Fahrenheit, and the sunshine in hours.

A similar, but more satisfactory set of formulations appears in the work of Baker & Davis (1951). They investigated the growth of two varieties of peaches (Phillips Cling, and Johnson) by measuring the "cross diameter" under the assumption of two main phases of development — development of the pit and flesh during the first stage of rapid growth, and growth of the flesh alone during the final stage of swelling, as shown in Fig. 6-3. The growth curve prepared for the time in days (X axis) against the increase in diameter in tenths of millimeters (Y axis) indicates a certain amount of overlapping of the first and last stages during the period of slow growth. By ignoring the slow stage of development, they chose an arbitrary date for each of the two varieties in order to separate the first and second stages, beginning with 43 days after May 1 for Phillips Cling and 40.5 days after May 2 for Johnson. These dates were selected on the basis of

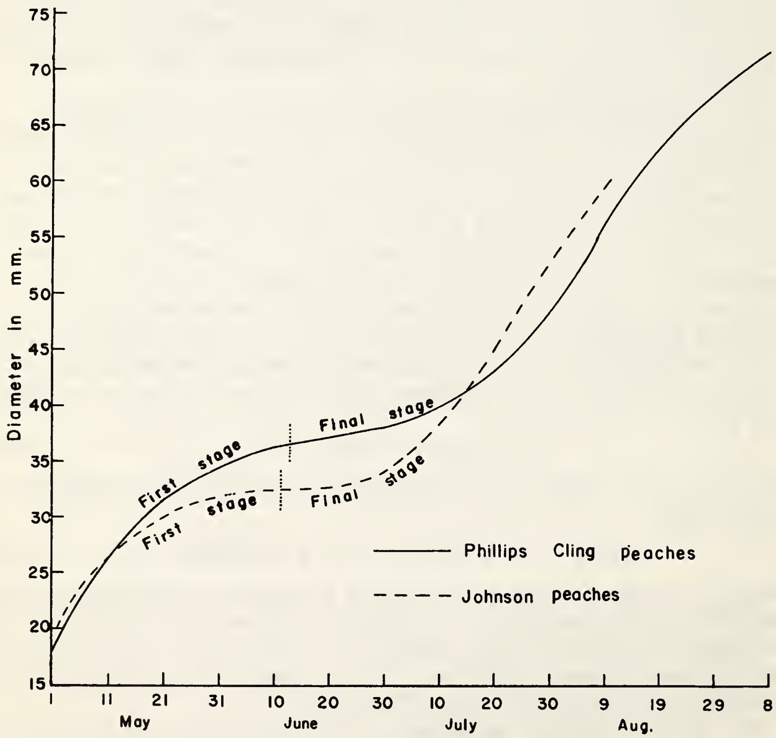


Fig. 6-3. Seasonal growth curve of the fruit of peaches.
After Baker & Davis, 1951

the beginning date of diameter measurement and the shape of the growth curve. Borrowing Karl Pearson's system of frequency curves,[34] they designated the "growth" as L in a linear dimension (i.e., the "cross diameter" in tenths of millimeters) and the time in days as t. Thus, the linear dimension of the growth curve can be expressed as

$$L = a t^{b} \tag{6-8}$$

and

$$L = A(1 - e^{-kt}), \tag{6-9}$$

where a, b, A, and K are constants. The first derivative of the growth curve satisfies the differential equation as below:

$$\frac{1}{y}\frac{dy}{dt} = \frac{a - t}{b_0 + b_1 t + b_2 t^2} \tag{6-10}$$

where y is the growth and a, b_0, b_1, and b_2 are constants. Integration of Equation (6-10) (the total area under the curve) represents the total growth. During the first stage of rapid growth for the Phillips Cling, the daily increment is given by

$$\frac{y_{(t+1)}}{y_t} = \frac{t - 10.6745}{0.7354t - 11.2713}, \tag{6-11}$$

and that for the Johnson by

$$\frac{y_{(t+1)}}{y_t} = \frac{t - 7.0817}{0.4673t - 6.5530}. \tag{6-12}$$

For the final stage of swelling, the daily increment of growth of the Phillips Cling is

$$\frac{y_{(t+1)}}{y_t} = \frac{t^2 - 19.4624t + 121.4820}{t^2 - 14.9108t + 83.5867}, \tag{6-13}$$

and that for the Johnson is

$$\frac{y_{(t+1)}}{y_t} = \frac{t^2 - 11.5320t + 39.4823}{t^2 - 9.6474t + 27.4387}. \tag{6-14}$$

In Equations (6-11) and (6-12), t is indicated in a unit of four days, while in Equations (6-13) and (6-14), t is in a seven-day unit. For all equations, $y_{(t+1)}$ and y_t are successive ordinates of the curve of the first derivative. It has been found that Equations (6-13) and

[34]A comprehensive system of ideal frequency distributions developed by Karl Pearson (1857-1936) is described by W.P. Elderton, 1953, *Frequency Curves and Correlation* (4th ed.), Harren Press, Washington, D.C. For a discussion of the Pearson and other distribution functions, see M.G. Kendall, 1947, *The Advanced Theory of Statistics* (3rd ed.), Griffin, London. Also see Chapter 7 by H.C. Carver in H. L. Rietz, *Handbook of Mathematical Statistics*, Houghton-Mifflin, New York, 1924.

(6-14) can be extrapolated backward much more successfully than Equations (6-11) and (6-12).

Wang & Bryson (1956) have suggested the use of the "Witscherlich" exponential equation for the study of maximum yield. Thus,

$$\frac{dY}{dc} = K(Y_{max} - Y), \quad (6\text{-}15)$$

or

$$Y = Y_{max}(1 - e^{-kc}). \quad (6\text{-}16)$$

where Y_{max} represents the maximum yield obtainable under the conditions available, and c is a combination of climatic factors. In this case, the combination of climatic factors can be obtained separately through both meteorological and statistical means. With these meteorological factors, one can make a refined classification of air masses affecting the growth and development of a plant. Since the air mass itself represents a combination of a group of meteorological factors, a specific value could be established on the basis of its frequency distributions.

Theoretically, an exponential expression may be set up for both positive and negative environmental factors. Positive environmental factors are those significant factors (or simply favorable factors) giving positive correlations to the growth and development of a plant. The reverse are negative environmental factors. Let α and β be a group of positive and negative factors, respectively, correlated with yield; the total yield (Y_t) is expressed as

$$Y_t = Ke^{-a\alpha}(1 - e^{-b\beta}) \quad (6\text{-}17)$$

where K, a, and b are constants to be determined.

Mathematically, the above equation gives the following information regarding the yield of the crop:

(a) If $b = 0$ or $\beta = 0$, then also $Y_t = 0$, or in other words, this group of positive factors determines the yield;

(b) If $a = 0$ or $\alpha = 0$, then $Y_t \neq 0$ and is not a function of α. In other words, this group of factors is not critical to the yield;

(c) At constant α, the yield increases logarithmically with the increase of β toward a maximum value $Ke^{-a\alpha}$;

(d) At constant β, the yield decreases logarithmically towards zero with an increase of α.

To determine whether α and β are positive or negative factors, a simple scatter diagram or a sorting device, to be described in Section 7.5.1, will do.

The use of empirical approaches is common in the study of flowering trees, particularly native species. Several Japanese phenologists have worked out empirical formulations for the calculation of flowering dates of cherry blossoms. To cite a few examples, Nakahara in

1940 correlated a combination of latitude, longitude, and altitude to the flowering date as

$$Y = 93.883 + 5.729(\varphi - 35°) - 0.162(\gamma - 135°) + 1.606h, \quad (6\text{-}18)$$

where Y is the flowering date, φ, the latitude, γ, the longitude, and h, the altitude in meters. According to this equation, the flowering date of cherry trees in Japan is expected to show a difference of five to six days per degree of latitude and two to three days per 100 m of altitude. Also, Aoki & Tazika (1921), on the basis of 20 years' data (1901–1920) in Tokyo, related the flowering dates of cherry blossoms to the mean temperature during February and March as

$$Y = 35.87 - 4.41x, \quad (6\text{-}19)$$

where Y is the flowering date in number of days, counting these days from the 25th of March, and x, the mean temperature between February 16 and March 31. With this equation, they were able to calculate the flowering date within two days of the actual date. Another example is that of the Kyoto Weather Station, based on 1926–1942 data, which calculates the full blossoming dates in terms of differences from the previous year's full blossoming date by employing the mean soil temperature, also in terms of differences from the previous year:

$$x = 0.213 - 1.310y, \quad (6\text{-}20)$$

where x is the difference from the previous year's full blossoming date, and y, the difference from the previous year's mean soil temperature between March 1 and March 10 at 30 cm from the soil's surface.

In England, Smith (1938) made a statistical analysis of phenological data by grouping plants according to the variability of the flowering date as

$$Y = \bar{x} + x_p + x_y + x_s + x_{py} + x_{ps} + x_{sy} + x_r, \quad (6\text{-}21)$$

where Y = any one observation in a particular year; $\bar{x}$ = the mean of all the observations within a group of plants, and for a given plant; x_p = the mean deviation from the mean of one locality; x_y = the mean deviation from the mean of all the years; x_s = the mean deviation from the mean for all stations; and then, x_{py} = the mean deviation from $(\bar{x} + x_p + x_y)$; x_{ps} = the mean deviation from station to station; x_{sy} = the mean deviation from year to year; and x_r = the residual deviation from a given observation. He also made a study on variability of altitude with localities and formulated the following regression equation on longitude, latitude, and altitude for the blossoming dates of the blackthorn for the years 1932–34:

$$W = 104.2 - 0.2x - 0.5y - 0.1x^2 - 0.2xy - 0.2y^2 + 0.14z, \quad (6\text{-}22)$$

where W = the flowering date; x = longitude measured in "squares" (about 19 miles) east of a district D 24; y = latitude measured in "squares" north of a district D24; and z = altitude in terms of feet above sea level. Smith, in his correlation study of meteorological data, plotted the mean flowering dates in each district (13 plants, 35 years) and related them with the corresponding mean of four meteorological factors: mean annual temperature in degrees Fahrenheit, mean sunshine duration in hr/day/year, mean number of rainy days per year, and the total rainfall per year. There were high negative correlations for the first two meteorological factors, low positive correlations for the latter two. Differences in the degree of accuracy of measurement seem to account for this result, since more accurate measurements are available for temperature and sunshine than for rainfall. Also, the number of rainy days as a criterion may result in a misleading effect, and further specifications may be necessary. From this point of view, the use of crop rainy days should be encouraged. A discussion of crop rainy days appears in Section 4.4.1a.

6.4.3 ***Experimental establishment***

Although phytophenology was originally and is still mainly concerned with native plants, increasing emphasis is being placed on the study of agronomic, horticultural crops and fruits. The achievements in phytophenology of native species, particularly the perennials, are a result of many years of observation of the same variety of plants grown in the same general environment. A similar approach would be applicable to agrophenology. The independent variables confronting phytophenologists are the seasonal changes that dominate phenological variations from year to year, provided that the age of the plant has been specified. Hence, in an experimental establishment, control of the crops is necessary. Some of the criteria are:

(a) Standard plants. Specification should be made on species and varieties in conjunction with specifications on environmental conditions of the seeds or root stocks during their parental maturation stage as well as in storage. When cuttings are made for propagation as standard plants, then the same parent plant should be used at all times in order to preserve the same genotype.

(b) Standard soils. Identical types of soils with respect to biological conditions, physical structures, and chemical properties should be employed. The less disturbance there is in the natural profile, the better the physical condition of the soil. Thus, the use of standard sterilized soil would be one of the recommendations.

(c) Standard environment. Maintenance of a similar site, including slope, elevation, surface characteristics, exposure, and surrounding objects such as obstructions, forests, bodies of water, is necessary if a change of site should occur. In addition, maintenance of uniform cultural practices is required, even if the same field is adopted. This is to say that the system of rotation, depths and space of planting (or simply density of population), weed and insect control, and fertility level should always be uniform.

These are, of course, ideal conditions and can be obtained only in an ideally controlled artificial environment, namely the phytotron. But in a partially controlled environment like the greenhouse, or a non-controlled environment such as a natural field, the above considerations are still essential. The degree of success depends upon the technique of observation. As a science, objective observations and quantitative expressions are absolutely necessary. Therefore , the future development of phenology should rely on the standardization of scales for the measurement of phenological events and a systematic recording device. For example, in the observation of leaf-coloring, a standard color scale should be introduced. The ripening of fruits may be tested by a pressure tester, or by analyzing the sugar content, such as in citrus fruits and sugarbeets. Juding the various phases of plant development by standardized photographic plates in the observer's field manual, as has been done by several European phenologists, is highly recommended. The use of phenometry, described in the previous chapter, is also important. In addition to what has been stated for the observation of perennials, either woody or herbaceous, the same plant or a group of plants should be chosen from year to year.

The experimental establishments in the study of phenology have been recognized as a valuable tool; studies have been carried out by various investigators with varying degrees of success. The following is a summary of their methods and results.

In 1921, Salisbury in his study of the phenology of the woodland in England recognized a need for modification in observations, such as the choice of standard plants and standard soil, etc. More recently, Gunton (1940), in his discussion of the phenological report of the British Royal Society, emphasized the importance of selecting plant varieties as a criterion for the improvement of phenological records. In 1932, Hiemeleers emphasized the influence of plant varieties on the flowering time of fruit trees. Baumgartner (1952), in his study of deciduous trees, observed that the development of each individual tree has its own peculiarities. He concluded that these peculiarities must be taken into account in applying phenology to local climatic studies. He found a fairly close relationship between the development of beech leaves and daily mean temperature. A close study of temperature influence (mean and extreme) on various varieties of lilacs was made by Mándy (1949). He examined 66 species of lilacs from his experimental plots to find variations in the length of their spring vegetative period. In short, Gunton, Hiemeleers, and Mándy emphasized the importance of varietal differentiation in phenological studies, and Baumgartner further elaborated the peculiar characteristics within a variety. Following the work of Salisbury (1921), Măde (1952) has recognized that the phenological network is not yet sufficient for detailed mapping. He suggested the use of soil-type charts for improvement of the maps. He illustrated the technique of constructing a phenological chart by using the floral isophane of the snowdrop and the beginning date of field work in the Saxony-Anhalt area near Berlin.

A large-scale experimental establishment known as the International Phenological Gardens was suggested by Schnelle & Volkert in 1957,[35] their purpose being to create possibilities for international comparative studies of phenological observations. They recommended the establishment of a few observational points in each country as "phenological stations of the first order." They suggested a group of hardy plants possessing relatively numerous and distinct phenological phases in all seasons as suitable material for observations, and that these plants should include pine, fir, larch (for conifers), and birch, red beech, and oak (for deciduous trees). Also, vegetative propagation should be adopted for obtaining genetically homogeneous material, and cuttings from the same "mother plants" in order to preserve the same genotype. Moreover, this genetically heterogeneous material, native and foreign, should be adopted for the sake of comparison and elimination of individual peculiarities of plants. Different groups of plants may be chosen to fit geographical areas, but attempts should be made to reduce them to as minimal a group as possible.[36] In regard to suitable sites, a partly sheltered area, preferably a forest area, was recommended as the ideal representative site. Experimental design on density population was also suggested. In addition, it was recommended that meteorological stations be located near the chosen sites. Their emphasis appears to be placed particularly on the study of forests. Up to date, more than 40 gardens have been established between the Scandinavian and Mediterranean countries.[37]

Some analytical techniques in biochemical analysis may be applicable to phenological studies. It should be pointed out here that biochemical analysis does not refer to those chemical treatments which are done in many experiments, such as application of auxins, adenine, and other growth-regulating agents. Rather, it refers to the detection

[35]For details, see F. Schnelle & S. Volkert, 1957, Suggestions for the establishment of "International Phenological Gardens" as stations in a network for international phenological observations, *Meteorol. Rundschau* 10 (4): 130-133.

[36]Măde (1952), in his proposals for making phenological observations, also indicated that a simpler and more representative item of observation would be useful. He gave illustrations by using phenological data at Halle for the period 1894-1939.

[37]According to Schnelle's report to the Fifth International Conference for Alpine Meteorology in Garmisch-Partenkirchen, September 14-16, 1958, 43 gardens are available from 63° Lat. in Sweden to 42° Lat. in Yugoslavia for alpine phenological studies.

of changes in the chemical composition of plants at various phenological stages under natural conditions. Jordan, in 1959, studied the effect of environmental factors on the carbohydrate and nutrient levels of creeping bentgrass (*Agrostis palustris*). In the same year, Beard studied the growth and development of creeping bentgrass roots as affected by certain environmental factors. In 1961, he furthered his study of environmental influences on seasonal variation in amide nitrogen fractions for a number of grasses under natural field conditions. The environmental factors were treated as independent variables for determining their relationships to the percentage of fructose in bentgrass leaf tissues. His statistical computations, expressed in terms of coefficients of multiple correlation, R^2, are given in Tables 6-3 and 6-4. The results indicate that the more factors considered, the higher the correlation would be.

Table 6-3. The Coefficients of Determination (R^2) with Percent Fructose of Bentgrass Leaf Tissue as the Dependent Variable

Independent Variable	R^2
Maximum soil temperature at 0.5"	0.425
Maximum soil temperature at 0.5" + soil moisture at 1"	0.578
Maximum soil temperature at 0.5" + soil moisture at 1" + light intensity	0.686
For all independent variables measured	0.886

After Beard, 1961

Table 6-4. The Coefficients of Determination (R^2) with the Total Amide Content of Bentgrass Leaves as the Dependent Variable

Independent Variable	R^2
Maximum soil temperature at 6"	0.293
Maximum soil temperature at 6" + minimum air temperature at 8'	0.362
Maximum soil temperature at 6" + minimum air temperature at 8' + light intensity	0.391
Maximum soil temperature at 6" + minimum air temperature at 8' + light intensity + soil moisture at 1"	0.431
For all independent variables measured	0.497

After Beard, 1961

Newman & Beard in 1961 emphasized the importance of biochemical techniques in phenological research.[38] They suggested five groups of chemical compounds which can be used as prime indicators of the

[38]As reported from the Third National Conference on Agricultural Meteorology in the revised paper entitled "Some Essentials in Making Phenological Observations," Kansas City, Missouri, 1960.

metabolic and physiologic conditions of the living organism. These compounds may be considered phenological indicators which are detectable only through biochemical means. The groups of compounds suggested are enzymes, toxic compounds, growth substances, reserved nitrogen compounds, and energy storing compounds. Although the techniques of enzyme analysis are still very complicated and not well adapted for environmental studies, potentially these techniques serve as one of the major biochemical parameters in ascertaining the influences of the physical environment. The importance of using toxic compounds, they point out, lies in the lethal effects exerted by those compounds when accumulated in an organism. A third group of compounds, the growth substances, controls or influences various mechanisms such as growth, morphological differentiation, metabolic regulation, movement, tropisms, abscission, flowering, and fruit development in plants. The utilization of reserved nitrogen compounds enables the detection of the degree of protein formation in the plant. For example, excess accumulations of reserve nitrogen compounds may be taken as an indication of unsatisfactory utilization of nitrogen in protein formulation. Glutamine, asparagine, arginine, and urea are the compounds which serve as reserve nitrogen sources. The importance of energy storing compounds is that the quantity and quality of these compounds indicate the equilibrium level between energy utilization and energy capturing processes, particularly in higher plants and animals. The primary compounds of this sort are the carbohydrates. Glycogen is the key storage carbohydrate in higher animals. Mannose, sucrose, fructose, and starch serve as storage carbohydrates in higher plants.

Among the above five groups, the last three have been widely used among biologists and biochemists in their study of environmental relationships. The further exploration of biochemical methods as suggested by Newman & Beard in the study of phenology is strongly urged.

6.4.4 *Time sequence and area analysis*

Phenological analysis of time sequence and space variation may be considered a significant contribution to agrometeorology. Time sequence analysis deals with orderly variations of one or more phenological events with respect to the progress of the seasons. Space variation analysis is concerned with the variation of phenological events at different locations and elevations in association with macro- and microclimatic conditions, and it employs parallelisms for comparison of the atmosphere and isophanes of the biosphere. Although time sequence analysis and area analysis are two different techniques, it should be pointed out that they overlap and no sharp boundary is distinguishable between them.

a. Time sequence. Various techniques have been introduced for the determination of causal relationships among phenological events. Four categories of comparison are considered in this analysis. They are (1) comparison of the same species of plant at the same locality, (2) specific single event of the same species at different localities, (3) events of different species occurring at the same time, and (4) events of different species occurring at different times. The following illustrations will serve as explanations for each of the above four categories.

(1) It has been observed that a certain relationship exists between two events of the same species of plant in a general locality. For some plants, the time interval between two events varies, while it is constant for other events. For example, in Wisconsin, Wang, in an unpublished report, has computed phenological data for the period 1953-60 on peas and corn. It was found that some 18 ± 2 days are required to bring maturation after 75% blossoming of peas and that the time interval between the half silking date and harvest for sweet corn is 25 ± 2 days. The former has a mean standard deviation of three days; the latter, four days. However, the period between sowing and emergence of peas varies from a few days to more than a week, and the time from sowing to silking for sweet corn varies from 2 to $2\frac{1}{2}$ months. A reliable measure of relationship could be established through a comparison of longer and shorter observational series of the duration of each single event, of the period between phases, and of the total life cycle and the natural limitation of the seasons. With accurate analysis, this type of technique can serve as a forecasting tool.

(2) The time sequence of the same event at different localities has been a popular subject among many researchers. According to Hopkins' Bioclimatic Law:

> (i) The periodical phenomena of plants and animals are in response to the influence of all of the complex factors and elements of the climate as controlled, primarily, by the motions of the earth and its position relative to the influence of solar radiation. (ii) The variations in the climate and consequent variations in the geographical distribution and periodical activities of the plants and animals of a continent are controlled by the modifying influences of topography, oceans, lakes, large rivers, and of other regional and local conditions, and the amount and character of daylight, sunshine, rain, snow, humidity, and other elements and factors of a general and local nature. (iii) There is a tendency toward a constant rate of variation in the climatic and biological conditions of a continent as a whole in direct proportion to variation in geographical position as defined by the three geographical coordinates, latitude, longitude, and altitude. (iv) Other conditions being equal, the variation in the time of occurrence of a given periodical event in life activity in temperate North America is at the general average rate of 4 days to each 1 degree of latitude, 5 degrees of longitude, and 400 feet of altitude, later northward, eastward, and upward in the spring and early summer, and the reverse in late summer and autumn. (v) Owing to the fact that all conditions are never exactly equal in two or more biological or climatic regions of the continent, and rarely alike in two or more places within the same region or locality, there are always departures from the theoretical time constant. (vi) The departures, in number of days from a theoretical time constant, are in direct relation to the intensity of the controlling influences. Therefore, the constant, as expressed in the time coordinates of the law, is a measure of the intensity of the influences.

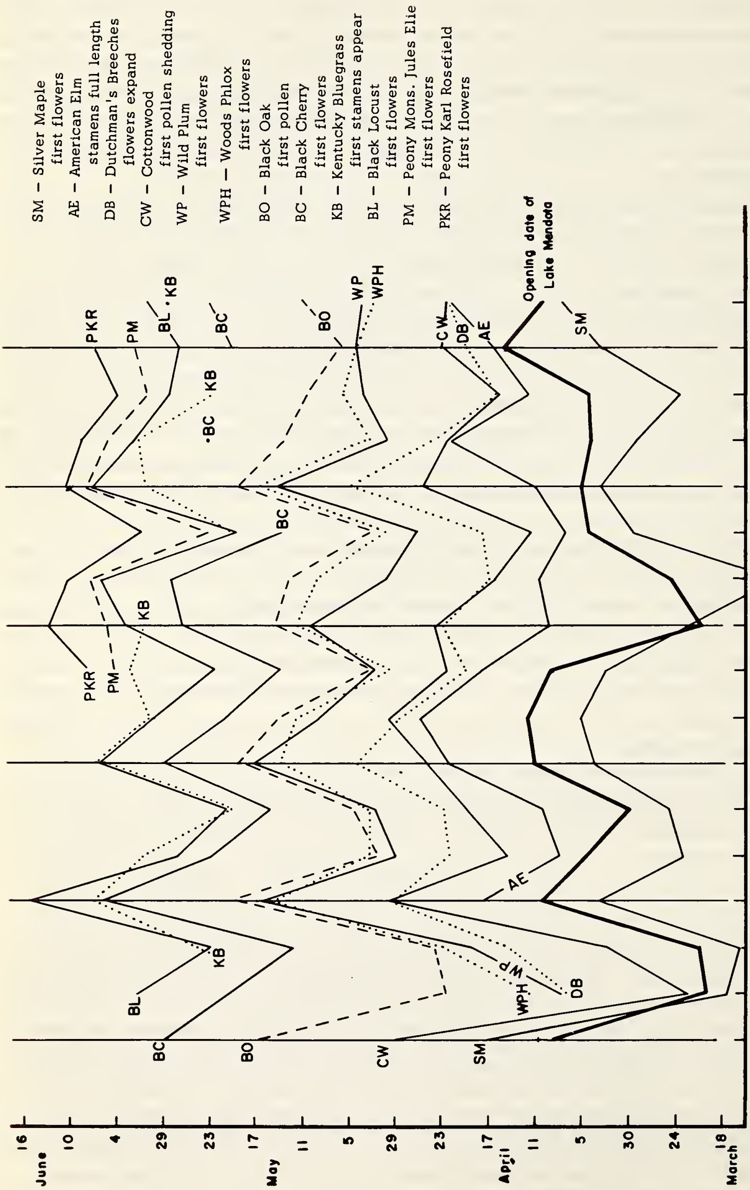


Fig. 6-4. The earliness in flowering of native plants as indicated by the thawing of Lake Mendota, Madison, Wisconsin, 1944-1960.

His law has attracted great attention from all fields of biological science, with both support and criticism.

The British phenologist, Jeffree (1960), in his statistical study of a 58-year record (1891-1948) of floral phenology in the British Isles, found a difference of 21 days in the flowering dates between Bristol and Aberdeen, or one day for every 19 miles (3.7 days per degree of latitude). Another British phenologist, Smith (1938), found that for hazel-nuts and hawthorns, the regression of the flowering date with altitude is about 1.3 days per 100 feet, i.e., 5.2 days per 400 feet. These two findings are fairly close to Hopkins' Law. Sekiguchi (1951) investigated the time variation of cherry blossoming at different altitudes in Japan. His findings indicate about five days' delay on the floral isophene movement for every 100-meter increase in altitude. In his analysis of the isophane and elevation relationship, southerly and northerly exposure factors were employed.

(3) The relationship between phenological events of different species occurring at the same time in the same general locality has been recognized since the early days of farming. For example, the utilization of natural guide plants for sowing and harvesting among the pioneer immigrants to the United States is indicated in the old saying that it was time to plant corn when the white oak leaves were the size of a "mouse's ears," or when the dogwood began to show white in the woods. As has been previously stated, Rosenkranz forecasted the blossoming date of acacia on the basis of the blossoming date of the sweet cherry. Many studies of this sort have been done, particularly in Europe.

(4) The phenological event of different species occurring at different times is another aspect of time sequence analysis. Wang & Zimmerman, in 1960, analyzed 12 different species of native woody and herbaceous perennials in Madison, Wisconsin, with regard to the earliness of spring flowering for the period 1944-1960. It was found that the earliest flowering species (two to three months earliness) could be used as an indicator for the prediction of the flowering date of the late flowering species. In other words, a delay of the flowering date of the early species in a certain year was followed by a delay in the flowering date of the late species, as shown in Fig. 6-4. In 1956, Wang studied the relationship between a five-years' mean yield of barley and that of peas and found similar results. About the same time, Bos, Post, & Kramer made several correlation studies between the leaf-unfolding date of wild chestnuts and the flowering date of early fruits such as apples and pears. Their linear regression proved accurate enough for the forecasting of flowering dates of those early fruits.

Schneider (1952) investigated the relationship between phenological stages on the basis of records obtained from 11 stations in south

Germany. He found close relationships between such stages as beginning of flowering of apples to that of winter rye, beginning of flowering of winter rye to its harvesting, and harvesting of winter rye to that of corn. He determined values of these relationships in terms of sum, mean, and mean extremes of temperature in each of the phenological periods.

b. Space variation. Almost all regional phenologists are concerned with isophanic analyses of all sorts for a large geographical area. In general, there are four factors to be considered in this analysis: latitude, longitude, altitude, and time. The south and north spread of latitude, the east and west extension of longitude, the variation in elevation, particularly the orientation of slope, and above all, the seasonal changes associated with these factors, constitute the isophanic analysis. Hopkins' Bioclimatic Law also comes under this category of analysis, although it does not account satisfactorily for the microclimatic situation, particularly the slope climate. Some important considerations in this approach need to be mentioned. Heterogeneous regions, such as mountainous areas with a large topographical contour, spotty bodies of water, various types of soil, and the presence of forests, shrubs, grasses, and other obstructions, will cause irregularity in the distributions of recurrence of seasonal phenomena. Conversely, regular variation and distribution are found in homogeneous regions. In addition, the circulation — general, secondary, or tertiary—affects the variation in weather patterns and tends to overshadow the analysis of different geographical areas. A global or even a continental area is too large to be of value for rational analysis. Instead, a reasonably uniform physico-geographical unit, such as a large forest, great plain, desert, strip of coastal land, piedmont range, or plateau, should be chosen. For a region containing heterogeneous areas, a further breakdown into smaller units of a homogeneous nature is necessary. Samoilov's study in 1946, on the cultivation of fruits and berries over the mountain slopes of Primor'e, USSR, is an example of experimental work on a unique physico-geographical region. His study was aimed at the selection of fruits and berries which could be cultivated in the general area concerned. The characteristics of the soil-climatic types and their importance for the development of cultivation were carefully analyzed. In observations of temperature, precipitation, snow cover, and biological-phenological events of 34 species of cultivated plants, special attention was paid to aspects of relief and slope influences.

The importance of microclimatic considerations in phenological area analysis is increasingly recognized among modern phenologists. Uhlig (1952) emphasized the value of phenological area analysis as an aid to microclimatological cartography. He proposed the use of certain phenological data in the preparation of climatic charts of a small size (scale of 1 : 10,000 to 1 : 25,000), emphasizing particularly the use of data on plant phases and plant stages at given dates. Another example of area analysis appears in the work of Seemann in Germany. Based upon the climatological and phenological condition of winter rye in northwestern Germany, Seemann, in 1949, concluded that planting of supplementary crops is possible after harvest of the first crops, i.e., during the months of August and October. In support of this statement, he presented large isoline charts of the mean, beginning, and duration of the season favorable to the additional crops. Factors such as the average and the frequency of various amounts of rainfall as well as insolation were employed in his analysis. Also, in 1950, on the basis of an extensive study of climatological and phenological reports from several stations in northwestern Germany, he discussed the intensity of the frost damage on the various fruit-growing areas during the blooming period. In the same year, Schnelle made informative phenological charts indicating frequencies of frost days during and outside the blooming period of cherries and apples in Bad Kissingen for the years 1936-49.

Preparation of regional phenological maps in association with microclimatic effects is another aspect of space variation studies. In 1905, Ihne prepared regional maps of the arrival of spring in the region of the former Grand Duchy of Hesse in Germany. His charts were capable of furnishing Hessian farmers with valuable information that ordinary weather stations could not supply. Hesse is a small state of approximately 8,150 square miles, but due to its mountains and valleys, there are marked contrasts in the climate among various districts, which results in a variation of agricultural patterns. Taking this peculiarity into consideration, Ihne's chart of the "normal advance of spring" divides the region into eight zones, representing successive periods of four days each in the spring calendar. The date adopted to represent the "arrival" of spring is the average flowering date of 13 common trees and shrubs and also coincides with the flowering date of early varieties of apple. This normal date varies among zones; for instance, it is April 21st for one zone, while for another it is May 20th. With the aid of these charts, Hessian farmers were able to improve their farming operations in scheduling planting and harvesting dates and in introducing new species and varieties. Since then, many European phenologists, particularly in Germany, have contributed a considerable amount of research to microclimatic phenology. Among them, Schnelle's work is worthy of special attention. In 1951, he pointed out the need for climatological summaries geared to natural periods of vegetation and stressed methodology in phenological climatology. In construction of phenological maps, Schnelle employed the criteria of area differentiation and variation of elevation. Areas in different geographical locations at similar altitudes, areas with different altitudes but in the same general localities, and areas with different altitudes and geographical locations were compared and evaluated in terms of their phenological relationships. The beginning of phenological phases, duration between phases, and speed of horizontal and vertical isophane movement were studied for areas of similar altitudes in different localities. A similar study was made for areas in the same general localities with different altitudes. Then he made a simultaneous comparison of areas with different geographical locations and different altitudes, and finally the phenological characteristics of the region were determined.

In considering the evaluation of locational differences in mapping, the following types of phenological maps were discussed by Schnelle in 1955: a map of individual phenological phases, a map of natural climatic cultivated areas, the combination of phenological and cultivation maps, a map of the equal departure of isakairs, phenological synoptic maps, a phenological simulated map, a systematic isophanic map, and a large phenological map. Various maps of individual phases have been analyzed by Schnelle, as illustrated in Figs. 6-5 and 6-6.

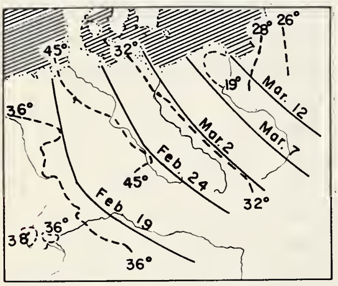


Fig. 6-5. Geographical distribution of snowdrop isophane and isotherms in Germany and Poland, 1936-39.

—— Isophane of snowdrop blossoming

--- Isotherms of February

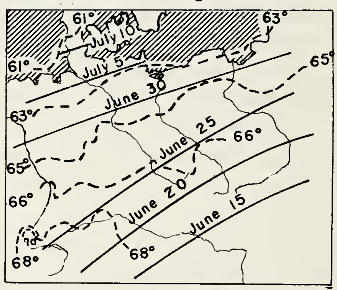


Fig. 6-6. Geographical distribution of the harvesting date of winter rye and oats in Germany and Poland, 1936-39.

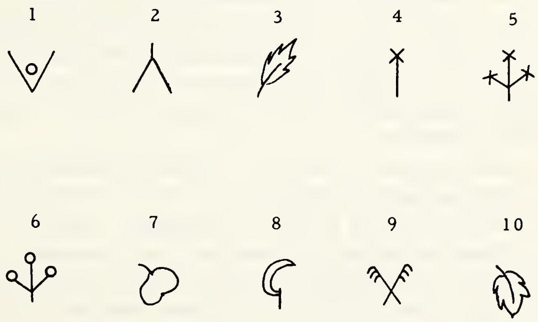
—— Isoline of winter rye and oats harvesting date

--- Isotherms of July

After Schnelle, 1955

Fig. 6-5 shows that the February isotherms of areas in Germany and Poland are almost parallel with the floral isophane of snowdrop. Fig. 6-6 shows that the July isotherms of the same areas are parallel with the isolines of the harvesting date of winter rye and oats. Areas concerned are under 200 square meters, having about the same altitude. Up to summer, the isophane and the isotherms show a fairly equal trend, as shown in Figs. 6-5 and 6-6. However, with the approach of autumn, these two kinds of isolines no longer display any similarity. By November, once again a similar course of both isophane and isotherms is observed.

Synoptic maps may represent day-to-day progress of individual phases or various growing phases on the same day. When the weather station symbols[39] and the phenological symbols (see Fig. 6-7) are plotted on a daily synoptic map, the investigator will be able to study the sequence of weather change as well as that of plant development. He may first consider the two sequences separately, and then jointly. This will help him to understand the complete picture of the synoptic pattern as related to the geographical distribution of the phasic development of plants. The phenological simulated map is an air-photo map taken simultaneously over a large area containing various stages of development of many species. The systematic isophanic map is designed after Hopkins' Bioclimatic Law. The large phenological map is representative of Smirnov's bioclimatic studies of Europe and the USSR, 1937 and 1938, respectively. In his study of the bioclimate of Europe, Smirnov established a station in the middle latitude where all European plants can be observed for the first blooming date, and made comparisons with the results of other stations throughout Europe. This type of map is suitable for phenological observations on a very large scale for one or more continents.



Red	1. Sowing
Green	2. Vegetative growth 3. First leafing
Red	4. First blooming 5. Full blooming 6. Last blooming 7. Fruit setting 8. Fruit picking 9. Harvesting of grains
Brown	10. Leaf falling

Fig. 6-7. Illustration of symbols of phenological phases.

After Riedat (see Schnelle, 1955)

[39]Weather station symbols and codes are issued by numerous weather services and may also be found in textbooks of general meteorology. The reader should refer to the newest published symbols and codes of the station nearest him. Symbols and codes do change at times.

6.4.5 *Periodicity and prediction*

During the past 40 years, attempts have been made at weather prognosis and crop prediction on the basis of phenological periodicity. Various degrees of success have been achieved. It may be said that there are two main avenues of approach: (a) forecasting weather by means of phenological techniques, and (b) forecasting crop by means of weather information.

(a) Weather prognosis. Early in history, many weather lores consisted of phenological events employed for a short-term weather forecast, i. e., a period of 6 to 12 hours in advance. From time to time, early synopticians faced the problem of making correlations between weather prediction and phenological events. It went fairly well when the phenological events of animals were used, because of their keen responses to weather change shortly before its occurrence. Ewer (1952), in his paper on "Animal Weather-Prophets," stated that careful observation of the behavior of animals would enable one to presage weather. His review of the literature on this subject cited many animal weather lores. Taylor's "Weather Guide" (1812) and Clouston's "Popular Weather Prognostics of Scotland" (1867) illustrate weather prediction through annotated weather proverbs of phenology. Napier Shaw (1911) recognized the use of biological events in weather lore as one possibility of weather prediction. Humphrey (1923), in his "Weather Proverbs and Paradoxes," provided scientific explanations for selected weather lores.

The use of phenological events for weather forecasting two years in advance was attempted by Margary in 1926. Observations of the date of leafing were made for birch, oak, beech, horse-chestnut, and lime, and the flowering date for snowdrop and hawthorn. To obtain reliable comparisons, the means of these seven plants were determined. He averaged the phenological dates of these plants for each year in a 123-year period. Then he computed the five-year running mean thus: the value of 1920 is the sum of 1918 through 1922 divided by five. The values so obtained were correlated with the five-months' mean air temperature (January to May) for each individual year. A regression line indicated that a 2°F seasonal temperature rise was associated with a five-day advance of phenological events. In other words, the higher the temperature, the earlier the occurrence of phenological events. Also, he was able to determine the periodicity of phenological events by means of the so-called "bloxamed" curve, which is the curve indicating the relationships between the mean dates of phenological events and the march of years. By the trend of the curve and the result of the regression line, he predicted that the spring of 1926 would be rather mild and early, but that of 1927 decidedly cold and late. The British Royal Meteorological Office reported the year 1926 as a mild year with about average rainfall, deficient sunshine, and earliness of spring isakairs. The year 1927 was reported as a wet, cold year with a dark and wet summer and late spring. This agrees very well with what had been predicted by Margary.

Schneider (1949) analyzed the 1870-1946 data of the horse-chestnut vegetative period. His findings indicated a close parallel between the 11-year rhythm and the sunspot cycle. The 11-year rhythm was also found in other vegetables on the Rhine Plain. His approach is similar to that taken by many others.

The type of study illustrated in the above two works is subject to much argument. Its usefulness depends not only upon the existence of periodicity of phenological events, but also upon whether or not there is a causal relationship between the earlier weather phenomena and the later, e.g., whether the weather in the spring of a certain year could be a guide to that of the summer for the same year. The persistence forecast[40] of weather has not yet been confirmed, while the existence of the phenological periodicity has often been observed. The scientific value of this type of study needs to be further justified. A more scientific approach to local weather prognosis is in order.

Bogorov (1938) studied biological seasons of the Arctic Sea. He found that the relationship between biological seasons in the plankton and ice conditions could be used for local ice prognosis. The seasonal distribution of phytoplankton and zooplankton in the different locales of the Arctic Sea was observed and a relationship was established between the two variables. The ratio of phytoplankton to zooplankton is a value characterizing the seasonal stage of plankton development in a given area.

Scorer & Ludlan (1953) studied the nature of convection as revealed by soaring birds and dragonflies. They indicated that birds and dragonflies can be used as phenological indicators of the extent and intensity of vertical currents, the direct measurement of which had not yet been done. In their study of the relationship between the soaring birds and upcurrents, they developed the so-called "bubble theory of convection."[41] The soaring of small birds indicates the beginning of

[40]In meteorology, a forecast that the future weather condition will be the same as the present condition. The persistence forecast is often used as a standard of comparison in measuring the degree of skill of forecasts prepared by other methods.

[41]The "bubble theory of convection" has been explained by Scorer on an aerodynamic dimensional idea that the rate of ascent ω of a bubble depends on its buoyancy, gB, where B is the percentage deficit of density, and a linear dimension, R, thus:

$$\omega = \text{const}\ (g\,B\,R)^{\frac{1}{2}},$$

and the constant is non-dimensional. The buoyancy is proportional to the temperature excess, so that if the amount of heat in the thermal bubble is constant, when it is diluted to size R_1 and buoyancy B_1, we find that $B_1 = B\,R^3/R_1^3$ and

$$\omega_1 = \text{const}\ (g\,B\,R)^{\frac{1}{2}}\ R/R_1,$$

and the velocity is decreased. Assume that the buoyancy of the bubble produced is proportional to the average excess, ϵ, of the temperature in that layer. Adiabatically, then, heat eddies, and that of large birds, the rising air that extends to a higher level of the atmosphere. On calm and hot sunny days, the air streams steadily upward from fixed localities for the first few meters. The soaring of birds indicates that convection develops upward, the heavier birds which soar at greater heights taking to the air last. The upper currents are stronger and wider at greater heights and drift with the wind, and when convection is intense, the upcurrents appear more sharp-edged. Puffs of wind are associated with the descent of air from above the superadiabatic layer to replace a part of that air that is ascending as a newly created bubble. When the air is stirred mechanically by the wind, the bubble formation in the lower air is reduced. Scorer & Ludlam's "bubble theory" was used to interpret the observation of Hankin (1913) on the soaring of birds in India. When the theory was used in conjunction with the daily synoptic analysis, it enabled the forecasting of weather by the observation of birds.

The recent interest among scientists in the relationship of upcurrents, birds, and insects is also seen in Rainey's study (1951) on "Weather and Movements of Locust Swarms," Förchtgott's study on "The Transport of Small Particles or Insects over the Ore Mountains," Mori's discussion (1940) on "Atmospheric Pressure and Insects," and Landsberg's research (1948) on the "Pressure Pattern and Migration of Birds."

(b) Crop prediction. In general, various studies mentioned in Sections 6.4.1 and 6.4.2 could be applied to crop prediction on the basis of weather phenomena. To cite a few examples, Bider (1946), in his "Attempts at an Early Forecasting of the Cherry Harvest," used meteorological elements together with phenological observations to predict the date of the cherry harvest. In the same year, he and Meyer predicted the cherry harvest in northern Switzerland by the use of the same method. Schneider (1952) found that a sum, mean, and mean extreme of temperature in phenological intercourse as related to flowering times in different years are close enough to warrant a forecast. Herbst & Lessmann in 1950 reported on the effect of weather on the development and yield of crops.

$B \propto R \propto \epsilon z$, where z is the height and the bubble is R. Then

$$\omega \propto (g\epsilon z \cdot z)^{\frac{1}{2}}$$

If the amount of heat transported upwards is the same at all levels, and the same fraction of the total areas is occupied by thermals, then the product $B\omega$ must be independent of height and so

$$\epsilon^{\frac{3}{2}} z^2 = \text{const}$$

In the layer which is transporting heat upwards by this process, we find that

$$\frac{\partial \theta}{\partial z} \propto z^{-\frac{4}{3}}$$

where θ is the potential temperature. This is quite typical on convection days and this lapse rate would give small bubbles a small vertical velocity with greater excess in temperature than the larger bubbles.

In conclusion, agrophenology, just as any other phenology, contributes particularly to the chronology of plants and animals. This involves events of visible and invisible morphological appearances, biochemical changes, and physical characteristics. The time interval of observations can be as short as hours and as long as days and even years. The results of these observations can be useful for analysis, interpretations, forecasts, and control with respect to production, quality, and maturity, which could be valuable guides to agricultural operations.

Since agrophenology is again a horizontal science, the reader is advised to consult related sections for a better understanding of the subject. For example, Section 6.4.2 on "empirical formulation" should be studied in conjunction with the "heat unit system" (see Section 4.2.3) and the "statistical and mathematical approach" in Chapter 7, particularly Section 7.4.1 on "phenological approach." Also, Section 6.3.3 on "phenological season" associates with the "growing season" in Section 4.2.2. Owing to the interrelationships among subjects, certain repetitions appear from time to time. It is hoped that these overlapping topics will aid in reinforcing one's understanding of the subject.

Studies on birds, native plants, etc., are not, strictly speaking, subjects of agrometeorology. The inclusion of these subjects here is due mainly to some valuable indirect links between agriculture and the applicability of methods used in these subjects to agrophenology. Since there is an enormous amount of complex information in phenology which cannot be dealt with in the space of a chapter, the reader should consult references for further study.

As pointed out previously, there are two schools of thought. The one group led by Berg believes that phenological data cannot be represented exactly by a sum of functions of different climatic elements. According to Berg, phenological data represent a climatic element *sui generis*. However, the greater majority of phenologists believes that there is a definite link between climatic changes and phenological events. A combination of methods of the two schools would be a valuable asset for future phenological research.

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CHAPTER 7

Statistical and Mathematical Approach

7.1 INTRODUCTION

The *quantitative expression* of growth and development of domestic species of plants and animals and their responses to the environment is essential in agrometeorological research. A systematic treatment of the subject by means of statistical and mathematical methods is absolutely necessary whenever applicable. This involves the replacement of less exact descriptive expressions with figures as well as statistical and mathematical notations, thus reducing individual bias to a minimum. It also allows for the verification of others' research findings without unnecessary arguments. Although it is sometimes difficult to achieve, statistical and mathematical analysis is indispensable for truly scientific studies. Such analysis and its expressions are nothing but a group of symbols which convey the ideas of the user in a systematic fashion. Therefore, the application of an appropriate method to each specific problem is important. Whenever any formulation is applied, its basic assumptions, its limits, and its validity should be fully understood. Thus, all formulations should be based upon the *interpretation* of physical principles and physiological laws. The purpose of this chapter is to introduce pertinent methodology in statistics and mathematics to the reader in order to make agrometeorology an "exact" science.

7.2 BASIC CONCEPT

Agrometeorology covers almost all subjects in the science of agriculture, involving biological sciences relating to both plants and animals, such as horticulture and poultry husbandry, and also physical sciences, such as soil physics and hydrology. In this wide area of coverage, intelligent schemes and methods are necessary guides to research. Since it is methodology that is of concern here, only some of the problems of statistical and mathematical application to crop-response studies are used for illustration. The proper use of methods and formulations in treating crop and environmental data depends upon some fundamental considerations of agrometeorological problems. The basic concepts which have been stated in Chapter 3 will be summarized and further elaborated shortly.

As shown in Fig. 1-1, the boundaries of agrometeorology are presented by a group of allied and related subjects. The recognition and differentiation of each subject as well as the relationships and interrelationships among them are our first consideration. In the study of plant response, for example, plant physiologists deal with a few individual cultivated plants or sometimes even one specific organ of these plants, while agrometeorologists deal with a large number of plants, covering areas of several acres. Should air temperature and moisture be significant environmental elements for a specific critical period of crop growth, the representative air temperature and moisture values of the entire field would be needed instead of only that of a single greenhouse. Should leaf area be an important measure in the study of photosynthetic efficiency, again the measurement or estimation of all leaves to the acre would be appropriate. The ideal is to obtain the average value of the environment in a four-dimensional space,[1] because point-source data are not representative. This is an illustration of the differentiation in methods of approach among subjects. Nevertheless, physiological laws governing plant growth and development which have been carefully and concisely treated by plant physiologists should be used as the first fundamental consideration for research by agrometeorologists. When soil is a factor, edaphology and soil physics should be the first two subjects referred to. The former deals with the relationships of soil, plant, and climate; the latter treats soil as a physical system. Principles, laws, theories, and even hypotheses and speculations in these two subjects would be important in statistical and mathematical formulations. Other related subjects, such as agrobiology and pedology, should of course be consulted when necessary. This is an illustration of the functional relationships among subjects.

Other basic concepts, such as the assumption of constancy of biotic factors, the principle of differentiation of growth and development, the theory of phasic differentiation, and the principle of physiological preconditioning, should also be considered in statistical and mathematical analyses.

The assumption of the constancy of biotic factors is a necessary step in the treatment of phenological data in agrometeorology, par—

[1]Length, width, height, and time. Thus, an agrometeorologist should consider the time variation of environmental elements both horizontally and vertically, e.g., the change of the vertical air temperature gradient with time.

ticularly long-term historical data. By applying this assumption, it is possible to isolate variables pertaining to biotic influences from those of the physical environment. A description of this assumption is given in Section 2.1.2, and its application is shown in Section 3.4.1, where graphical methods for constant trends and variable trends in crop yield are described. The mathematical presentation for a constant trend is described below.

A simple mathematical formulation[2] can be set up by means of the actual yield (Y_a), the actual mean yield ($\bar{Y}$), and the modified factor (b). Thus, the modified departure (Y'_d), which is the difference of any individual case (Y_i) from the modified mean ($\bar{Y}'_d$), can be expressed as

$$Y'_d = Y_a - (\bar{Y} + b) . \tag{7-1}$$

The modified factor b can be obtained from

$$b = k\sigma(2n_i - N)/N , \tag{7-2}$$

where k is any fraction of standard deviation of the mean yield; σ is the standard deviation of the mean; n_i is the number of linear units used, counted from the first year; and N is the number of linear units between the first and last years. For further use of this assumption, the reader should justify the use of each individual case for specification. In other words, he has to decide which trend to follow in order to eliminate the influence of biotic factors affecting the yield. This holds true for the study of other biological events, such as flowering and maturity date.

The differentiation of growth from development, as explained in Section 3.1, has been further elaborated in Chapter 6, with special emphasis on the problem of development. The choice of methods should be based upon the recognition of the distinction between growth and development. Such consideration, in association with physiological preconditioning or predetermination, as well as the theory of phasic division, is the most fundamental and necessary step before proceeding with statistical and mathematical operations. Physiological predetermination is described in Sections 3.1 and 4.2.1, and will be further elaborated in Section 8.3.

As mentioned previously, the application of greenhouse results to the natural field is a task of the agrometeorologist. Naturally, greenhouse records should be modified to some extent in order to be useful under field conditions. This is possible by employing the basic concepts stated above, and will be discussed shortly in Section 7.4.3.

[2]Equations (7-1) and (7-2), obtained by constructing two similar triangles between the actual mean yield line and the modified mean yield line and by ratios of corresponding sides of these trianges, are illustrated in Fig. 3-7, where k is $\frac{1}{2}\sigma$, i.e., the modified mean yield is adjusted one-half standard deviation below the arithmetic mean yield line for the first year, and one-half above the mean yield line for the last year; n_i would be 6, if the year 1951 is taken, because the first year is 1945; N is 14 because the first year is 1945 and the last year is 1959.

7.3 SOME FUNDAMENTAL KNOWLEDGE

As mentioned earlier, modern statistics, particularly biostatistics, is a powerful tool in the development of modern agrometeorology. Here we emphasize that statistics is a tool, and not a way to solve our problems. The way or method is based, first, upon fundamental concepts which include physical laws and physiological principles; secondly, we should have reliable instruments for measuring the microenvironment. The use of a statistical treatment depends upon the type or nature of the problem, amount of data, and methods of computation. For a large amount of raw material, or for a complicated and lengthy operation, electronic computation is recommended. There are several publications the reader can use for reference.[3]

7.3.1 *Statistical manipulations*

The statistical approach to a specific problem involves careful evaluation, analysis, and control of the chances that must be taken when making a generalization. In using statistics as a tool, we must not merely concern ourselves with looking at sets of data, performing certain calculations, and arriving at conclusions, but it is important to ask how the data were collected and how the whole experiment or investigation was planned. A brief review of some fundamental principles and operations involved in agrometeorology is presented in Appendix B.

[3]Recommended references on statistics and biostatistics as related to agriculture are:
a. Snedecor, G.W. 1956. Statistical methods (Applied to experiments in agriculture and biology). 5th ed. Iowa State College Press, Ames, Iowa. 534 pp.
b. Steel, R. G. D., & J. H. Torrie. 1960. Principles and procedures of statistics, with special reference to the biological sciences. McGraw-Hill Book Co., Inc., New York. 481 pp.
c. Fraser, D. A. S. 1957. Nonparametric methods in statistics. John Wiley & Sons, Inc., New York. 299 pp.
d. Cochran, W. G., & G. M. Cox. 1957. Experimental designs. 2nd ed. John Wiley & Sons, Inc., New York. 611 pp.

Recommended references for statistics in meteorology:
a. Brooks, C. E. P., & N. Carruthers. 1953. Handbook of statistical methods in meteorology. Her Majesty's Stationery Office, London. 412 pp.
b. Penofsky, H., & G. W. Brier. 1958. Some applications of statistics to meteorology. Pennsylvania State University, University Park. 224 pp.

Recommended references for reviewing basic mathematics:
a. Fisher, R. C., & A. D. Ziebur. 1958. Integrated algebra and trigonometry. Prentice-Hall, Inc., Englewood Cliffs, New Jersey. 427 pp.
b. Taylor, A. E. 1959. Calculus with analytic geometry. Prentice-Hall, Inc. Englewood Cliffs, New Jersey. 762 pp.
c. Kaplan, W. 1952. Advanced calculus. Addison-Wesley Press, Cambridge, Mass. 679 pp.

Recommended references for electronic computer programming:
a. Jeenel, J. 1959. Programming for digital computers. McGraw-Hill Book Co., Inc., New York. 507 pp.
b. McCracken, D. D. 1961. A guide to fortran programming. John Wiley & Sons, Inc., New York. 88 pp.
c. Leeds, H.D., & G.M. Weinberg. Computer programming fundamentals. McGraw-Hill Book Co., Inc., New York. 368 pp.

7.3.2 *Mathematical operations*

Mathematical approaches are somewhat different from those of statistics, even though the boundary between them is hard to delineate, for the former provide principles, theories, laws, and even methods for the latter. Much of the world of mathematics is a world of imagination,[4] expressed in numbers, symbols, lines, circles, and whatever, the practical end of which results in setting up the foundation of sciences. Appendix C gives a summary of mathematical operations employed in agrometeorology.

7.4 METHODS OF FIRST APPROXIMATION

At the present stage, the available data on crops and environments are still inadequate for an accurate statistical treatment. Neither do we have enough quantitative expressions for all crop events established, nor do we have sufficient microclimatic environments well measured. Even if we had these data, factors other than environmental factors which influence the growth and development of crops are not altogether known. Thus, the conclusion is that a one-to-one relationship cannot be established at the present time as far as crop-response studies are concerned. The only possible means is to obtain a first approximation; from there on a closer relationship can be established through methods of systematization, as will be explained in Section 7.5. Three approaches are suggested for the first approximation: the phenological, meteorological, and phenometeorological approaches.

7.4.1 *Phenological approach*

As was fully discussed in the previous chapter, the relations of an earlier event and a later event of the same plant, of different plants of the same species, and of different species, have been studied by many authors with various degrees of success. In Section 6.4, various statistical and mathematical formulations have been introduced for research on both native and cultivated plants. As a matter of fact, plant phenologists and agriculturists are highly interested in this type of study. This approach is possible because one considers that a plant is an integrator of all climatic changes surrounding it, besides the internal effects due to the genetic make-up. Accordingly, no direct environmental measurement is needed. Thus, an avenue of approach for the agrometeorologist is first to leave the physical environmental factors aside, and to deal with the biological relationships between

[4] Mathematics is a purely human invention, which we use as a tool, a method of describing idealized experiments including measurements and observations which are exact duplicates of real ones. Measurements and observations can be neither strictly accurate nor perfect. However, the idealization of mathematics guides sciences through the right avenues.

events. The degree of relationship should be established statistically, distinguishing the good and poor correlations. If a good relationship is found, it would serve as the first approximation, to his satisfaction. If a poor relationship appears, he may improve it by using the environmental factors in further consideration. Stated another way, in general, no perfect correlation has been found between events; therefore, the deviations from perfect association can be further tested by environmental factors. For example, Wang in 1961 made an intensive investigation on the tons-per-acre yield, Y, and quality, Q (in tenderometer readings, or T.R.), of Early Perfection peas grown in Janesville, Wisconsin, and Rochester, Minnesota, as related to the various stages of growth, such as number of days from planting to blooming, D_1, from blooming to harvesting, D_2, and from planting to harvesting, D_3. He used 263 samples for Janesville, and 361 for Rochester, and for both localities, five-year data (1956-1960) were investigated. The statistical manipulations are listed in Table 7-1.

Table 7-1. Pea Phenology Analyses in Janesville, Wisconsin, and Rochester, Minnesota

A. Mean and Extreme

Locality	Mean Number of Days (Extreme range of variation)			Standard Deviation			Mean Y (range)	Mean Q (range)
	D_1	D_2	D_3	D_1	D_2	D_3	Tons/Acre	T. R.
Janesville	47 (36-57)	20 (15-28)	67 (56-84)	5	3	6	2.03 (0.66-4.95)	107 (84-164)
Rochester	44 (12-59)	21 (12-29)	65 (33-79)	7	3	7	1.86 (0.30-3.44)	109 (80-147)

B. Correlation Coefficients (r):

	Janesville					Rochester				
	Q	Y	D_1	D_2	D_3	Q	Y	D_1	D_2	D_3
Q	1.00	0.31	0.09	0.09	0.12	1.00	0.29	-0.03	0.51	0.21
Y		1.00	0.14	0.22	0.23		1.00	0.20	0.21	0.31
D_1			1.00	-0.02	0.88			1.00	-0.29	0.89
D_2				1.00	0.46				1.00	0.18
D_3					1.00					1.00

In Table 7-1.B, the correlation coefficients are listed for Janesville and Rochester; Q versus Y for the former is 0.31, and for the latter, it is 0.29. Thus, the most significant relationship among all possible correlations is D_1 versus D_3 for both localities. It is $r = 0.88$, or $r^2 = 0.77$ for Janesville, and $r = 0.89$, or $r^2 = 0.79$ for Rochester. The significance level for both cases is $P < 0.01$. This signifies that there is a close relationship between "the number of days from the planting to the blossoming date, D_1," and "the number of days from the planting to harvesting date, D_3;" they have a coefficient of determination around

0.80, and a confidence level of over 99%. Their relationships can be expressed as:

$$D_3 = 1.283\,D_1 + 6.694 \text{ (for Janesville);} \qquad (7\text{-}3)$$

$$D_3 = 1.096\,D_1 + 16.646 \text{ (for Rochester).} \qquad (7\text{-}4)$$

The above findings would be useful in forecasting when D_1 is known.

As far as the tenderometer reading and yield are concerned, it shows that Y has a multiple correlation of 0.37 with Q and D_3 both for Rochester and for Janesville. These are the highest multiple correlations among all possible combinations of all available factors. The respective regression equations are:

$$Y = 0.01317\,Q + 0.01857\,D_3 - 0.6282 \text{ (for Janesville);} \qquad (7\text{-}5)$$

$$Y = 0.00891\,Q + 0.01974\,D_3 - 0.3971 \text{ (for Rochester).} \qquad (7\text{-}6)$$

However, the simple correlation between Y and Q is $r = 0.31$, or $r^2 = 0.10$, and $P < 0.01$ for Janesville; the regression equation is

$$Y = 0.1426\,Q + 0.494. \qquad (7\text{-}7)$$

For Rochester, the multiple correlation for Q, D_2, and Y is 0.54; $r^2 = 0.29$, and $P < 0.01$. The regression equation is

$$Q = 1.951\,D_2 + 4.792\,Y + 58.89. \qquad (7\text{-}8)$$

Again, for Rochester, the simple correlation between Y and Q is smaller than the multiple correlation; it is $r = 0.29$, or $r^2 = 0.08$, and $P < 0.01$. The regression equation is

$$Y = 0.1102\,Q + 0.661. \qquad (7\text{-}9)$$

This does not necessarily imply that all functional relationships between phenological events in this example are linear. This may partially account for the poor correlation, particularly in equation (7-9). Poor correlations are caused mainly by variations in environmental factors. Therefore, the deviation of phenological events from the normal trend can be further correlated with environmental factors. For example, in the case of Janesville, when Y is plotted against Q for each individual year, the perpendicular distance from the scattering point to the regression line which is described in equation (7-7) can be tested by the environmental factors, such as the variation of temperature, rainfall, and the like. Thus, any regression line, either linear or curvilinear, among phenological events can be used as the trend and as a guide for environmental studies.

Since Chapter 6 has a full account on phenological approaches, no further illustrations will be given in the present section. For further studies, the reader may refer to the references listed in Chapter 6.

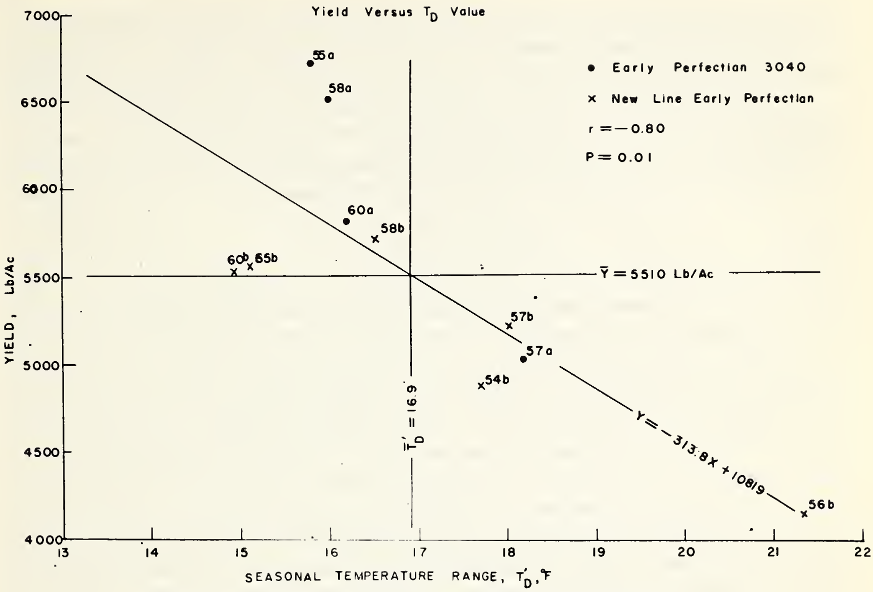

Fig. 7-1. Peas grown in Janesville, Wisconsin.

7.4.2 *Meteorological approach*

Emphasis is placed here upon physical factors, such as temperature and rainfall, instead of phenological events, such as germination and flowering. First of all, we are interested in finding the causal relations between one meteorological element and another. In the study of temperature-rainfall interaction, it is necessary to know the quantitative relationship between the two elements in the same locality. The number of warm or cold spells in a season, as characterized by temperature, in relation to the number of dry and wet spells, as characterized by rainfall in the same season, is an example of such a study. The amount of rainfall in each individual rainy day as related to the minimum temperature of that specific day would be another example. Of course, specifications, such as intensity, duration, amount, and type of rainfall, and those of temperature, should be made. Further specification of frontal movement (e.g., cold or warm front), wind direction and speed, cloudiness condition of synoptical situations, and the like should also be made in order to establish a reasonable physical link between meteorological factors (or rather between the environmental factors). This type of pure physical approach may involve a pair of single elements such as wind velocity versus frequency of maximum temperature, or a group of elements versus another group such as photothermal unit and energy degree unit.

Environmental factors fall into the following three basic categories: photoclimatic, thermoclimatic, and hydroclimatic units. In view of plant response studies, these three groups are established primarily for the purpose of studying the crop-environment relationship in a large geographical area. For example, the photothermal unit (P.T.U.), which has been defined in equation (4-40) in Section 4.2.3, is one of the expressions of the photoclimatic unit. Nuttonson (1955) has made a comparative study of the cumulative degree-day (i.e., the remainder system; see equation (4-35) in Section 4.2.3) and the photothermal unit requirements of wheat varieties grown in different parts of North America and in some of their climatically or thermally analogous areas in wheat-growing regions of the Soviet Union and Finland. His method of agroclimatic analogues attempts to disclose the thermal and photothermal requirements of both winter and spring wheat grown under field conditions, to provide a means for a physiological-thermal classification or indexing of wheat varieties, and to develop criteria for predicting dates of heading and maturity of wheat. He recommended 40°F as an appropriate threshold value for the summation of temperatures in various phenological stages, such as sowing to heading, emergence to heading, and heading to ripening, from station to station in a large geographical area. The statistical results indicated that the 40°F threshold, of all possible threshold values, yielded the smallest coefficient of variation in the mean thermal requirement of wheat from year to year. He recognized that the summation of degree-days of the same variety of wheat varies with changes in latitude, altitude, and precipitation. Thus (i) within areas of fairly similar elevation, an increase in latitude shows a decrease in degree-days summation; (ii) within areas of a fairly narrow range of latitudes, an increase in elevation results in a decrease in degree-days summation; and (iii) within areas of similar temperature, latitudes, and altitudes, more adequate soil moisture conditions appear to be associated with an increase in degree-days summation. However, as concluded by Nuttonson, under the above three conditions, these variations are greatly reduced when the summation of photothermal units is used. This shows that the photothermal unit is a better parameter than the degree-days unit for a large geographical area study. The former reveals not only the thermal effect, but also the photoperiodic response of crops. In fact, Nuttonson has made a series of comparative studies on ecological crop geography of several European and Asiatic countries with that of North America. Various agronomic plants have been investigated by him in terms of climatic analogue, since 1947.

The product of temperature and day length was formulated as early as 1852 by Fritsch, as indicated in equation (4-36) where he computed the thermal sum for some 889 species of plants from the stage of flowering to maturity. Smith (1920) calculated the "sunshine-hour degree" by multiplying the mean effective temperature and the total possible hours of sunshine from planting to harvesting. He found that the sunshine-hour degree for corn is 80,313 between latitudes 30 and 35, 65,778 between latitudes 35 and 40, and only 47,887 between latitudes 40 and 45 degrees in the eastern part of the United States.[5]

Another photoclimatic unit is the product of the effective temperature and the solar intensity, which may be termed the "energy-degree unit" or E. D. U. Mathematically, it can be defined as

$$EDU = \sum_{i=p_1}^{p_2} (\bar{T} - T_C)\, E\,, \qquad (7\text{-}10)$$

where p_1 stands for the first phase, p_2 the successive phase, $\bar{T}$ the daily mean temperature, T_C the critical temperature for the species of plant in question, and E the daily accumulation of solar radiation in ly per day. In the computation of the energy-degree unit, the choice of temperature, such as daily mean, daily maximum, or hourly temperature at a specific time, as well as the choice of a certain upper or lower threshold value for solar intensity, should be noted. For a cloudy day, in winter, the light intensity can be too low for a certain plant to grow in the greenhouse. For a bright sunny day in summer, the light intensity can be too high and photo-oxidation processes arise. Neither of these two conditions would allow the use of equation (7-10); therefore, specification of conditions is required.

As has been pointed out in Sections 4.2.3, 6.4.1, and 6.4.2, the thermal climatic unit can be expressed in numerous ways, the majority of which involve the heat summation with air temperature as the sole climatic element. Seeley (1917) pointed out the faults of heat summation[6] due to the presence of large variations in the effective tem-

[5]The geographical distribution of the heat sum, as well as the summation of the photothermal units, varies with latitude. The total heat requirements of a plant vary, too, with latitude — a result of the adaptation to climatic environment by plants. Lissner's Law, which states that the sums of the effective daily temperatures for the same phase of vegetation in two different localities are proportional to the annual sum total of all effective temperatures for the respective localities, would reduce the latitudinal variation in the heat sum. Smith (1920) applied Lissner's Law in the computation of the sum of the effective temperature for the Burbank plum as follows:

Location	Sum of Temp. Above 32°C from Jan. 1 to Blossoming	Sum of Temp. from Jan. 1 to Dec. 31	Lissner's Ratio
Stillwater, Okla.	967	7409	0.130
Parry, N.J.	909	7044	0.129
State College, Pa.	725	5578	0.129
Burlington, Vt.	577	5292	0.109

It shows that there is a considerable difference between Parry and State College in the heat sum, but the Lissner ratio, known as Lissner's aliquot, is practically the same. Should any type of summation be employed, the weighted mean, such as Lissner's aliquot, would be needed.

[6]Seeley used Mikesell's phenological record in computing the heat sum of maize and Crawford peach for various phenological stages. He found that in the case of peaches be-

perature computation from year to year, and suggested the use of plant temperature rather than air temperature. After having made a large number of observations, he concluded that in the sun on clear still days, the leaf temperature can be as much as 20°F higher than that of the air in the shade. Also, leaves are generally cooler than the air at night and in early morning, particularly so in the early evening. For example at 7 a.m., the mean leaf temperature was 3.4° lower than the shelter temperature, and at 7 p.m., it was 6.6° lower, but at 2 p.m. the mean leaf temperature was 10.7°F higher than the shelter temperature. By and large, Seeley's findings agree with Shaw's observations in 1954, Noffsinger's observations in 1961 (see Section 4.2.1), and others.[7] According to Seeley, the effect of cloudiness on plant temperature is significant. He found that, on the average, the plant temperature at noon exceeded the air temperature by 15.2°F in full sunshine, by 9.7°F in partial sunshine, but by less than 1°F on cloudy days. On the basis of these averages, he defined the effective temperature as:

$$T_E = t + 15 D_c + 10 D_p, \tag{7-11}$$

where T_E is the sum of effective temperature; t equals $T_M - 42n$ (T_M is the sum of all maximum temperatures in n days); D_c is the number of clear days; and D_p, the number of partly cloudy days.

Wang (1958) found the diurnal, interdiurnal, and seasonal change of temperatures important in plant response studies, and treated the summation of these temperatures at various developmental stages as a significant parameter. The diurnal temperature range is the difference between the minimum and maximum temperatures of the same day. When this difference is divided by the time interval between the occurrence of the minimum and maximum, the result is the mean rate of warming. The interdiurnal temperature, which is the change between the maximum of one day and the minimum of the following day, usually indicates the cooling process. Again, when this change is divided by the time lapse between the two measurements, it is the mean rate of

tween blossoming and ripening, the least temperature summation is 2766 and the greatest, 3991, the percentage of the former to the latter being 69. For other stages, the percentage varies from 39 to 72. Seeley recommended the use of the daily maximum temperature rather than the daily mean temperature, but he admitted that very little improvement was accomplished by using the former.

[7]Several investigators have indicated that leaf temperatures are higher than the surrounding air when the sun is shining. For instance, the temperature of pine needles in bright sunshine, even in winter when the insolation values are at their lowest, was 3.6°F to 18°F higher than the surrounding air, as observed by Ehler (1915). Other observers such as Askenasy, Ursprung, Matthaei, and Smith have found leaves of plants warmer than the air, the difference in temperature depending on the clearness of the sky, season of the year, time of day, wind velocity, humidity, and possibly other factors. This difference amounted to 40°F or more in some extreme cases.

cooling. The duration of the interdiurnal temperature depends upon a number of factors, namely latitudinal, seasonal, and synoptical differentiations. The magnitude of the interdiurnal temperature range depends upon cloudiness, and in turn upon solar radiation, unless abrupt changes of the synoptic situation intervene. In the case of a clear day and clear night, most of the radiative energy during the day appears as sensible heat when the soil is dry, thus raising the temperature to a high daily maximum. Much of the heat escapes during the night by the process of long-wave radiation, and a low daily minimum results. Hence, with dry soil, the combination of clear day and clear night introduces a large interdiurnal temperature range. When the soil is wet, much of the daytime energy is stored as latent heat. In this case, less interdiurnal temperature range is expected. A small interdiurnal range is also expected in a cloudy day and cloudy night situation, due to low incoming radiative energy in the daytime and less outgoing radiation at night.

From the above reasoning, a good linear correlation exists between the five-day mean interdiurnal temperature and the five-day mean daily solar radiation. Due to time lag, the day-to-day relationship between these factors is not revealed. The summation of the interdiurnal temperature has been introduced by Wang & Bryson (1956) as an important element for the significant period of pea yield. In the same year, Lindsey & Newman made use of the diurnal temperature summation to test for the flowering date of a group of native plants in Indiana. Their findings proved the usefulness of the diurnal temperature (see equation 4-41 in Section 4.2.3). In fact, a combination of interdiurnal temperature and soil moisture would be a better parameter to use.

Numerically, there is no difference between the interdiurnal temperature summation and the diurnal temperature summation within a complete cycle of temperature change, for instance, one year. However, this would not be the case if a certain trend is present in a growing season. For a cold trend, the summation of the interdiurnal temperature is greater than that of the diurnal temperature, and vice versa for a warm trend. The mathematical expression of the mean interdiurnal temperature is

$$\bar{T}_I = \frac{1}{x - 1} \sum_{i=1}^{n} (T_{M_i} - T_{m_{i-1}}), \qquad (7\text{-}12)$$

where $\bar{T}_I$ is the mean interdiurnal temperature difference in the significant period of n days; i, the date of the calendar day; T_M, the daily maximum temperature; and T_m, the daily minimum temperature in degrees Fahrenheit. Thus, T_I has a unit of degrees Fahrenheit per day.

The seasonal temperature difference, $\bar{T}_D$, has been defined by Wang (1962a) as the temperature of the harvesting time ($\bar{T}_H$) minus the temperature of the planting time ($\bar{T}_p$), hence,

$$\bar{T}_D = \bar{T}_H - \bar{T}_p, \tag{7-13}$$

where $\bar{T}_D$ is the mean seasonal temperature difference, $\bar{T}_H$, the mean minimum temperature at harvesting time, and $\bar{T}_p$, the mean minimum at planting time. It has been found that the minimum temperature gives the best result in comparison with other temperature expressions. For a typical diurnal temperature cycle, the duration of the minimum temperature is longer than that of the maximum temperature. Also, the minimum temperature is apt to be the limiting factor for the temperature requirement of peas. Since peas are heat-sensitive plants, the combination of a warm spring and a cool summer contributes to better yield and quality than the combination of a cold spring and a hot summer (see Fig. 4-16). In the former case, we have a large T_D value. This can be seen when T_D values are plotted in a diagram against yield and where a negative correlation results. Fig. 7-1 shows the yield of Early Perfection 3040 and New Line Early Perfection peas in pounds per acre versus T_D value in degrees Fahrenheit, at Janesville, Wisconsin. The linear correlation or r is −0.80, r^2 is 0.64, and $P < 0.01$. The regression equation is

$$y = -313.8\,(T_D) + 10819, \tag{7-14}$$

where y is the yield in pounds per acre, and T_D is the seasonal difference in degrees Fahrenheit. In this study, the 20-day mean daily minimum temperature after planting was used for $\bar{T}_p$, and the 20-day mean daily minimum temperature prior to harvesting for $\bar{T}_H$.

The hydroclimatic system, which is another group of climatic units, has been intensively used during the past half century. The Meyer Precipitation-Saturation deficit or simply N-S quotient (see equation 2-6), is a combination of precipitation, P, and vapor pressure deficit, $e_s - e$. This equation has been widely adopted in the study of climate as a factor in soil formation. Penman's equation on the evaluation of potential evapotranspiration (see equation 4-50), contains four elements: temperature, wind velocity, relative humidity, and sunshine hours. These are controlling factors in evaporation. Smith (1920) has formulated Livingston's index of moisture-temperature efficiency for plant growth as

$$I_{mt} = I_t - \frac{I_p}{I_e}, \tag{7-15}$$

where I_{mt} is the efficiency index of moisture and temperature, I_t, the index of temperature efficiency derived by means of the physiological summation (see equation 4-39), I_p, the index of precipitation (representing the total rainfall for the period concerned), and I_e, the index of evaporation, denoting the total evaporation for the period. Kincer (1915), in his study of monthly departure of rainfall and temperature as related to cotton yield in Texas during 1894-1913, formulated an equation, known as the "weather-cotton equation." He assumed that the departure of yield, Y_d, is a function of departures from the normal for rainfall and temperature, or p' and T' respectively. Hence, the empirical assignment of accumulated effect is

$$Y_d = Y' - \frac{(cP' + c_1T')_1 + (cP' + c_1T')_2 + \ldots + (cP' + c_1T')_n}{N}$$

$$= Y' - \frac{\Sigma(cP' + c_1T')}{N}, \qquad (7\text{-}16)$$

where Y' (a constant, 100 by Kincer's data) denotes the number of points as computed from the departure of rainfall and temperature to represent the average yield of cotton, and is an adjusted factor for the completion of the equation; c and c_1 the relative weights to be assigned to P' (departure of monthly rainfall) and T' (departure of monthly mean temperature), respectively;[8] N, the total number of months; and the Arabic subscripts for the brackets are the order of the months in the growing season, such as April, May, June, etc.

[8]The values assigned to c as computed by Kincer are shown below:

	Conditions	April	May	June	July	August	September
1	+ following 0 or +	4	8	8	4	4	4
2	+ following −	4	4	2**	2**	2**	3
3	− following −*	4	5	6	8#	10#	8#
4	− following 0 or +	2	2	3	6#	8#	4

where condition No. 1 is a month of positive departure of rainfall following a month of positive departure of rainfall; No. 2 is a month of positive departure following a month of negative departure; No. 3, negative following negative; and No. 4, negative following positive. One star (*) refers to negative departures of less than 0.3" for April and May, considered normal. Two stars (**) refer to a continuation of two or more months of negative departure, substituting 1 if $P' > 1''$ and substituting 0 if $P' < 1''$. The # sign represents these cases: (i) for the fourth consecutive month of negative departure, increase the value by 2; (ii) for the fifth month, by 6; and (iii) for the sixth month, by 8. If all negative departures for July and August are more than 2", a value of 12 is assigned.

The following are values for c, assigned to temperature auxiliary factors:

	Conditions	April	May	June	July	August	September
1	+ temperature with 0 or + rainfall	1	1	1	1	1	1
2	+ temperature with − rainfall	1	1	2*	2*	2*	1*
3	− temperature with − rainfall**	1	3	2	2	2	2
4	− temperature with + rainfall**	1	4	4	2	2	2

where there may be four combinations for temperature: (1) a plus temperature departure occurring with a plus rainfall departure; (2) a plus temperature with a minus rainfall departure; (3) minus temperature with the like for rainfall departure; and (4) minus temperature with plus rainfall departure. One should note that if it is the third month of minus rainfall, the value is increased by two, and if the fourth, fifth, or sixth month, by three. This is indicated by the single asterisk (*). As for the double asterisks (**), they mean that if it is the third month of minus temperature departure, the value is increased by one; if the fourth month, by two, and if the fifth or sixth month, by three.

Thornthwaite (1931, 1948) has formulated his well-known "precipitation effectiveness ratio" and "thermal efficiency ratio" for the classification of climate in view of plant, soil, and climate relationships. Actually, his work is a conglomeration and revision of a number of precipitation effectiveness indices prepared by various researchers (Transeau, 1905; Lang, 1920; De Martonne, 1926; Köppen, 1918, 1923, 1928; Meyer, 1926; Ångström, 1936; Setzer, 1946; etc.). In his 1931 formulations of the "precipitation effectiveness ratio," or P-E ratio, and "thermal efficiency ratio," equations (7-17) and (7-18) respectively define them as

$$\text{P-E ratio} = 115\left[\frac{P}{T - 10}\right]^{10/9}, \tag{7-17}$$ [9]

$$\text{T-E ratio} = \frac{T - 32}{4}, \tag{7-18}$$ [10]

where P and E are in inches and T in degrees Fahrenheit. It is assumed by a number of researchers who have been engaged in studies of indices that evaporation and transpiration tend to increase with an increase in temperature. A brief review of their work on precipitation effectiveness (I) is in order. Transeau (1905) produced an index of precipitation as

$$I = \frac{P}{E}, \tag{7-19}$$

where P is the annual precipitation in inches, and E the annual evaporation (pan measurement) in inches. In 1920, the German soil geneticist Richard Lang made an intensive study on weathering and soil formation with the formulation

$$I = \frac{P}{T}, \tag{7-20}$$

where P again is the annual precipitation, but now in millimeters, and T the mean annual temperature in degrees Centigrade. His formula is known as "Lang's Rain Factor." This factor was later modified by De Martonne (1926) with the addition of a constant 10 to the denominator, this modification being known as "Martonne's Index of Aridity,"

$$I = \frac{P}{T + 10}, \tag{7-21}$$

Similarly, Köppen in 1918, 1923, and 1928 presented three formulas for delimiting dry climates as

$$I = \frac{8P}{(5T + 120)},$$

[9] The sum of the 12 monthly P-E ratios is called the P-E index by Thornthwaite, and is expressed as

$$\text{P-E index} = \sum_{1}^{12} 115\left[\frac{P}{T-10}\right]^{10/9}.$$

[10] Similarly, the sum of the 12 monthly T-E ratios is named the T-E index. The mathematical expression for this is

$$\text{T-E index} = \sum_{1}^{12}\left[\frac{T-32}{4}\right].$$

$$I = \frac{2P}{T + 33}, \qquad (7\text{-}22)$$

and

$$I = \frac{P}{T + 7}.$$

In fact, De Martonne was more or less influenced by Köppen's earlier work. In 1936, Ångström suggested a modification of De Martonne's Index of Aridity, as the Ångström Humidity Coefficient,

$$I = \frac{P}{1.07^t}, \qquad (7\text{-}23)$$

where P is precipitation in millimeters, and t the temperature in degrees Centigrade. Setzer (1946) published a map of the moisture index in the state of Saõ Paulo, Brazil, which is quite similar to Ångström's map for northwestern Europe, although both of them developed their work independently. The similarity of Setzer's equation and equation (7-23) is found in the utilization of Van't Hoff's law of indexing. Thornthwaite (1948) further developed formulas for the determination of monthly potential evapotranspiration as

$$e = c\,t^a, \qquad (7\text{-}24)$$

where e is the monthly evapotranspiration in centimeters, t is the mean monthly temperature in degrees Centigrade, and a and c are constants which vary from place to place and can be determined by $a = 0.000000675\,I^3 - 0.0000771\,I^2 + 0.01792\,I + 0.49239$. Here

$$I = \sum_{i=1}^{12} (t/5)^{1.514}, \text{ and } c = \frac{1}{I}.$$

From these relations a general equation for potential evapotranspiration is formulated as

$$e = 1.6\left(\frac{10\,t}{I}\right)^a. \qquad (7\text{-}25)$$

Equations (7-10) to (7-25) are only a few examples of existing empirical formulations. At best, these formulas can serve as first approximations for a specific agrometeorological purpose in a certain locality or in a general geographic area. Sometimes, they are good only for a certain set of data. Therefore, it is not necessary to know all the existing formulations nor to test them as to how well each is suited to the specific problem. In short, a mere collection of information is not at all useful for the selection of formulations, but the establishment of a general equation according to fundamental concepts (see Chapter 3) is of paramount importance. Furthermore, testing the interrelationships between the photoclimatic, thermoclimatic, and hydroclimatic units is needed.

7.4.3 *Phenometeorological approach*

The biotic events and environmental elements have been grouped separately under Sections 7.4.1 and 7.4.2, respectively, but it is necessary to join them together so as to find their functional relations, if any. This type of approach is encouraged for future research. The qualitative description of plant response to a single environmental factor has been mentioned in Chapter 4, and quantitative treatment by means of phenological techniques has been discussed in Section 6.4. Further discussion of the single-element approach to the study of physical elements versus biological responses will be presented in this Section. This may be termed the "phenometeorological approach," and serves as a method of first approximation in crop-response studies.

In this study, first of all, the crop-response model of a single element such as the thermal response of a crop should be established for the following purposes: (a) to obtain a comprehensive over-all picture of crop response for a specific element, (b) to find the effect of that specific element as related to the age of a plant, and (c) to transfer greenhouse measurements to natural field application. The thermal response of a crop model for tomatoes and sweet corn is used for illustration.

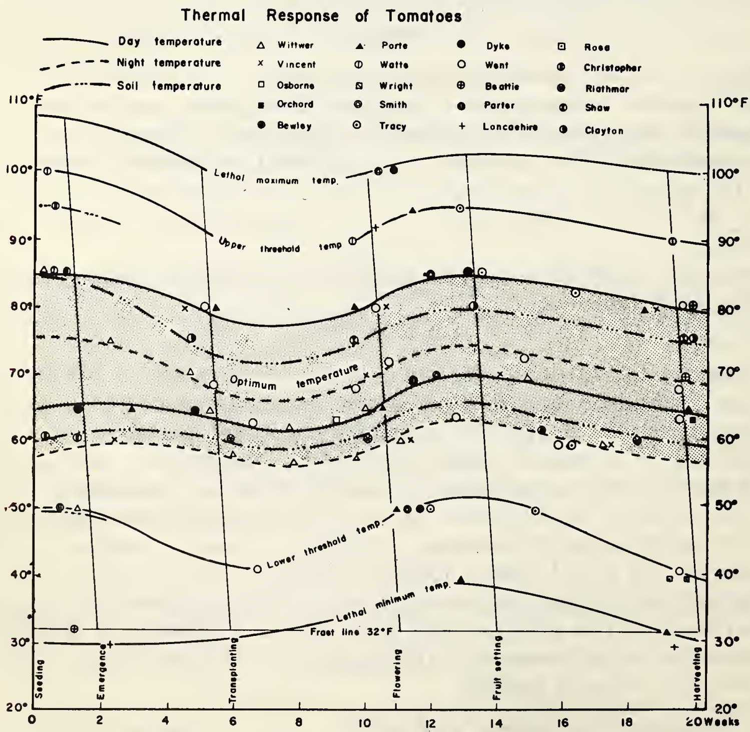

Fig. 7-2. Thermal response of tomatoes.

As shown in Fig. 7-2, Wang (1962b) prepared a model of the thermal response of tomatoes from the experimental results of various researchers. The experiments were conducted under many variations in the environment, such as field trials, greenhouse testings, and phytotron experiments. This includes the differentiation of soil types, cultural practices, crop species, varieties, and types, and even kinds of temperature sensing element used. Smooth curves for thermal response were drawn to average out these differentiations. These curves represent the lethal minimum and maximum temperatures, upper and lower threshold temperatures, and the optimal temperature ranges. Three types of temperature employed as indices of the thermal requirements of tomatoes are the daily mean, night, and soil temperatures. These temperature types are significant elements provided the correct choice of significant period has been made. The temperature scale, or abscissa, extends from 20° to 110°F; however, the critical temperatures reported by various researchers are located between 30° and 100°F. The ordinate ranges from 0 to 20 weeks for seeding and harvesting time, respectively, where a two-week period from seeding is designated as the time of emergence, six weeks for transplanting, 11 weeks for flowering, and 14 weeks for fruit-setting. These are average conditions, referring to the most frequent occurrence of the events. The time periods and calendar dates of events are interchangeable. As to the specific calendar dates, they vary with geographical distribution and seasonal differentiation. They vary, too, with the individual case. Since tomato is a warm season crop, it requires a relatively long season to produce a profitable yield and achieve marketable quality. Also, it is generally recognized that tomatoes are tender and will not withstand freezing temperature. This means that the lethal minimum temperature should be higher than the freezing point, 32°F. Nevertheless, it is not altogether true, according to the model. As shown in Fig. 7-2, freezing damages do not occur at 32°F, but at 30°F, prior to transplanting and at about harvesting time. But they occur at about 38°F between flowering and fruit-setting (Lancashire et al., 1935; Beattie & Beattie, 1942; and Porte, 1959). The lower threshold temperature follows almost the same trend as the minimum lethal temperature. The upper and lower optimum temperature range has comparatively less variation with advancing age than the lower threshold temperature. Similar trends exist in the upper threshold and lethal maximum temperatures. Some workers do not agree on the differentiation of threshold from lethal temperature for the upper and lower levels. They assign a minimum temperature to the average condition of the lower threshold and lethal minimum, and a maximum temperature to the upper threshold and lethal maximum. This can be seen in Table 4-8, where one-half of the upper lethal temperatures have not been specified.

A similar model for sweet corn has been prepared by Wang & Nakamura (1960), and is shown in Fig. 7-3. Note the narrow range of optimum temperature 30 days after planting, in contrast with the uniform band of temperature in the tomato Model. Note also the wide spread between the minimum and maximum lethal temperatures. The phenological phases described are planting, emergence, tasseling, silking, and harvesting.

Fig. 3-3 serves as a general guide to selecting significant elements such as temperature, soil moisture, and evapotranspiration for the construction of a crop model. More specific individual tests of various significant elements for crop response are necessary. Thus, these significant elements are the relative minimum and maximum temperatures, the frequency of temperature during a certain phenological period, the diurnal, interdiurnal, and seasonal temperature changes, etc., for the temperature parameter, and similarly for other parameters, as defined and described in previous chapters. Illustrations for the use of these significant elements will be given shortly. It is important to recognize the characteristics of these parameters; they are signified by one or more of the following essentials: (a) the relative and absolute magnitude of each element, both in intensity and in duration, (b) the changes of magnitude for various time sequences, and (c) the computation of the extremes of each element. With these characteristics,

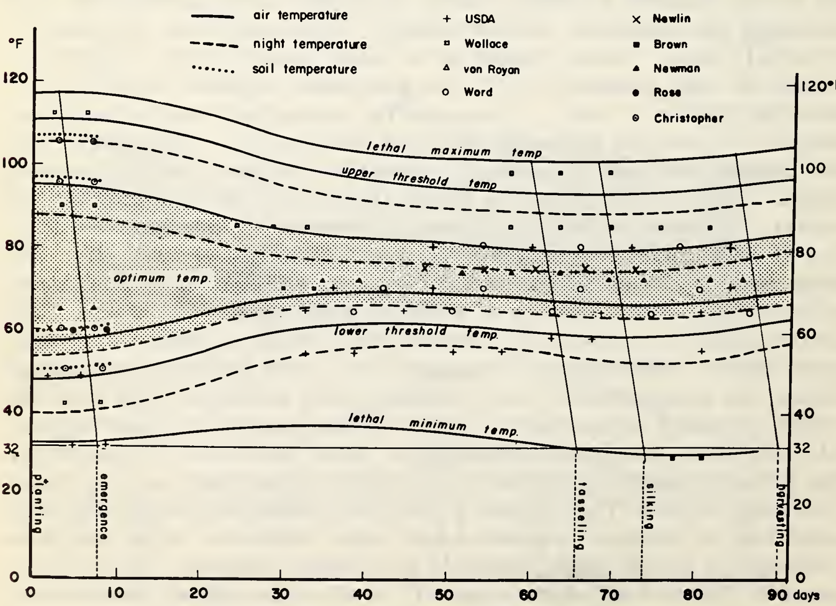

Fig. 7-3. Thermal response of sweet corn.

the reader may be able to find a certain new parameter for tackling his problem. The following examples on tomatoes, sweet corn, peas, cucumbers, and snap beans are used as guides to the approach.

The relative magnitude of a parameter, such as relative minimum rainfall, as explained in Section 4.4.1a and illustrated in Fig. 4-28, is by far more important than the absolute value as far as crop response studies are concerned. Since relative minimum rainfall is defined as the lowest accumulation of rainfall in a given period for a specific growing season, it is the driest period in that season. If a week is used as the time unit, then the multiple of weekly units, such as 1, 2, to n weeks, can also be assigned as time units. The growing season refers to the period from the date of planting to the date of harvesting of a crop. Similarly, we have the relative maximum rainfall, which would be the wettest period in a growing season, if rainfall is a measure of moisture. Thus, the relative minimum and maximum temperatures are those occurring in the coldest and warmest periods of a season, and the relative minimum and maximum cloudiness refer to the amount of clouds occurring in the most and least cloudy periods of the season, respectively.

In the study of tomato yield in Wyoming, Delaware, for the period 1948-58, Wang (1963) found that the relative maximum rainfall, R_R, serves as a good rainfall parameter. Year-to-year R_R values during the flowering period have been evaluated; they varied from 1.26" to 7.03" with a mean of 3.50" for a one-week interval, and from 2.35" to 10.08" with a mean of 5.27" for a four-week interval. The crop yield varied from 4.1 to 13.7 tons per acre with a mean of 9.03, standard deviation of 3.69, and coefficient of variation of 40.86%. A series of scatter diagrams has been plotted with the yield of tomatoes in tons per acre as the ordinate and the R_R values in inches as the abscissa. This is given in Fig. 7-4A. The numerals, such as 48, 49, etc., next to the scatter points indicate the years 1948, 1949, etc. It appears that when the R_R values (below 2.40") are too low during the flowering stage, the yields fall off, i.e., rainfall acts as a limiting factor. This also holds true when the R_R values (above 7.10") are too high, where rainfall acts as a retarding factor. Yields beyond half a standard deviation above the mean yield (i.e., approximately 11.0 tons per acre) are arbitrarily chosen as the optimal yield. If this 11.0-ton line were drawn parallel with the mean yield line, then any yield above this line is assumed as an optimal yield. Hence, the R_R values which fall into this area indicate the desirable amounts of rainfall for the best yield.

Two sets of scatterings appear in each of the scatter diagrams, and thus positive and negative linear regression lines can be drawn by means of a least-squares fit. Three points of intersection result from the $\bar{Y}$ line and the two linear regression lines. A parabolic curve can

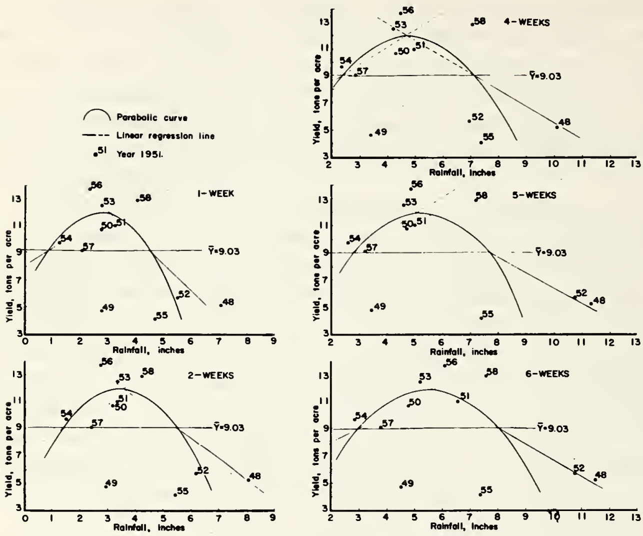

Fig. 7-4A. Weekly relative maximum rainfall versus yield of tomatoes during blossoming period, Wyoming, Delaware, 1948-1958.

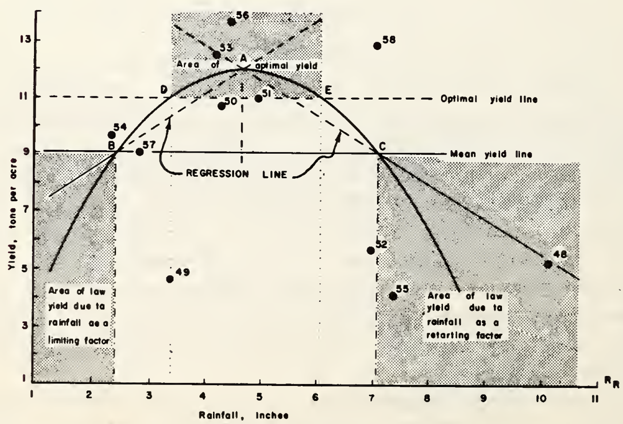

Fig. 7-4B. 4-weeks relative maximum rainfall versus yield of tomatoes during blossoming period.

be drawn through these three points, as indicated in Fig. 7-4A. The R_R values which correspond with the intersecting points on the left-hand side of each of the scatter diagrams (i.e., the intersection between the left-hand regression line and the $\bar{Y}$ line) determine the lower limit, below which the yield will fall off. Similarly, the R_R values which correspond with the intersecting points on the right-hand side determine the upper limit above which the yield will again fall off. When these R_R values are plotted against weeks, we have the cumulative (or ogive) curves for the upper and the lower limits, as shown in Fig. 7-5. The optimum range in Fig. 7-5 is obtained by the corresponding R_R values from the two points of intersection between the parabolic curve and the 11.0-ton line in Fig. 7-4A. Fig. 7-5 gives us the first approximation to the relative maximum rainfall requirement of tomato plants. The thermal effect on tomato plants will be studied shortly.

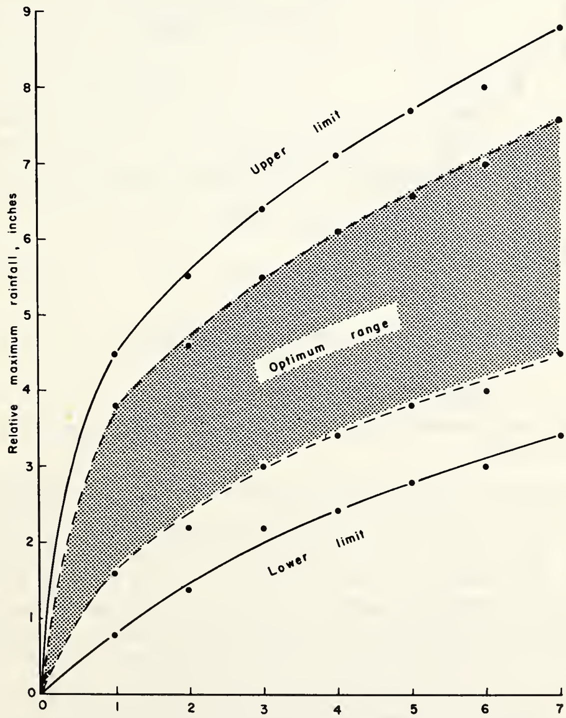

Fig. 7-5. Relative maximum rainfall in successive weeks versus tomato yield, Wyoming, Delaware, 1948-1958.

The relative minimum rainfall parameter, R_r, has been applied to the study of sweet corn, peas, tomatoes, cucumbers, and a number of other vegetable crops by Wang (1956, 1958, 1960, and 1963). He found that the evaluation of R_r for a time interval of three to five weeks correlates best with yield of crops. The correlation can be positive or negative, depending upon the species and variety of the crop and stage of development. For a set of experimental data with sample size of 10 to 20, the coefficient of linear correlation runs between 0.58 and 0.94. The appearance of a wide range of linear correlation suggests that sometimes the multiple environmental effects dominate, rather than a single factor, namely R_r. In the case of tomatoes, Fig. 7-4B shows R_R versus yield in a four-week interval during the reproductive stage.

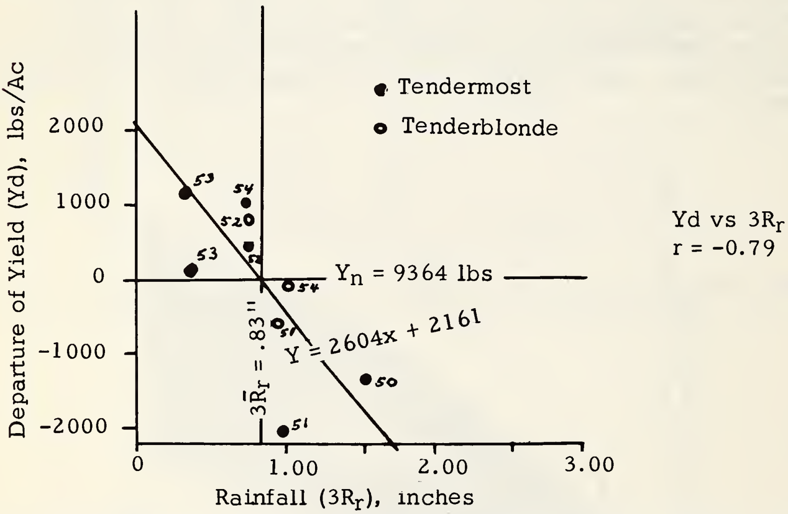

Fig. 7-6. Sweet corn grown in Green Bay, planting to first tasseling stage (1950-1954)

Fig. 7-6 shows the relationship between sweet corn yields for individual years (1950-1954) and rainfall from planting to tasseling (R_r), at Green Bay, Wisconsin. The ordinate is the departure of yield, and the abscissa, the relative minimum rainfall. The year is indicated at the upper right of the dot mark, as in Fig. 7-4A, with the black dot representing the variety as Michael Leonard Tendermost, and the blank dot, the Michael Leonard Tenderblonde variety. The yield of the Tendermost variety varies from 7351 to 10333 pounds per acre, with a mean yield of 9050, and that of Tenderblonde, 8811 to 10623 pounds per acre, with a mean yield of 9756. The mean yield for both varieties is 9364 pounds per acre, indicated in Fig. 7-6 as the zero departure line. The mean number of days from planting to harvesting is 98 for Tendermost and 95 for Tenderblonde, varying from 87 to 109 days for both varieties. The mean time-interval from planting to first tasseling for Tendermost and Tenderblonde is 53 days, with a range from 46 to 60 days. For the 3 R_r values (referring to three successive weeks) during this period, there was an average of 0.83" of rainfall, which varied between 0.33" and 1.62" from year to year. It has been found that if the rainfall is lower than 3 $\bar{R}_r$ or 0.83", the yield is at or higher than the normal yield. Conversely, if the rainfall is higher than 3 $\bar{R}_r$, the yield is at or lower than the average yield. The negative coefficient of linear correlation (r) thus obtained is -0.79 ($r^2 = 0.62$; P = 0.02), and the regression line can be expressed as

$$Yd = -2604\,(3\,R_r) + 2161\,, \qquad (7\text{-}26)$$

where Yd is the departure of yield in pounds per acre, 3 R_r, the relative minimum rainfall at the three-week interval. The zero departure line and the mean 3 $\bar{R}_r$ line divide the scatter diagram into four quadrants. The second quadrant shows the rainfall favorable to yield, while the fourth quadrant shows the unfavorable. The latter indicates that rainfall was a retarding factor — or the usual amount of rainfall was too high — during this period.

Fig. 7-7 shows the relationship between Victory Golden sweet corn yield and the amount of relative minimum rainfall (3 R_r) from first silking to harvesting for the years 1949-59 in Janesville, Wisconsin. The coordinates and presentation of the scatter diagram are similar to those

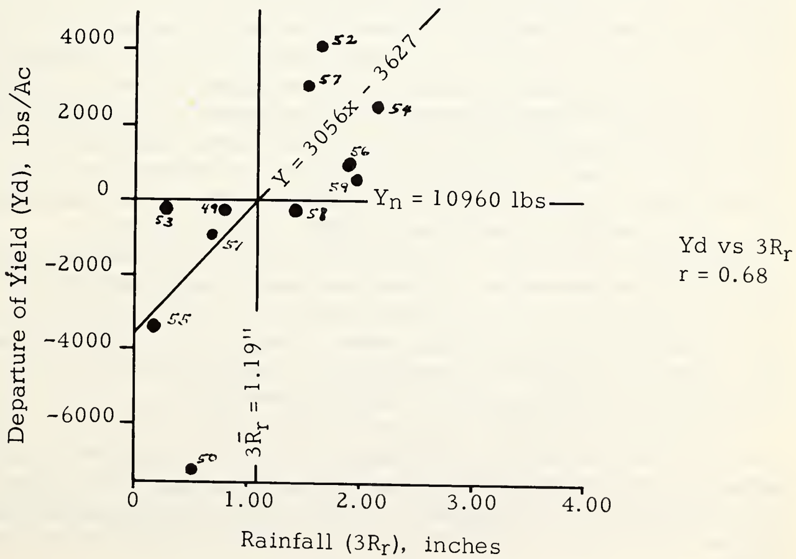

Fig. 7-7. Sweet corn grown in Janesville, first silking to harvesting (1949-1959)

of Fig. 7-6. The yield varies from 3802 to 15,223 pounds per acre, with a mean yield of 10,960 pounds per acre. The 3 R_r values during this period varied from 0.16" to as high as 2.15", with a mean of 1.19". The regression line for Fig. 7-7 is

$$Yd = 3056(3\,R_r) - 3627\,, \qquad (7\text{-}27)$$

where the r value is 0.68, r^2 is 46, and P is 0.02. In comparison to Fig. 7-6, the reverse situation exists for Fig. 7-7 because of the difference in developmental stages, locality, and variety involved.

In the case of Green Bay, when the 3 R_r parameter is applied to phenological stages other than planting to first tasseling, negative linear correlations, ranging from -0.14 to -0.75, were obtained. The phenological stages used were planting to first silking, first silking to harvesting, full silking to harvesting, and planting to harvesting. Of various time-intervals employed in the correlation studies, it has been found that a three-week interval is the significant period during the vegetative stage, and thus 3 R_r is the significant element. When rainfall parameters, crop-drying day of eight successive dry days (C_8)[11], and crop-rainy day (R_c) (see Section 4.4.1) were used for the study during the phenological stage of first silking to harvesting, linear correlations of 0.60 and -0.46, respectively, were obtained. These correlations were lower than the 3 R_r parameter ($r = -0.75$). However, for the total accumulative rainfall (T_r) and for the total number of rainy days (R) during the same phenological stage, correlations of 0.40 and 0.07 were found, respectively. These low correlations show that the classical statistical study using T_r and R would not have revealed the crop response. In other words, growth and development of the crop are not affected by the T_r and R parameters. For example, the crop-rainy day as indicated in Section 4.4.1a always gave a higher correlation than the rainy day, for all crops being tested, for R_c is a measure of effective rainfall, while R is not.

Similarly, in the case of Janesville for the phenological stage of first silking to harvesting, the recommended rainfall parameters such as 3 R_r, C_4, and R_c have linear correlation coefficients of 0.68, -0.64, and 0.40, respectively, whereas the linear correlations of T_r and R are 0.10 and 0.31, respectively. Again, this proves that the recommended rainfall parameters should be adopted.

In the case of Alaska-type peas in Rosendale, Wisconsin, during 1946-54, Wang & Bryson (1956) found that rainfall acts as a limiting factor if R_r for four successive weeks is at or below 1.03", resulting in a yield below 2124 pounds per acre. The crop data show that the highest and lowest yields ranged from 1596 to 2584 for the period studied.

[11] C_1, C_2, . . . C_n refer to successive dry spells of 1, 2, . . . n days, respectively, according to the overlapping system as defined in Section 4.4.1a.

In the case of cucumbers grown in Alma, Michigan (see Fig. 3-7), Wang & Singh (1961) found that when R_R in five successive weeks is between 4.23" and 7.02", the optimal yield ranges from 103 to 206 bushels per acre. It is 1.21" to 2.14" for the same optimum yield range when R_r is employed. The crop data show that the mean yield is 103 bushels per acre, the standard deviation, 43, the coefficient of variation, 42%, and the extreme variation, from 41 to 206.

Still another useful rainfall parameter is rainfall peaks, discussed in Section 4.4.1a, Fig. 4-25, and Table 4-14. The yield of snap beans and sweet corn in Hancock and Janesville, Wisconsin, will be used as illustrations. The yield of two varieties of snap beans, Tendergreen and Processor, grown in Hancock during the period 1953-58 was used for the study of the rainfall peak parameter. The purpose was to test the effect of duration and magnitude of rainfall peaks on the yield of snap beans. Consequently, it follows that the final goals were to schedule the time of irrigation and forecast the yield. The average yield for Tendergreen was 3036 pounds per acre, and for Processor, 3660. The averages were of about the same order of magnitude as the 40-year state average in Wisconsin, 1918-57, which was 3130 pounds per acre, according to Garoian & Mueller (1958). The standard deviation and coefficient of variation for Tendergreen were 1691 pounds per acre and 56%, respectively, and for Processor, 1977 pounds per acre and 54%. The yield for Tendergreen ranged from a low of 862 to a high of 5700 pounds per acre, and for Processor, from 1165 to 6340. The rainfall peaks are classified as the primary and secondary weekly rainfall maximum and are termed the first and second peak, R_1 and R_2, respectively. The intensity of weekly rainfall in inches for the first high accumulation after sowing is R_1, and for the second high accumulation, R_2. The time-interval in days from the sowing date to the central date of R_1 is D_1, and that between R_2 and the harvesting date is D_2. For Processor, R_1 and R_2 ranged from 0.92" to 2.95". The mean is 1.62" for R_1, and 2.25" for R_2. The corresponding values for D_1 and D_2 ranged from 7 to 27 days, with means of 17 days for D_1 and $15\frac{1}{2}$ days for D_2. For Tendergreen, R_1 and R_2 ranged from 0.68" to 2.70", respectively, with means of 1.72" for R_1 and 1.81" for R_2. The corresponding D_1 value ranged from 7 to 24 days, with a mean of 16 days; D_2 ranged from 7 to 21 days with a mean of $12\frac{1}{2}$ days.

It was found that yield varies directly with R_2 and inversely with D_2 and R_1. The three parameters which associate with the estimated yield of snap beans (Y_e) have been formulated by the Spearman rank correlation (Equation B-51) as

$$Y_e = \bar{k}\left(\frac{x_1}{D_2} + \frac{x_2}{R_1} + x_3 R_2\right), \qquad (7\text{-}28)$$

where $\bar{k}$ is the coefficient of the mean converting factor of rainfall into yield, and x_1, x_2, and x_3 are weighted coefficients for D_2, R_1, and R_2, respectively. The values $\bar{k}$, x_1, x_2, and x_3 are varietal constants; their units are adjusted to meet the requirement of dimensional consistency. Thus, when equation (7-28) is applied to Tendergreen, it becomes

$$Y_e = 29.5\left(\frac{17.0}{D_2} + \frac{41.5}{R_1} + \frac{41.5}{R_2}\right), \qquad (7\text{-}29)$$

and that for Processor becomes

$$Y_e = 15.8\left(\frac{2.8}{D_2} + \frac{15.1}{R_1} + \frac{82.1}{R_2}\right). \qquad (7\text{-}30)$$

The x_1, x_2, and x_3 values of the above equations were obtained by means of the Spearman coefficient of rank correlation. This is done by setting the yield data for each individual year at 1000-pound class-intervals (e.g., $\frac{1}{D_2}$ vs. 5000-5999 lbs/A yield). The rank correlation for $\frac{1}{D_2}$ for each variety is designated at x_1'. Similarly, for $\frac{1}{R_1}$ it is x_2', and for $\frac{1}{R_2}$ it is x_3'. The results, after weighing x_1', x_2', and x_3' in percentage terms, may be termed x_1, x_2, and x_3. These are the coefficients of $\frac{1}{D_2}$, $\frac{1}{R_1}$, and $\frac{1}{R_2}$, in equations (7-29) and (7-30). The k value of each individual year is obtained by substituting in given values of each year, i.e., Y_a, $\frac{1}{D_2}$, $\frac{1}{R_1}$, and R_2 into equation (7-28). Note that Y_a (actual yield) instead of Y_e is used to obtain the k value. The arithmetic mean of all k's of each individual year is designated as $\bar{k}$. Thus, $\bar{k}$ for Tendergreen is 29.5, and that for Processor is 15.8. What has been obtained from the above two equations is the estimated yield. Equating the estimated yield, Y_e, to the actual yield, Y_a, for each year, we have for Tendergreen:

$$Y_a = 2.02\,Y_e - 3900; \qquad (7\text{-}31)$$

for Processor, we have:

$$Y_a = 1.19\,Y_e - 631. \qquad (7\text{-}32)$$

Plotting Y_e against Y_a for Tendergreen and Processor, then Figs. 7-8 and 7-9, respectively, are constructed.

Applying the same technique to the Janesville Victory Golden sweet corn data (see Fig. 7-7), with the exception of using a two-week interval for rainfall peak, the following equation is formulated:

$$Y_e = 12.8\,(38.5\,R_3 + 38.5\,R_4 + 23.0\,D_2), \qquad (7\text{-}33)$$

where R_3 and R_4 are the third and fourth rainfall peaks of two weeks' duration, respectively. With the above equation, a linear correlation of $r = 0.72$ is obtained.

In the study of temperature and yield relationships, the thermal models of tomatoes (see Fig. 7-2) and sweet corn (see Fig. 7-3) would be useful guides to research. The tomato data of Wyoming, Delaware,

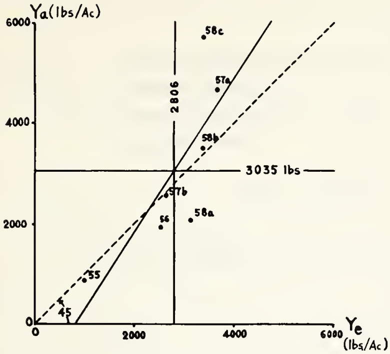

Fig. 7-8. Yield of Tendergreen and R_p evaluation.

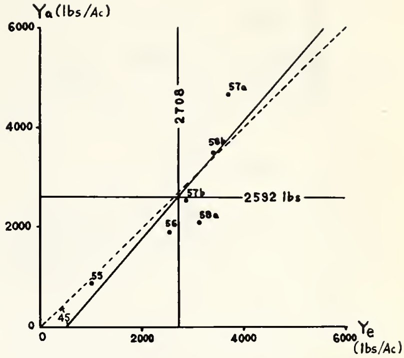

Fig. 7-9. Yield of Processor and R_p evaluation.

mentioned previously (see Fig. 7-4), are used here as an illustration. Since the upper limit of the optimum range for tomatoes between flowering and harvesting is 83°F, and the lower limit, 66°F (see Fig. 7-2), a high yield is expected when the daily mean temperatures fall between 66°F and 83°F. Conversely, a low yield is expected if the daily mean temperature is either higher than 83°F or lower than 66°F. The percentage frequency of temperature higher than 83°F during the reproductive period has been computed. A negative linear correlation coefficient of $r = -0.90$, $r^2 = 0.81$, and $P < 0.01$ were obtained, with the exclusion of the year 1948. The result is given in Fig. 7-10. The regression equation is

$$Y = -0.29\,T_f + 13.29\,, \tag{7-34}$$

where Y is the yield of tomatoes in tons per acre and T_f is the temperature frequency in percentage. During the reproductive stage, the year 1948 had 10.08" as relative maximum rainfall, or R_R value, for the four-successive-weeks period, and 2.70" as relative minimum rainfall, or R_r, in contrast with an over-all year's mean of $\bar{R}_R = 5.27"$ and $\bar{R}_r = 1.33"$. This shows that the year 1948 was exceptionally wet, with little sunshine and low temperatures. Warm spells with runs of one, two, and three days above 92°F daily maximum temperature have also been computed. This 92°F is obtained from an average value of the upper optimum and upper threshold temperatures in the thermal model for tomatoes during the reproductive stage by transferring the daily mean to a daily maximum value. Correlation coefficients of $r_1 = -0.79$, $r_2 = -0.79$, and $r_3 = -0.80$, for one-, two-, and three-day warm spells, respectively, are obtained. Following similar procedures, the thermal model for sweet corn (see Fig. 7-3) was tested for its validity and usefulness by using the Janesville and Rosendale, Wis-

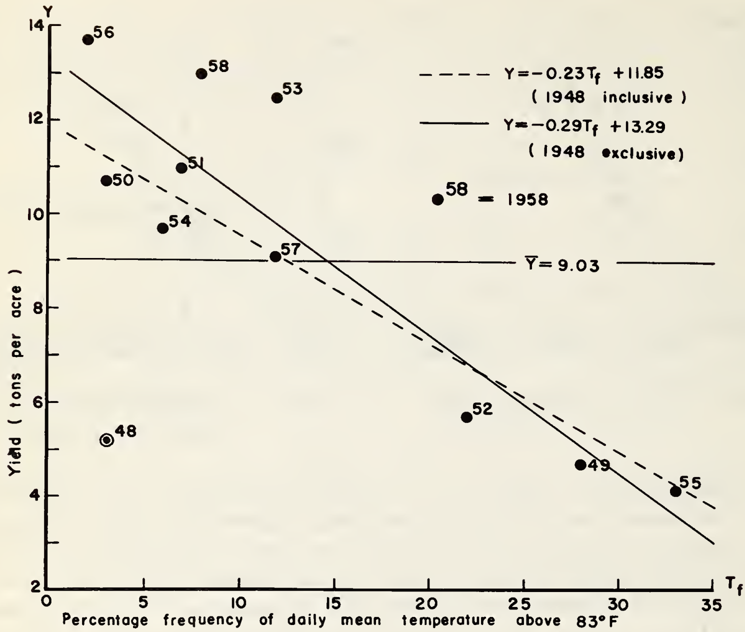

Fig. 7-10. Tomato yield versus daily mean temperature frequency during blossoming period, Wyoming, Delaware, 1948-1958.

consin, records. The sweet corn data of Janesville have been described briefly (see Fig. 7-7). The Rosendale data consisted of 276 plantings for the period 1946-54. The highest yield for one year is 5.32 tons per acre, while the lowest record is 1.81. The mean yield for all the years is 3.60. It has been found that the lower optimum and lower threshold temperatures during 20 to 40 days after planting, and tasseling to silking, as well as the upper optimum during harvesting, as shown in the model, are significant. The other portions of the model are insignificant, and a few portions are inconsistent. The coefficient of correlation between the yield of corn and temperature of various levels for the two localities is tabulated in Table 7-2 to show the degree of consistency. Whether or not the appearance of inconsistencies suggests errors in the model has to be tested with a large sample of data. With Janesville and Rosendale data alone, there are considerable contradictory trends between the two sets of data. Therefore, regional, varietal, and many other factors should be taken into consideration. The high correlations between the number of days with mean temperature below 67°F and corn yields ($r = -0.88$ for Rosendale, and $r = -0.39$ for Janesville) during 20 to 40 days after planting would be useful as a first approximation for prediction. The regression equation for Rosendale is

$$Y = -0.86D + 15.9, \tag{7-35}$$

where Y is the yield of sweet corn in tons per acre and D is the number of days with daily mean temperature below 67°F. For Rosendale at a stage between 60 and 80 days after planting, it is

$$Y = -0.61D + 13.9. \tag{7-36}$$

Equation (7-36) will be useful for the confirmation of equation (7-35).

The study of single environmental parameters other than temperature and rainfall deals with radiation, evapotranspiration, soil moisture, soil temperature, and so forth. The leaf area index and light interception concept as developed by McCloud & Alexander in 1961 will be used to illustrate the influence of light on plant growth.[12] In their study of the efficiency of light utilization, they emphasized the interrelationship of the quantity of leaves, light profile, and net photosynthesis of plant communities. It is the plant community which is important to the concept of efficiency of light utilization, rather than the individual plant or leaf. Thus, the determination of the leaf area index and the net photosynthesis rate at various light intensities becomes necessary. The relationship has been shown by McCloud & Alexander to be closely approximated by the rectangular hyperbola. They found that the net photosynthesis, P, is

$$P = bI/(1 + aI) - R, \tag{7-37}$$

where I is the light intensity, R is the respiration rate, and a and b are constants which characterize the shape of the hyperbolic curve. The light distribution in the plant community depends upon the leaf

Table 7-2. Correlation Coefficients Between Yield and Various Temperature Levels of Sweet Corn Grown in Janesville and Rosendale, Wisconsin

Arbitrary Classification of Phenological Stages	Station	The first 20 days after planting	From 20 to 40 days after planting	From 40 to 60 days after planting	From 60 to 80 days after planting	From 80 days after planting to harvesting
Number of days with daily maximum temperatures above the optimum temperature of:		92°F	85°F	82°F	80°F	82°F
	R	---	0.32*	-0.24	0.33*	<u>-0.55</u>
	J	0.12	0.32*	0.37*	0.09	<u>-0.45</u>
Number of days with daily mean temperatures below the optimum temperature of:		60°F	67°F	70°F	68°F	68°F
	R	0.90*	<u>-0.88</u>	0.36*	<u>-0.76</u>	0.34*
	J	0.03	<u>-0.39</u>	<u>-0.40</u>	<u>-0.46</u>	<u>-0.69</u>
Number of days with daily minimum temperatures below the lower threshold temperature of:		42°F	54°F	57°F	54°F	56°F
	R	0.06	<u>-0.39</u>	0.24*	<u>-0.61</u>	0.18
	J	0.16	-0.19	<u>0.51</u>	<u>-0.61</u>	0.03

R stands for Rosendale, J for Janesville. Asterisks indicate that the sign of the coefficient is inconsistent with the model. Underlined figures show that a consistency exists between coefficients, and is significant.

[12]Personal communication.

angle and the behavior of individual leaves. An increase in amount of leaves will cause a nonlinearity in the net assimilation and will result in a negative assimilation for the deeply-shaded lower leaves.

7.5 METHODS OF SYSTEMIZATION

So far, the basic concepts in agrometeorology, the essentials of mathematical and statistical operations, and the first approximation of crop-environment relationships by means of phenological, meteorological, and phenometeorological approaches have been discussed. Most of these approaches dealt with a single significant factor, such as temperature or rainfall, for a certain stage of growth. Thus, the success of such approaches depends upon (a) the choice of the most representative microclimatic elements of the field concerned, (b) the choice of the most significant element or elements at different developmental stages, (c) integration of the physical environment according to physiological principles and physical laws, and (d) the combination of biological responses of the physical environment.

An appropriate choice of the environmental element or elements which are representative of a locality is important. For example, in an area of five square miles, the percentage of possible sunshine, the intensity, duration, and quality of light, and the winter and spring rainfall are more representative than temperature and humidity. However, these representative elements of the microenvironment may not always be the significant elements. For example, prior to and at the tasseling stage of field corn, rainfall is one of the significant elements. But this phenological stage usually occurs during the summer season in most of the cornbelts in the U. S. A. Since summer rain is rather sporadic, a single raingage record within a five-square-mile area will not represent the actual distribution of rainfall, but rather a single-point rainfall record. Therefore, instruments which measure a large area, as described in Chapter 5, are desperately needed. Another improvement in the application of the single-element approach is the integration of several single environmental factors. Unfortunately, a climatic integrator has not been invented, and climate is usually observed for its physical elements. Thus, the integration of the physical environment can be done only through statistical means. Some illustrations on the integration of the physical environment have been given in Section 7.4.2. More study in the establishment of combined environmental parameters is necessary. Still another improvement can be made — the combination of biological responses. Since the physical environment has been represented by single environmental factors, the effects of these single parameters on plant growth and development should be combined. For example, the number of inches of rainfall during certain stages of plant growth is important and at the same time, the night-time temperature is also important. Therefore, the combination of their effects on plants should be studied.

In view of the above considerations, plant-environment relations should first be analyzed, then synthesized, and finally standardized. Standardization means the systematization of plant-environment relationships according to the order of the physiological development of plants and the time sequence of physical environments. Analysis, synthesis, and standardization are the three major procedures in plant-environmental studies. Of the three, synthesis is the most important step, and this will be elaborated at length.

7.5.1 *Analysis*

An analysis is the first step in methodology in order to explore and interpret the relations between plant and environment through the breakdown of the latter into appropriate physical units with respect to varietal and phenological stages of responses. The physical units, for example, may be expressed in terms of heat, moisture, light, and carbon dioxide; the phenological stages may be divided into seedling, early vegetative growth, rapid growth, and reproductive stages. This procedure is analogous to quantitative analysis in chemistry, separating a chemical compound into elements. The reverse is the synthesis by which two or more chemical elements are combined to form a compound. Climate or weather as a whole is comparable to a chemical compound, while a climatic factor is analogous to a chemical element. Accordingly, analysis and synthesis are two alternating procedures to be taken in order to establish reliable and logical relations between plants and their environments.

In the past 30 years, Azzi (1956) has demonstrated the responses of many agronomic crops, fruits, and vegetables to rainfall and temperature by means of the "meteorological equivalent." He sought to find quantitative relationships between meteorological factors and yield, with emphasis on stages of development. The threshold value of rainfall, for example, at a specific phenological stage which is responsible for a good or a poor yield, is called a rainfall-equivalent. Thus, a line drawn on the rectangular graph representing this threshold value is the equivalence line. When rainfall acts as a limiting factor to the yield, the equivalence line represents the drought line. The general term for the equivalent of any climatic element is the "meteorological equivalent" or the "environmental equivalent." It has been found that at various developmental stages, these equivalents tend to separate crop yields into much above and below the normal yield on the graph. With respect to crop yield, all the high-yield area or areas on the graph are termed "positive zones"; all the low-yield areas, "negative zones." Areas having both high and low yields are named "mixed zones." One of Azzi's zonal diagrams, a study of rainfall

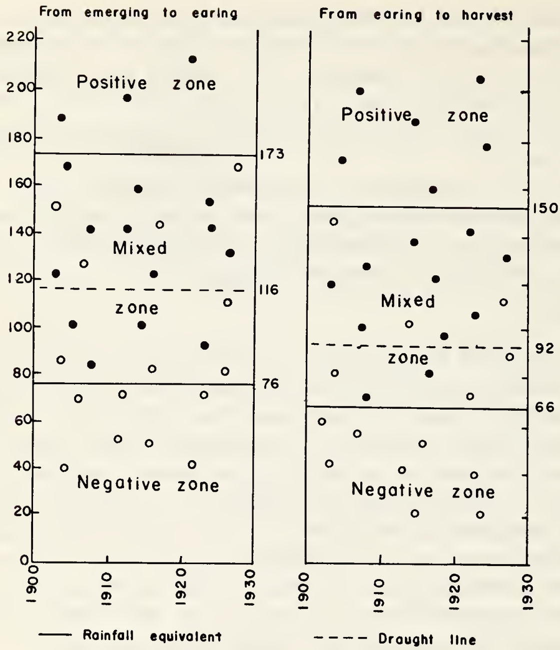

Fig. 7-11. Azzi's meteorological equivalent on wheat. After Azzi

effects on the yield of wheat in Italy, is shown in Fig. 7-11. In this diagram, the ordinate is rainfall in millimeters; the abscissa, the phenological stage of various years; the solid black dots, the years with much-above-normal yield; and the blank dots, the years with much-below-normal yield. According to his findings on rainfall equivalent, rainfall at the rapid growth stage is beneficial to yield for most crops, but harmful when it occurs at the seedling stage. Whether this statement is generally true or not depends upon the degree of damage done during the seedling stage and the subsequent environmental conditions. In the case of sweet corn in Green Bay, Fig. 7-6, the negative effect of rainfall on yield was located between the planting phase and the first tasseling. The low yields may be caused by low temperature, because the high rainfall during the spring in Green Bay may associate well with high cloudiness and low temperature. In one of Azzi's experiments on the yield of corn, it was shown that a drought in the vegetative stage resulted in a poor stand and performance, but the consequent yield was not affected at all, provided sufficient water was supplied during the rapid growth stage. Canners of the northern U. S. A. have made comparisons of the yield of tomatoes coming from

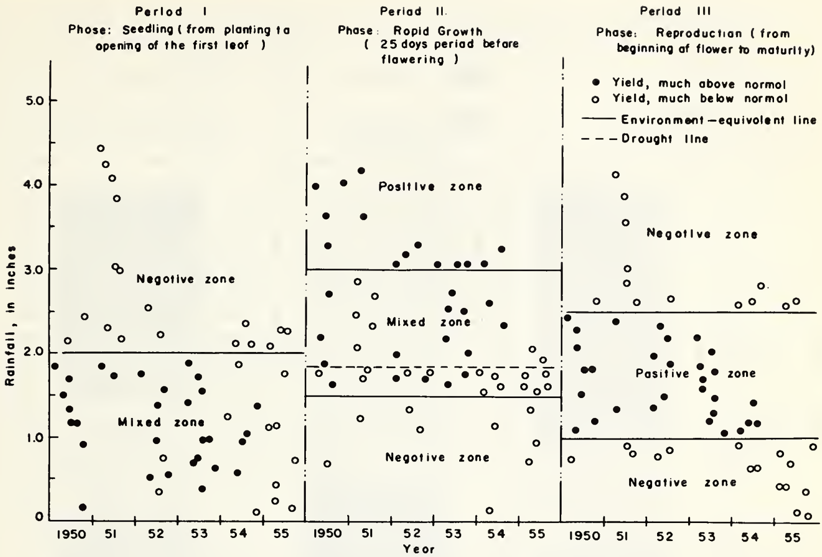

Fig. 7-12. A single model of sorting device.

various sources. It was found that potted plants from local greenhouses usually gave better field performance and higher yield at the early harvest than seedlings obtained from Georgia. However, the total yield of the latter always overtakes the former, due to the fact that the latter establish better root systems after transplanting and manifest less consumption of storage food during the early harvesting stage.

The time sequence of crop response should be investigated in conjunction with the effect of multiple factors as well as the single factor. Wang (1958; 1962b) has designed a series of sorters for crop-response studies. A schematic diagram of the single-element sorter is given in Fig. 7-12, and that of the multiple-element sorter in Fig. 7-13. Presumably, when a series of such single-element sorters, each sorter having a different environmental parameter for its own ordinate, is applied one at a time to crop yield, the mixed zone would eventually disappear if the available environmental parameter meets the following conditions: (a) it is the only determining factor of yield; (b) it is sufficient to cover all possible environmental effects; (c) it is correctly chosen; and (d) it is reliable and representative of an over-all microenvironment. The choice of the right parameter for the sorter is exceedingly important; for example, crop-rainy day is superior to rainy day, relative minimum and relative maximum rainfall are better than monthly rainfall, and the interdiurnal temperature is much more use-

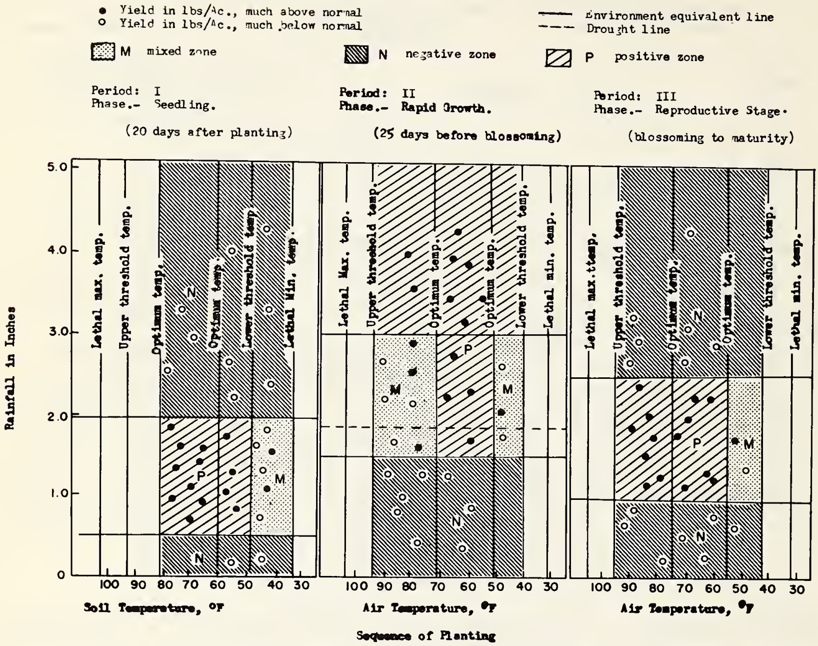

Fig. 7-13. A multiple model of sorting device.

ful than the monthly mean temperature. Also, when accurate data for soil moisture are available, the rainfall and evaporation data are not as necessary. If all the above conditions were met, then a single-element sorter would furnish answers to the following questions:

(a) How many environmental parameters are involved, and which parameters are more significant than the others?
(b) In which significant period is each parameter involved?
(c) What are the values for the environmental equivalents?
(d) How are scatterings distributed in each zonal area?

The environmental equivalents determine boundaries of zonal areas and hence the positive, negative, and mixed zones are distinguished. When the daily mean temperature is employed as a parameter, the upper and lower equivalence lines are similar to the upper and lower optimum range lines or the threshold lines of the thermal model (see Figs. 7-2 and 7-3). As shown in Fig. 7-5, when the relative maximum rainfall parameter is used for the reproductive stage of tomatoes, the upper and lower rain-equivalence lines are similar to the boundaries of the optimum range line. When the relative minimum rainfall is adopted, the lower boundary of the positive and the upper boundary of the negative zone define the drought line. But in this case the order of sorting various parameters is alternated and there are changes in the values of the equivalence line although the significance of parameters is unchanged. The order of sorting can be set up according to the descending order of the degree of environment-response. This can be determined by methods of first approximation, as described in Section 7.4.3. In short, the most significant parameter or the most important parameter to plant response should be sorted first. When a multiple-element sorter is applied, the interrelationships between two environmental parameters can be readily seen. In the use of either a single- or a multiple-element sorter, the statistical significance of equivalents depends upon the distribution of scatterings between zonal areas. In practice, electronic computation may be used in place of graphical presentations for the sorting device. In summary, the main task of a sorting device is to break an environmental complex into single elements, or a multiple factor into single factors, according to environment-crop relationships. This is a process of analysis; the reverse is synthesis.

7.5.2 *Synthesis*

Synthesis is here designated as a process or method of combining environmental factors. In the process of synthesis, both environmental parameters and phenological events are considered at the same time. The integration of environmental factors has been described in Section 7.4.2, and the interrelation of phenological events in Section 7.4.1. Three problems are usually encountered in combining the factors. They involve (a) the problem of combining two or more entirely different units, e.g., the addition of 2" of rainfall and 80°F of temperature, and the multiplication of 567 ly day^{-1} of light by 89% relative humidity and an addition of 5" day^{-1} evapotranspiration; (b) the problem of combining two or more factors of different weights with respect to plant responses; and (c) the problem of the final expression of the combined factors so that systematization will be possible.

Several methods of combining the factors or variables of plant-environment relationships have been developed by Wang (1958). They may be conveniently classified, according to their method of approach, into graphical, mathematical, and statistical approaches.

In the graphical approach, Wang & Tibbitts (1956) studied the water requirement of cigar-binder tobacco in Madison, Wisconsin. They first analyzed the relative minimum rainfall in weekly intervals during the growing season, and entered the results in a rectangular coordinate graph with rainfall as the ordinate and years as the abscissa. The isohyetal line for every inch of rainfall is drawn and the yields of tobacco are also entered. This is shown in Fig. 7-14. With respect to these values, it is interesting to note that there is a general tendency for the isohyetal ridges to coincide with the low yield years, and the

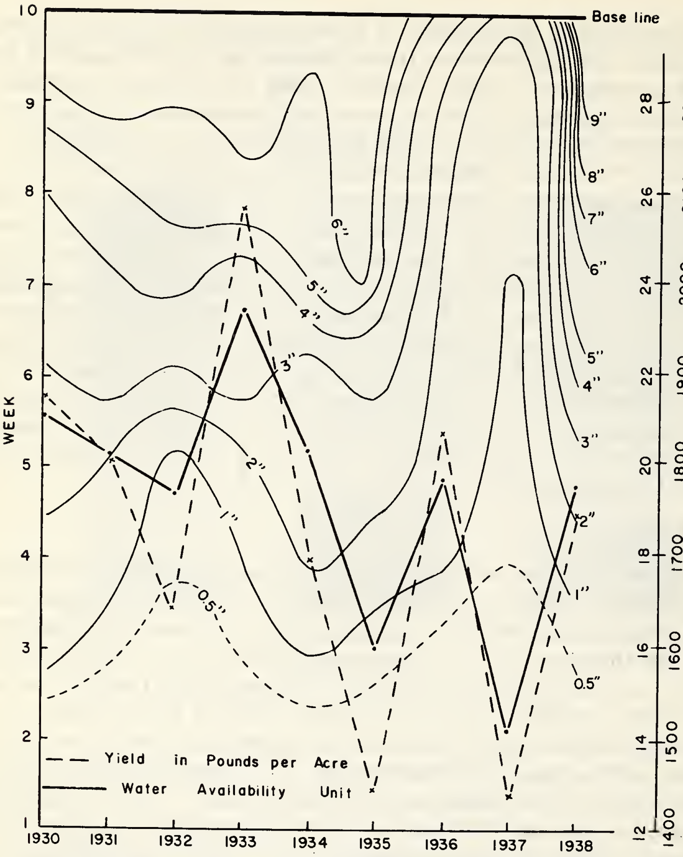

Fig. 7-14. Water availability unit and yield of tobacco, Madison, Wisconsin, 1930-1938.

trough with the high yield years. For instance, the pronounced ridge situated in the year 1937 developed in the lowest yield year, while the trough in 1938 occurred in the high yield year. Note also the year 1934, where the isohyets of lower values such as 1.00" and 2.00" are in the trough, while those of higher values such as 3.00" and 6.00" are definitely in the ridge. In this case, the tendency mentioned above still exists. By balancing effects between ridges and troughs, an average yield year is expected, for the nine-years' mean yield of tobacco is 1730 pounds of leaf weight per acre, and it is 1699 pounds per acre for 1934. This is within 31 pounds of the mean value. The standard deviation of the mean is 206.4, and the coefficient of variation, 11.9%. The phenological data, such as the topping date and vegetative period, on tobacco for this particular year are also very close to the means. The mean topping date was August 8 and the mean vegetative period, 57 days; for the year 1934, it was August 9 and 57 days, respectively. This shows that the isohyetal pattern, representing the lowest available amount of rainfall at various time sequences, determines the yield as well as the vegetative growth. In Fig. 7-14, a base line is arbitrarily chosen. Measure the distance from this base line to the intersection of one of the isohyetals and the axis of one of these years. In most of these years, the yield varies in proportion to the measured distance. Similar procedures can be repeated for parameters other than the relative minimum rainfall. Thus, a different position of the base line would be set up and a different distance would be expected for each measurement. Regardless of where the base is located, or what unit is used for measuring the distance, the final result would be the same, because it is the relative, and not the absolute, values of the parameters that count. Since all of these distances are expressed in the same unit, namely inches, a combination of factors of two or more different units becomes possible. The result of the algebraic sum of these distances measured from each graph for each year can be designated as a "combined unit." The algebraic sum of the relative minimum rainfall, precipitation prior to the growing season, vapor pressure deficit, and crop-rainy day has been used by Wang & Tibbitts to correlate with the tobacco yield.

The "combined unit" here has been called the "water availability unit," and is shown in Fig. 7-14. The yield of tobacco leaf in pounds per acre is indicated by the solid straight lines, while the water availability units are indicated by dash-lines. A linear correlation of the water availability unit and the yield of tobacco has been found to be $r = 0.92$, $r^2 = 0.85$, and $P = 0.01$. The graphic presentation can be further refined if either soil moisture or evapotranspiration measurements are available. Wang & Bomalaski (1958), in their study of objective methods for correlating various moisture factors with yield and quality of Alaska peas' growth in the Gillet-Bonduel area of Wisconsin, have further tested the significance of "water availability units." They classified pea yields according to tenderometer readings (T.R.) into three classes: T. R. = 90-99, T. R. = 100-109, and T. R. = 110-119. The result is that the mean actual yield is 1394 pounds per acre, while the mean estimated yield is 1376. The departure between the actual and estimated yields for each individual year ranged from 13 to 182 pounds per acre. The mean standard deviation of the yield for the three tenderometer readings was 354.3, and the mean coefficient of variation, 25.2%.

Engineers make the most skillful use of graphical solution to practical problems. Nomographs such as the ones in Figs. C-6 to C-11 in Appendix C would be useful here if coordinates were appropriately chosen. The environmental units such as photoclimatic, thermocli-

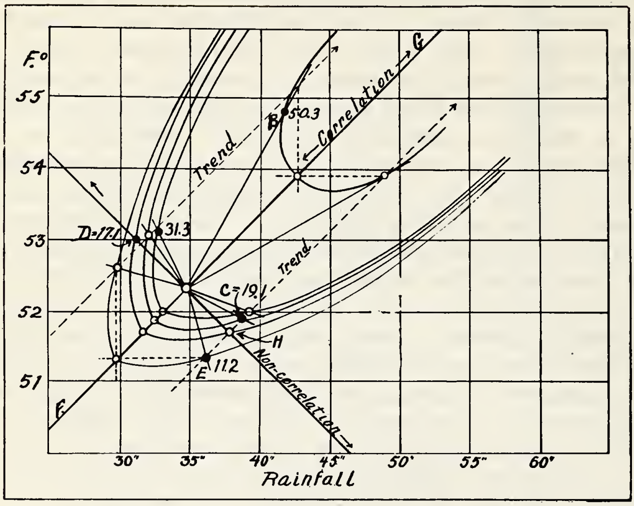

Fig. 7-15. A hythergraph indicating intensity of wheat leaf rust attacks in Illinois, 1922-1926.

matic, and hydroclimatic units (see Section 7.4.2), and the various phenological events (e.g., Fig. 4-15) can serve as coordinates. Meteorologists, climatologists, and geographers have widely adopted the graphical approach in making analyses of many parameters pertaining to regional characteristics. Plant pathologists and climatologists use the climograph and hythergraph. The climograph is a graphic representation of temperature vs. relative humidity, and the hythergraph (see Figs. 7-15 and 8-2); temperature vs. rainfall. Tehon, as early as 1928, studied the intensity of wheat leaf rust attacks in Illinois by using the hythergraph, where the abscissa is the annual rainfall and the ordinate, the annual mean temperature. This is given in Fig. 7-15. The most serious attack of wheat leaf rust can be seen by an index of 50.3, at point B, and the intensity decreases as it moves toward the outskirts of the concentric elliptical curves, as at points D and E. Fig. 7-15 is an illustration of the use of three variables in a two-dimensional chart. When the date of occurrence of these variables is entered, a fourth variable is added into the two-dimensional chart.

The use of four variables in three-dimensional charts would give a combination of four factors at one glance. For example, Went (1957) used four variables in three-dimensional charts for the interpretation of phytotron experimental results. They are given in Figs. 7-16 and 7-17. Fig. 7-16 demonstrates the relationships between the day- and night-temperature and the photoperiod and optimal growth of a number of garden flowers, denoted as follows:

S African Violet, *Saintpaulia ioantha*
P *Petunia*
Z *Zinnia elegans*
C China aster, *Callistephus chinensis*
A *Ageratum conyzoides*
M Stock, *Matthiola incana*
PA Iceland Poppy, *Papaver nudicaule*
B English Daisy, *Bellis perennis*

The monthly climates of Pasadena (upper ellipse) and Denver (lower ellipse) are shown in heavy black lines. The orthogonal projection of the two ellipses can be seen in each of the three-sided planes, where a two-dimensional relationship is shown. Fig. 7-17 demonstrates the relationship between growth in the first month after storage (ordinate) and length of storage at 2°C (abscissa) for the Itchweed plant, *veratrum viride*, obtained from field during the periods of July 21-August 18, and October 3-20.

It was found that corms that were collected during or after the growing season went into a deep dormancy which could be broken only by storing at 2° to 4°C, whereas practically all corms stored at 6°C or higher rotted or remained dormant.

As stated before, assigning a single numerical value to a given climatic or environmental complex has not yet been possible. Therefore, it becomes necessary to work with individual climatic components, the combinations of all components being made by means of partial differential equations. In such mathematical operations, then, the differentiation of constants and variables, as well as the elimination of variables, would be of fundamental importance. A single phenological event, namely, the yield of a crop, is used to illustrate the processes of mathematical formulation below.

Let potential yield (Y_p) be a function of biotic (b), edaphic (e), climatic (c), and time (t) factors. This may be expressed mathematically as

$$Y_p = Y_p(b, e, c, t) . \qquad (7\text{-}38)$$

The "potential yield," Y_p, is defined here as the yield that might be realized at the end of the growing season. Early in the growing season, a crop may be developing nicely with a good outlook for an optimum yield. At this time, the "potential yield" is high. Later, however, a midseason frost or other climatic catastrophe may reduce the potential yield to zero. This illustrates the fact that the potential yield is actually a variable function of time during the growing season.

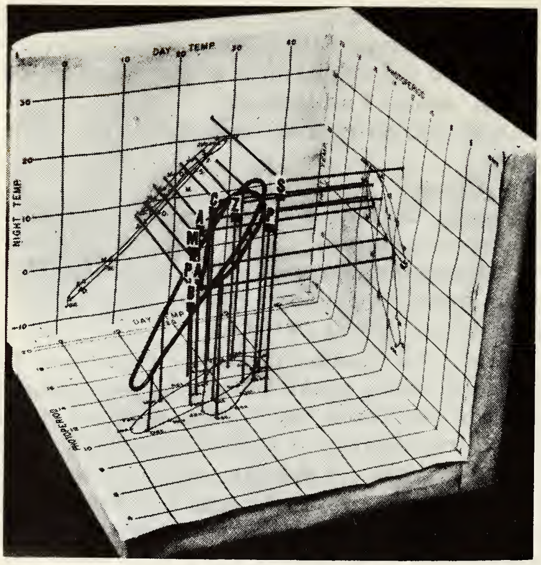

Fig. 7-16. Relationships between day temperature, night temperature, photoperiod and the optimal growth of a number of garden flowers.
After Went, 1957

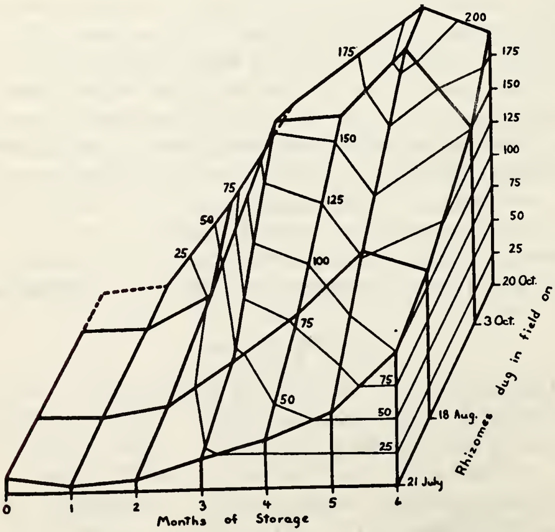

Fig. 7-17. The dormancy period of *veratrum viride* in storage as related to time of storage and time of digging. After Went, 1957

If all environmental factors were held constant, the yield would vary, but slightly; and if all environmental factors were joined optimally, maximum yields would be expected. It follows that a normal yield occurs only with certain combinations of environmental conditions, such as all being normal. It is the departure from the normal with which we are concerned, for it is this departure which is responsible for the difference of yield in each planting sequence.

Let dY_p be the change of potential yield, and isolate the variables as

$$dY_p = \left(\frac{\partial Y_p}{\partial b}\right)_{e,c,t} db + \left(\frac{\partial Y_p}{\partial e}\right)_{b,c,t} de + \left(\frac{\partial Y_p}{\partial c}\right)_{b,e,t} dc + \left(\frac{\partial Y_p}{dt}\right)_{b,c,e} dt, \quad (7\text{-}39)$$

where subscripts denote the factors being held constant. Then the total time-variation of potential yield, dY_p/dt, will be

$$\frac{dY_p}{dt} = \left(\frac{\partial Y_p}{\partial b}\right)_{e,c,t} \frac{db}{dt} + \left(\frac{\partial Y_p}{\partial e}\right)_{b,c,t} \frac{de}{dt} + \left(\frac{\partial Y_p}{\partial c}\right)_{b,e,t} \frac{dc}{dt} + \left(\frac{\partial Y_p}{\partial t}\right)_{b,c,e} \quad (7\text{-}40)$$

The interpretation of the expressions in equation (7-40) is as follows:

$\frac{dY_p}{dt}$ the change of the potential yield (Y_p) with time.

$\int_{D_p}^{D_M} \frac{dY_p}{dt} dt$ is the actual yield at harvest where D_p is the date of planting and D_M is the date of maturity (presumed to be the date of harvest);

$\left(\frac{\partial Y_p}{\partial b}\right)_{e,c,t}$ the partial change of the potential yield with respect to biotic factors — edaphic factors, climate, and time being constant;

$\frac{db}{dt}$ the total rate of change of biotic factors with time;

$\left(\frac{\partial Y_p}{\partial e}\right)_{b,c,t}$ the partial change of the potential yield with respect to edaphic factors — biotic factors, climate, and time being constant.

$\frac{de}{dt}$ the total rate of change of edaphic factors with time;

$\left(\frac{\partial Y_p}{\partial c}\right)_{b,e,t}$ the partial change of the potential yield with respect to climatic factors—biotic factors, edaphic factors, and time being constant;

$\frac{dc}{dt}$ the total rate of change of climatic factors with time;

$(\frac{\partial Y_p}{\partial t})_{b,c,e}$ the partial change of the potential yield with respect to time, independent of biotic, climatic, and edaphic factors.

With constant cultural practices, or applying the rule of constancy of biotic factors, the partial derivative in the first term, $(\frac{\partial Y_p}{\partial b})_{e,c,t}$, will probably equal zero, even though the db/dt may be rather large. Thus, the first term on the right-hand side of equation (7-40) is approximately zero. That is,

$$(\frac{\partial Y_p}{\partial b})_{e,c,t}\frac{db}{dt} \simeq 0 .$$

The last term of equation (7-40), $(\frac{\partial Y_p}{\partial t})_{b,c,e}$, is the partial change of the potential yield with respect to time, if all other factors are held constant. A little reflection will show that by holding biotic, edaphic, and climatic factors constant, the yield at the end of the growing season, i.e., the potential yield, depends only on the genetics of the plant. Since for a given variety, this is either constant, for hybrids, or constant for the average yield in a whole field, the rate of change of the potential yield in this case must be zero:

$$(\frac{\partial Y_p}{\partial t})_{b,c,e} = 0 .$$

With the above considerations, equation (7-40) can be rewritten as

$$\frac{dY_p}{dt} = (\frac{\partial Y_p}{\partial e})_{c,t}\frac{de}{dt} + (\frac{\partial Y_p}{\partial c})_{e,t}\frac{dc}{dt} . \qquad (7\text{-}41)$$

The actual yield, Y_a, can be obtained from the integration of the above expression, thus

$$Y_a = \int_{D_p}^{D_M}\frac{dY_p}{dt}\,dt = \int_{D_p}^{D_M}\left\{(\frac{\partial Y_p}{\partial e})_{c,t}\frac{de}{dt} + (\frac{\partial Y_p}{\partial c})_{e,t}\frac{dc}{dt}\right\}dt . \qquad (7\text{-}42)$$

Then, as a first approximation, the departure of yield from normal will be

$$\Delta Y_p = Y_a - \bar{Y} = \sum_{i=p}^{M}\left\{(\frac{\partial Y_{pi}}{\partial e_i})_{c,t}\Delta e_i + (\frac{\partial Y_{pi}}{\partial c_i})_{e,t}\Delta c_i\right\} \qquad (7\text{-}43)$$

where the range of time is between the date of planting and the date of harvest, i.e., a specified growing season. $\bar{Y}$ is the mean yield, and $Y_a - \bar{Y}$ indicates the departure of yield from the mean.

Each term of the right-hand side of equation (7-43) is a symbol which expresses the relationship of one group of elements to the others. A further breakdown of each group according to individual elements is rather complicated, but useful, and therefore electronic computation is needed. For the sake of convenience, a climatic factor is used to illustrate how a breakdown of equation (7-43) may be accomplished. Let this climatic factor be C; then the consecutive weekly intervals can be designated as C_1, C_2, C_3, . . . etc., representing the first-week interval, second-week interval, third-week interval, and so forth, respectively. The use of weekly intervals instead of five- or ten-day intervals is purely arbitrary. Then, for a certain year "x", equation (7-43) becomes·

$$(\Delta Y_p)_x = \left\{ \frac{\Delta Y_p}{\Delta C_1} dC_1 + \frac{\Delta Y_p}{\Delta C_2} dC_2 + \frac{\Delta Y_p}{\Delta C_3} dC_3 + \ldots \right\}_x , \qquad (7\text{-}44)$$

where the subscript "x" refers to the specific year, and

$$\frac{\Delta Y_p}{\Delta C_1}, \frac{\Delta Y_p}{\Delta C_2}, \frac{\Delta Y_p}{\Delta C_3}, \text{ etc.,}$$

are the coefficients and are quasi-constant for a given week-interval. They can be designated by the symbols k_1, k_2, and k_3, respectively. The terms dC_1, dC_2, dC_3, etc., are the changes of the particular climatic factors in different consecutive week-intervals. For a number of years, a group of linear equations may be established, as follows:

$$\begin{aligned} (\Delta Y_p)_1 &= (k_1 dC_1 + k_2 dC_2 + k_3 dC_3 + \ldots)_1 \\ (\Delta Y_p)_2 &= (k_1 dC_1 + k_2 dC_2 + k_3 dC_3 + \ldots)_2 \\ (\Delta Y_p)_3 &= (k_1 dC_1 + k_2 dC_2 + k_3 dC_3 + \ldots)_3 \\ (\Delta Y_p)_4 &= (k_1 dC_1 + k_2 dC_2 + k_3 dC_3 + \ldots)_4 \end{aligned} \qquad (7\text{-}45)$$

and the like.

The constant k's in the above equations can be determined by given Y and C simultaneously, in the case (for example) of an eight-year record for eight unknown k values. In general, a least-squares solution is required. Then, finally, a single-environmental parameter, which represents one climatic element, is obtained.

For any given year, a temporary yield prediction can be computed from the single-environmental-parameter equation for any one element. Let $(\Delta Y_e)_{C_a}$ and $(\Delta Y_e)_{C_b}$ indicate the departures of predicted yield due to the elements C_a and C_b, respectively. Thus a combination of different elements is possible for this one particular year as

$$\Delta Y = a + b(\Delta Y_e)_{C_a} + c(\Delta Y_e)_{C_b} + d(\Delta Y_e)_{C_c} , \qquad (7\text{-}46)$$

where C_a, C_b, C_c, etc., are the factors concerned. The nature of these weighting factors will be considered further.

The constants of equation (7-46) are determined by the usual multiple correlation method. After solving the constants a, b, c, etc., a prediction equation is obtained. Both edaphic and climatic factors in equation (7-43) can be classified as positive or negative in order to facilitate the computation. The positively correlated elements are the edaphic or climatic factors which give an increase in the yield of a crop within certain limits or amount or intensity. For instance, increased precipitation usually increases yield. However, too much precipitation will reduce the yield as well; therefore, a certain amount of precipitation should be established as a limit. Below the limit, it is a positive factor, while above the limit it is a negative one. Similarly, the negatively correlated elements (either edaphic or climatic) give rise to a decrease in yield with an increase in the intensity of the negative elements. All the positive factors, when applied to equation (7-45) should be added, while the negative factors will be subtracted.

It should be pointed out that crop-environment relationships are generally non-linear. The use of essentially linear equations such as (7-45) and (7-46), therefore, is to achieve a first approximation to the non-linear phenomenon. In this respect, the use of equations (7-42), (7-43), and (7-44) is more satisfactory, as they are non-linear. Usually, the contingency table approach and the polynomial approach, which can be used for the study of crop-environment relationships, are also non-linear.

Table 7-3. Dry Weight of Pasture Yields Grown in New Zealand (Averaged Over Three Replications)

Week of Cutting	Week of Closure			
	0	1	2	3
1	87			
2	443	184		
3	689	485	157	
4	1433	1186	676	237
5	2870	2580	2057	1612
6	3359	3475	2488	2134
7	4496	4516	3572	3035
8	6195	5527	4772	4211
9	6331	5847	5450	4855
10		6287	6214	5551
11			6907	6950
12				7497

After Brougham, 1955

Similar to the above approach, Glenday (1955) has applied the statistical method of constant-fitting to weekly weather effects on pasture field growth. Data were obtained by Brougham (1955), who laid down the field trial design running on a short-rotation of ryegrass, white clover, and red clover pasture. Each plot series had been cut at weekly intervals for nine weeks with four starting dates at weekly intervals. This is shown in Table 7-3. The design involves replication both in time and in space. The observations of maximum and minimum air temperatures, 4" depth soil temperature, and rainfall are expressed in weekly intervals (w), and the corresponding weekly growth (g), expressed as dry matter in pounds per acre, is measured. The mathematical model by Glenday is

$$y_{i(j+i)k} = g_i + w_{(j+1)} + \ldots + w_{(j+i)} + r_k + e_{i(j+i)} + e'_{1(j+i)k}, \quad (7\text{-}47)$$

where

$y_{i(j+i)k}$	is the yield of the plot at stage of growth i, closure date j, and replication r;
g_i	is the contribution from i intervals of growth (including the general mean, since the prediction equation for each plot contains a single g_i); i = 1, . . . , I;
$w_{(j+1)} + \ldots + w_{(j+i)}$	are the contributions from each of the weather intervals during which growth took place (there being i weather constants in each equation); j = 0, . . . , J;
r_k	is the contribution from the k^{th} replication; k = 1, . . . , K;
$e_{i(j+i)}$	is the contribution common to all replications of the $i_{(j+i)}{}^{th}$ treatment not explained by g_i and w_j;
$e'_{i(j+i)k}$	is the unassigned residual for the plot in question.

If replications are distinct and complete, the (r) parameters of equation (7-47) will be orthogonal to the others. This means that the average of several replications can be expressed by a simpler model without loss of generality, thus,

$$y_{i(j+i)} = g_i + w_{(j+1)} + \ldots + w_{(j+i)} + e_{i(j+i)} . \quad (7\text{-}48)$$

The procedure is then to fit the above model to the data by minimizing the residual variance, i.e., $e_{i(j+i)}$, through an ordinary procedure of minimization in the differential calculus; hence equation (7-48) becomes

$$y_{i(j+i)} = g_i + w_{(j+1)} + \ldots + w_{(j+i)} . \quad (7\text{-}49)$$

Applying equation (7-49) to the fourth cutting of each starting date in Table 7-3, the values are as expressed below:

$$1432 = g_4 + w_1 + w_2 + w_3 + w_4 ;$$

$$2580 = g_4 + w_2 + w_3 + w_4 + w_5 ;$$

$$2488 = g_4 + w_3 + w_4 + w_5 + w_6 ;$$

$$3035 = g_4 + w_4 + w_5 + w_6 + w_7 .$$

The sum of the above expressions is

$$9536 = 4g_4 + w_1 + 2w_2 + 3w_3 + 4w_4 + 3w_5 + 2w_6 + w_7 . \quad (7\text{-}50)$$

In this trial, since I = 9 and J = 3, a set of 21 normal equations can

Table 7-4. Normal Equations

4									1	1	1	1									g_1	=	665	(A)
	4								1	2	2	2	1								g_2		3,216	(B)
		4							1	2	3	3	2	1							g_3		6,066	(C)
			4						1	2	3	4	3	2	1						g_4		9,536	(D)
				4					1	2	3	4	4	3	2	1					g_5		14,128	(E)
					4				1	2	3	4	4	4	3	2	1				g_6		17,502	(F)
						4			1	2	3	4	4	4	4	3	2	1			g_7		21,024	(G)
							4		1	2	3	4	4	4	4	4	3	2	1		g_8		25,206	(H)
								4	1	2	3	4	4	4	4	4	4	3	2	1	g_9		27,022	(I)
1	1	1	1	1	1	1	1	1	9	8	7	6	5	4	3	2	1				w_1		25,903	(J)
1	2	2	2	2	2	2	2	2	8	17	15	13	11	9	7	5	3	1			w_2		55,903	(K)
1	2	3	3	3	3	3	3	3	7	15	24	21	18	15	12	9	6	3	1		w_3		87,569	(L)
1	2	3	4	4	4	4	4	4	6	13	21	30	26	22	18	14	10	6	3	1	w_4		122,320	(M)
	1	2	3	4	4	4	4	4	5	11	18	26	26	22	18	14	10	6	3	1	w_5		118,788	(N)
		1	2	3	4	4	4	4	4	9	15	22	22	22	18	14	10	6	3	1	w_6		109,669	(O)
			1	2	3	4	4	4	3	7	12	18	18	18	18	14	10	6	3	1	w_7		98,213	(P)
				1	2	3	4	4	2	5	9	14	14	14	14	14	10	6	3	1	w_8		82,594	(Q)
					1	2	3	4	1	3	6	10	10	10	10	10	10	6	3	1	w_9		61,889	(R)
						1	2	3		1	3	6	6	6	6	6	6	6	3	1	w_{10}		39,406	(S)
							1	2			1	3	3	3	3	3	3	3	3	1	w_{11}		21,354	(T)
								1				1	1	1	1	1	1	1	1	1	w_{12}		7,497	(U)

Table 7-5. Equations to Give (w) Parameters

27	15	4	-6	-6	-6	-6	-6	-6	-6	-3	-1	w_1	=	-20,753
15	35	13	-7	-8	-8	-8	-8	-8	-8	-6	-2	w_2		-24,453
4	13	28	-2	-5	-6	-6	-6	-6	-6	-5	-3	w_3		-18,273
-6	-7	-2	10	4	1							w_4		+ 6,313
-6	-8	-5	4	10	4	1						w_5		+11,668
-6	-8	-6	1	4	10	4	1					w_6		+ 8,138
-6	-8	-6		1	4	10	4	1				w_7		+ 9,546
-6	-8	-6			1	4	10	4	1			w_8		+ 9,260
-6	-8	-6				1	4	10	4	1		w_9		+ 4,300
-6	-8	-6					1	4	10	4	1	w_{10}		+ 5,122
-3	-6	-5						1	4	7	2	w_{11}		+ 6,166
-1	-2	-3							1	2	3	w_{12}		+ 2,966

be derived, as has been done in the matrix notation (see Table 7-4). The next step in the procedure is to eliminate one set of parameters to reduce the number of variables in the final calculations. Thus, as indicated in Table 7-5, 12 equations are established to give (w) parameters in the matrix notation, $Xp = a$.

If the restriction $w_s = 0$ is imposed, the equations for the solution become

$$Yq = b\,,$$

where Y is the symmetric 11×11 matrix obtained by deleting the s^{th} row and column from X, and q and b are the column vectors p and a with the s^{th} element deleted. The final solution will then be

$$q = Y^{-1}b. \tag{7-51}$$

Suppose the general linear restriction $\sum_1^{12} k_i w_i = 0$ is imposed. Without loss of generality, this can be taken to be

$$w_s = -\sum_1^{s-1} k_i w_i - \sum_{s+1}^{12} k_i w_i .$$

Then, substituting this value of w_s and deleting the s^{th} row as before, the equation for solution becomes

$$YZ_q = b \tag{7-52}$$

where Z is the 11 × 11 matrix

$$\begin{vmatrix} 1+k_1 & k_2 \cdots & k_{s-1} & k_{s+1} \cdots & k_{11} & k_{12} \\ k_1 & 1+k_2 \cdots & k_{s-1} & k_{s+1} \cdots & k_{11} & k_{12} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ k_1 & k_2 \cdots & k_{s-1} & k_{s+1} \cdots & 1+k_{11} & k_{12} \\ k_1 & k_2 \cdots & k_{s-1} & k_{s+1} \cdots & k_{11} & 1+k_{12} \end{vmatrix}$$

Solutions will be obtained from

$$Zq = y^{-1}b, \tag{7-53}$$

i.e.,

$$\begin{vmatrix} 1+k_1 & k_2 & \cdots & k_{12} \\ \cdots & \cdots & \cdots & \cdots \\ k_1 & 1+k_2 & \cdots & k_{12} \\ k_1 & k_2 & \cdots & 1+k_{12} \end{vmatrix} q = Y^{-1}b .$$

Subtraction of any pair of equations in this set shows that the solutions for $(w_i - w_j)$ are independent of the k's, the set from equation (7-51) being those for the trivial case in which $k_s = 1$ and all other k's are zero. Thus, any linear restriction gives the same set of w's except for a constant.

Imposing the usual restriction $w_{12} = -\sum_1^{11} w_i$ gives equations for solution such as in equation (7-52) so that any recognized method of inverting the symmetric matrix Y or the non-symmetric product YZ can be used and a set of w's with zero mean will be obtained.

Applying these methods to Table 7-5, we get

$w_1 = -464$	$w_7 = +215$	$g_1 = 439$	$g_7 = 5073$
$w_2 = -204$	$w_8 = +380$	$g_2 = 1068$	$g_8 = 6061$
$w_3 = -322$	$w_9 = -338$	$g_3 = 1770$	$g_9 = 6507$
$w_4 = -100$	$w_{10} = -199$	$g_4 = 2494$	
$w_5 = +662$	$w_{11} = +386$	$g_5 = 3377$	
$w_6 = -201$	$w_{12} = +185$	$g_6 = 4207$	

the values of g_i being obtained by substituting the values of w in equations (A) to (I) of Table 7-4.

By expanding the expressions for the parameters in terms of the original $y_{i(j+1)}$'s, the standard errors of the estimates can be obtained.

The above are illustrations of graphical, mathematical, and statistical approaches to the combination of environmental factors for crop response studies or simply "the process of synthesis." Although there are many statistical approaches for the same purposes, the reader in making a choice of methodology should be aware of the fact that there are not many methods which follow the basic concepts of agrometeorology, and some are misleading.

7.5.3 *Standardization of procedures*

The standardization of procedures is a scheme to join individual methods together into a unified sequence and to formulate a simple procedure that will include all necessary information for a specific problem. A unified sequence refers to a time sequence or a space sequence, or both, depending upon the nature of the problem in question. A simplified procedure includes graphs, nomograms, alignment charts, tables, and equations, or a combination of these. Sometimes, a simple tool such as a special slide rule or a dial is useful. Once the procedures are standardized, they serve as guides to the statistical and mathematical approach.

In this connection, some fundamental procedures as listed below may serve as a guide. The practical application and description of the procedures are illustrated in other chapters as indicated. In principle, procedures should follow two avenues: the physiological development of crops with age, and the physical changes of the environment associated with them.

I. How are statements of the problem made?
   A. What is the type of problem?
      1. To appraise farming area or site.
      2. To improve cultural practices (irrigation, fertilization, rotation, spraying plan — insecticide, fungicide, weed control, etc.).
      3. To prevent weather hazards (Refer to Chapter 12).
      4. To control the microclimate of the farming area (Refer tp Chapter 11).
      5. To modify the production pattern most suitably for harvest management and factory operation.
      6. To decide on the treatment of storing and stored materials for better quality.
      7. To predict crop maturity date, yield, quality, etc. (Refer to Chapter 8).
      8. Other types of problem.

B. How large or small is the problem?
   1. Establishment of limits.
      a. In the physical environment — subject matter limits.
      b. In biological responses — choice of indicator limits.
   2. Size of samples (number of species and varieties of crops associated with environmental types).

C. How is the problem to be analyzed?
   1. By using the assumption of the constancy of biotic factors (Refer to Sections 2.1.2 and 3.4.1).
   2. By formulating the problem in a solid, explicit manner (Refer to B.1 above for delineation).
   3. By selecting the problem in view of its peculiar characteristics for the purposes of:
      a. Leading to a design.
      b. Making an operational decision.
      c. Interpreting a fact.

II. What type of data is available?
   A. What is the nature of the raw material?
      1. Phenological data (Refer to Section 6.2).
      2. Environmental data (Refer to Section 2.2).
   B. What is the length of record suitable for an adequate solution?
   C. What is the representative quality of the data (at the spot, in the area, over the region)?
   D. How accurate are the data with respect to the time indication (Refer to Section 3.2.3 and Chapter 3) and the location of sensors (e.g., on the leaf or above the ground)?

III. How are the data to be analyzed?
   A. Do local peculiarities of physical environments affect the usefulness of the existing data?
   B. Do biological and statistical limitations impose on the existing data?
   C. Are estimations needed for those data which were never observed or were inadequate?
   D. Are modifications of environmental or crop data required (Refer to Sections 3.4.1 and 7.2)?
   E. Are solutions available for analogue climatological problems?
   F. Are combinations of environmental elements required? If so, what are they, and are their relationships known?

IV. What is the procedure for the first approximation to a solution?
   A. Should "sorting" techniques be applied (Refer to Section 7.5.1)?
   B. Should a check be made with the crop response model (Refer to Section 7.4.3)?
   C. Should a test (or choice) be made with (or from) various environmental parameters (Refer to Chapter 4 and Sections 7.4.2 and 7.4.3)?
   D. Should the significant element and significant period be located (Refer to Section 3.2)?
   E. Should tentative conclusions for the first approximation be established?

V. How should the final decision be made?
  A. What are the quantitative differentiation of environmental influences on plants at various stages?
    1. Positive.
    2. Negative.
    3. Neutral.
    4. Linear or non-linear.
  B. How is the combination of various single environmental effects at various developmental stages reached?
    1. By the algebraic sum (to be additive or simply a summation).
    2. By mathematical formulation.
    3. By graphical solution, particularly projections of three-dimensional concepts (Refer to Section 7.5.2).

In summary, statistical and mathematical methods have been applied to agrometeorology since 1920. These methods, as established by Fisher, have been applied in crop-weather relationships to a tremendous amount of statistics. However, only recently has there arrived a better measurement of the microenvironment, arising from modern advancements of statistics in agriculture. In this new phase of development, more accurate observations of phenological events as well as of the physical environment, are the cornerstones of agrometeorology. Remember, statistical methods are only tools, and the successful use of these methods depends on insight into physical law and physiological principles.

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CHAPTER 8

Crop Forecasting

8.1 TREATMENT OF DATA

Two major kinds of data are involved in crop forecasting. They are crop data and environmental data. Crop data consist of measurements of the growth and development of plants. Plant growth involves plant height, leaf area, fresh weight, dry weight, top root ratio, diameter of the stem, and the like. Plant development is concerned with germination date, emergence date, leaf count, flower count, and fruit count.

In a broad sense, environmental data include all available data which describe the environment of a crop, such as slope and drainage, vegetative cover, and nearby bodies of water. Data fall into two groups, biotic and abiotic. The biotic factors, such as the competition for light and moisture between plants, can be eliminated in the study of agricultural meteorology, due to the assumption of constancy of biotic factors, pointed out in Section 3.4.1. Abiotic factors in the narrow sense can be taken simply as the physics of the environment, such as soil-air temperature, soil-air moisture, and the like. As pointed out in Section 2.2.1, intensity, duration, and quality of light are also included as environmental data, though strictly speaking, they are not physical properties of the environment, but are extraterrestrial factors.

8.1.1 *Crop data*

Crop data obtained in raw form from field observations are not pertinent to the study of environment-crop relationships. Therefore, two steps should be taken to transform the data into a form which will facilitate statistical manipulation. They are (a) classification and presentation of data, and (b) modification of data.

(a) Classification and presentation of data. A detailed classification and description of data of yield, quality, and other phenological events are necessary prior to the introduction of various methods to correct crop data.

Yield and quality are economically important to farmers, but they are not necessarily the best indicators for the study of the environment of a crop. Other indicators may be more sensitive to changes in the environment. These can be called the "phenological events."

Usually, the length of record for one crop variety is too short to be of statistical value. Therefore, means for the combination of crop data from two or more different varieties would be important. The reliability of records is also a big problem. For instance, commercial records are not as reliable as experimental data. The use of historical data depends upon the reliability of these data. They are not usually ideal, but they are available. On the other hand, new experimental data are ideal, but are not usually available for a large sample.

The classification and presentation of yield, quality, and phenological records, the three major categories of crop data for forecasting, should be further specified.

(1) Yield. Yield of crops can be expressed in a number of ways. It can be measured by weight, volume, size, number, and by other means. Each measurement can be expressed in terms of its absolute value, such as pounds per acre (lbs/A) or bushels per acre (bu/A). These expressions are given in terms of the arithmetic mean value of an area. Other central values of parametric statistics, such as median and mode (see Appendix B), should be introduced. They are better parameters than the mean. Unfortunately, the mean value is popularly adopted. For the sake of convenience, the mean value is used as illustration and the reader may use other central values as needed. The departure from the desirable central value (e.g., mean departure, standard deviation, and coefficient of variation) should also be used. The percentage departure from central value is useful because it makes possible comparison of crops grown in widely differing regions, as well as different varieties in the same region. The weighted mean, as presented in Appendix B (2), equation (B-3), would also serve the purpose. When yield is expressed by weight, it is imperative to know what fraction of that weight is moisture, or simply the "moisture content." Other specifications are also necessary and may also be considered aspects of the quality of a crop. For example, yield can be specified in terms of sieve size for snap beans and peas. Further elaboration of quality is necessary.

(2) Quality. The "quality" of a crop can be defined as the value of the economical parts or organs of that crop. It has been expressed in many ways, such as color, odor, taste, hardness, crispness, and size. It has not been as clearly defined as the yield, but has usually been described only in a qualitative sense. Therefore, effort should

be expended toward finding quantitative indicators of the quality of a crop. Some quantitative techniques have been applied to a few crops. Examples are tenderometer reading (T.R.) and alcoholic insoluble products (AIS) of canning peas, burning index of tobacco leaves, starch content of potatoes, waxy consistency of small grains, and sugar content of the sheath of sugar cane. For quantitative measurements of biotic material, the reader may refer to Sections 5.1.3 and 5.7.1.

The quality of crop has occasionally been recorded in commercial data. These records can be used only as a reference, for the consistency in observations, which is important, is usually lacking.

The commercial grading system can be another expression of the quality of a crop. It can serve as an important quantitative description for the crop, provided these parts have economic importance, but sometimes it may not be of importance in the study of the growth and development of a plant. For example, Grade A Tomato is generally described as "90% of the surface well-colored," which is one of the indicators for quality, while for the parts to be "free from injury and disease" has little to do with "quality" as far as agrometeorological study is concerned. Also, the "weight per bushel," "moisture content," and "odor" are useful grain grading standards to agrometeorologists, while the presence of "foreign matter" or of "damaged grains" is not as useful.

(3) Phenological events. As mentioned previously, the objective measurement of phenological events with instruments is the ideal. Almost all the phenological events now available in records were obtained by visual observation. When referring to a field of crops, they are usually in terms of percentages of the entire field area, for example, 75% of blossoming of Alaska peas, or 80% emergence of winter wheat. The dates of harvest are measured by all sorts of subjective means, and are thus poorly defined for most crops and far from being ideal for objectivity.

The record should be long enough to reach a point of stability. The word "stability" designates that there would be almost no significant change in the average value of the data if more data were added. This is applicable to both environmental and crop data, even if the environment and crop are governed by different factors. Crop data will reflect varietal differentiations and cultural practices as well as regional differences; in fact, cultural practices may have more of an effect on farm production than the changing environment. These facts make it impossible to state a set length of record which is required for any crop. For ideal crop data with a constant cultural practice, the longer the record is, the better the data will be. Usually, long records are available for yield only, rather than for quality and phenological events. Occasionally, a record of yield has been kept for 50 years or more, but it is still not useful without the presence of phenological records such as dates of planting, blossoming, and harvesting, etc. For example, Leith et al. (1952) have presented a 51-year record of Oderbrucker barley grown in Madison, Wisconsin, published as a study of the relation of date of planting to yield of barley in which only yield in bushels per acre and the date of planting for these 51 years were presented; Anderson (1953) published a record of 114 years of combined production of all types of tobacco grown in Connecticut which contained only yield in pounds per acre. If we had phenological data as well for these 114 years, the data would be ideal. On the other hand, some published papers dealing with crop-environment relationships have utilized records of only two to five years in length. Data would not be easy to handle satisfactorily by any statistical method unless there are more than nine measurements or observations in those years.

Once crop data have been properly classified, they must be presented in a way which will make possible their most efficient and widespread use. The importance of phasic division and sharpness of phases has already been discussed in Section 3.2. These considerations are applicable to the presentation of data and should be kept in mind. The completeness and accuracy of crop data is of paramount importance as the foundation of agrometeorological study, particularly in crop forecasting.

Ideal data would consist of complete records of phenological events and precise measurements of morphological and chemical developments. Most historical data, either commercial or research from universities or private industries, are lacking in such standards. In fact, volumes of crop data have been published in the past which consisted of only one statistical element, yield per acre. These data are not too useful as far as agrometeorological studies are concerned.

Phenology of sweet corn is used as an illustration of ideal and minimum requirements, where minimum requirements are designated by the numeral (1), more comprehensive observations by (2), and extensive phenological observations involving either a large amount of work or a very difficult observation by (3). Items designated by (p) are those for which the following should be reported: the date of the first sign of that event (such as germination, leafing, blossoming[1], etc.), the date at which 50% of the plants per unit of field area (e.g., per acre) exhibit the event concerned (such as 50% of the plants in the field blossoming), and also dates for 75% and 100% of the plants exhibiting the event. Items not designated by (p) should be specified by calendar date, which will be determined by the observer according to the variety, locality, climate, etc.

The ideal and minimum phenological events of 12 sweet corn plants

[1]In the case of sweet corn, it is tasseling for male flowering, and silking for female flowering.

are used to represent the phenology of a field of a uniform environment. Spacing methods, such as drilled, hill-dropped, and checked, should be specified. By applying the assumption of constancy of biotic factors, for example, on fields of checked corn, a hill that is surrounded by complete hills on all sides is chosen at random. If three plants per hill are used, four hills will be needed for observation. Similarly, if there are four plants per hill, data from three hills are needed in order to observe all 12 plants. Four stages of development of sweet corn are listed below.

(a) Underground Stage
- Weight and number of kernels[2] 2, 3
- Date of planting (specifying hour of planting) 1, 2, 3
- Date of germination (recording date of first signs of rupturing of the seed coat of the neighboring hill[3]) 2, 3 (p)
- Rate of growth of adventitious root (measuring the extended root at weekly intervals until tassel emergence from neighboring hills) 3

(b) Vegetative Stage
- Date of emergence 1, 2, 3 (p)
- Date of third leaf 2, 3 (p)
- Date of fourth leaf 2, 3 (p)
- Number of plants per 100-foot row (observing at fourth leaf stage and marking rows) 2, 3
- Height of each individual plant (measuring the height above ground to the highest part of shoot, leaf, or tassel, weekly) 1, 2, 3
- Number of suckers (observing biweekly after emergence) 2, 3
- Number of vascular bundles of stems and leaves of plants from neighboring hills (measuring biweekly) 3
- Number of leaves (weekly observation, ignoring those under 4" long) 2, 3
- Length of each individual leaf (weekly observation, ignoring those under 4" long) 2, 3
- Mean width of individual leaves (weekly observation, ignoring those under 4" long) 2, 3
- Dry and fresh weights of vegetative parts (measuring biweekly from neighboring hill) 3
- Ending date of formative stage 2, 3 (p)

(c) Flowering Stage
- Date of tassel emergence 1, 2, 3 (p)
- Date of tassel pollen shed 1, 2, 3 (p)
- Date of silking 1, 2, 3 (p)
- Height of first ear from ground (measuring at first silking date) 3
- Number of plants per 100-foot row (observing at full silking date on same row as before; see b above)

[2]Expressed by number of seeds per pound, and number of pounds per acre.

[3]Hereafter, when reference is made to "neighboring hill," a similar plant should be chosen in order to be representative.

(d) Harvesting Stage (all of the following items are measured at the day of harvest)

Number of usable ears 2, 3
Sum of diameters of all usable ears 2, 3
Number of non-usable ears 2, 3
Tip cover of ears (see Section 3.2.2, footnote 5) 3
Yield (measured in pounds per acre, fresh weight basis) 1, 2, 3

Most of the above phenological events are observed with the 12 plants (four hills) distributed at random in the field under investigation, except those items marked (p), which concern the entire field. The index of total leaf area can be computed by multiplying the length by the mean width of each individual leaf. Of course, there are diverse opinions regarding phenological observations of all crops. Nevertheless, some events related to responses of environment should be recorded.

A good presentation of data depends upon the format, time of observation, and the ability of the observer. Field records used by the Wisconsin Agrometeorological Stations for sweet corn and peas are shown for illustration in Tables 8-1a, 8-1b, and 8-2. Table 8-2 shows the back of the field recording card and is practically the same for various crops under observation. For vegetables other than peas and sweet corn, the reader may refer to the Observational Manual of Vegetable Phenology (Wang, 1962).

For crop forecasting, the accuracy of predicted values of yield, quality, and maturity date should be studied. Since yield of crop is of general interest, it is used as an illustration.

Let Y_a be the actual yield, Y_e the estimated yield; then the relation of the actual yield to the estimated yield, Y_r, would be

$$Y_r = \frac{Y_a}{Y_e}. \qquad (8\text{-}1)$$

The weighted departure of the actual yield from the estimated yield, f, in percentage terms, is

$$f = \frac{100\,(Y_a - Y_e)}{Y_a}. \qquad (8\text{-}2)$$

Equating Y_r to f by eliminating Y_a and Y_e from equations (8-1) and (8-2),

$$Y_r = \frac{100}{(f - 100)}. \qquad (8\text{-}3)$$

By means of equation (8-3), three conditions of yield estimates can be established according to either parameter Y_r or f.

(a) According to Y_r, then

$Y_r = 1$ perfect estimation;
$0 < Y_r < 1$ over-estimated;
$Y_r > 1$ under-estimated.

Table 8-1a. Weekly Record for Corn Phenology

Station No.____ Field No.____ Planting Sequence No.____ Month__________ Date__________ Variety____________________

EVENTS		DATE A. M. P. M.	MEASUREMENT
Plowing (C_1)			Spring ( ) Fall ( )
Condition seed bed (C_2)			Good ( ) Fair ( ) Poor ( )
Method of Planting (C_3)			Checked:___ Hill dropped:___; Drilled__; Kernels per hill:___; Distance between hills:____inches
Planting (P)			Acres:___ Depth:___inches; No. of seeds:____per lb.; Seeds:___lbs. per acre; Row spacing:____inches
Emergence (E)			Uniformity: Good ( ) Fair ( ) Poor ( )
Stand count:	7 days after E (N_1)		Plants per 100 ft. of row:_____
	at time of T_1 (N_2)		Plants per 100 ft. of row:_____
*Plant height — Leaf extended (H)			Average height of 10 tagged plants:_____ inches
*Weed condition (W)			Heavy ( ) Normal ( ) Rare ( )
*Number of leaves (N_3)			Average per 10 tagged plants:_____
Tassel emergence (T_1)			First appearance of tassel in field
Tassel pollen shed (T_2)			First appearance of pollen in field
First silking (S_1)			Appearance of first silk in field
75% silking (S_2)			75% of field silking
Stalks and tillers — at time of harvest (N_4)			Total number for 10 tagged plants:______
Usable ears — at time of harvest (N_5)			Number of ears per 100 stalks:____
Harvest (Y)			Yield in lbs. per acre of snapped corn:__ of cut corn:____ Instrument used:______; Readings:________________

*Observations should be made weekly.

(b) According to f, then

$f = 0$ perfect estimation;

$0 < f < 100$ under-estimated;

$f > 0$ over-estimated.

By plotting f against Y_r on a rectangular coordinate paper by means of equation (8-3), Fig. 8-1 is constructed. The solid curve located in the first and second quadrants of the coordinate indicates the significance of yield estimates, while the broken-line curve is the theoretical line which will never occur. The vertical straight line parallel to the Y_r axis and perpendicular to the f axis is the asymptotic line

Table 8-1b. Weekly Record for Pea Phenology

Station No.___ Field No.___ Planting Sequence No.___ Month__________ Date__________ Variety____________________

EVENT	DATE	A.M.	P.M.	MEASUREMENT
Plowing (C_1)				Spring ( ) Fall ( )
Condition of seed bed (C_2)				Good ( ) Fair ( ) Poor ( )
Planting (P)				Depth:___inches; Seeds:___lbs. per acre; No. of seeds:___per lb.; Rowspacing:___inches
Emergence (E)				Uniformity: Good ( ) Fair ( ) Poor ( )
Stand count: at 4" height (N_1)				Plants per 3 ft. of row:____
Stand count: at time of B_1 (N_2)				Plants per 3 ft. of row:____
*Plant height — Length of stem (H)				Average height of 10 tagged plants:_____inches
*Weed condition (W)				Heavy ( ) Normal ( ) Rare ( )
*Node count — Begins with 1st node (N_3)				Average number of nodes per 10 tagged plants:_____
First flowering (B_1)				First sprinkling of visible flowers observed
75% flowering (B_2)				75% of field flowering
Usable pods — 10 days after B_2 (N_4)				Number of pods per 100 plants:____; Peas per pod per 10 plants:____
Harvest (Y)				Yield in lbs. per acre: Gross:____ Net:____ Tenderometer:____

*Observations should be made weekly.

to the two curves. The accuracy of the crop-yield prediction can easily be visualized according to the orientation of the solid curve.

(b) Modification of data. A change of data for a certain year or group of years, to eliminate or reduce in importance any factors other than environmental ones which might cause a change of data for that particular time interval, is referred to as data modification. This process, which is absolutely necessary to render data representative for a long range of records, may be called "correction of data." The method of data correction is a powerful tool which satisfies the assumption of the constancy of biotic factors. To be sure, not all crop data must be modified before statistical treatment, but it is necessary under some conditions. Unwanted environmental factors can also be eliminated by this method, for example, crop data affected by serious frost damage, wind, or hailstones. In another case, when the solar intensity-crop yield relationship is of interest, factors other than solar

Table 8-2. Back of All Vegetable Phenology Record Cards

WEATHER REPORT:

Type of Raingauge:__________ Number of Raingauges:______

Day of Month	
Rainfall, Gauge #1	
Rainfall, Gauge #2	
Rainfall, Gauge #3	

If there are more than 3 gauges, please report them on separate sheets.

CULTURAL REPORT:

	Date of Application	What and/or How Much
Seed treatment		
Fertilizer		
Cultivation		
Insecticide		
Herbicide		
Fungicide		
Kind of major weed		

*DISEASE REPORT (Specify extent of damage):

Date:__________ Kind:__________ Damage:__________

OTHER DAMAGES (Specify extent of damage):

Frost:__________

Storms:__________

Drought:__________

INSECT REPORT (Specify extent of damage):

Date:__________ Kinds:__________ No. of:__________

*Observations should be made weekly.

intensity can be partially eliminated, as described in Section 7.5.1.

Various methods of correction of yield data, such as the graphical method for constant trends and variable trends of crop yield (see Section 3.4.1), and the mathematical method (see Section 7.2), have been described. These methods may be applied to crop data other than yield. After data have been corrected, statistical applications should be used to find central values and variabilities. The computation of central values, such as averages, medians, and modes, is useful in minimizing variation in varieties, areas, and time. This applies to uncorrected data as well. For example, Fig. 7-6 shows that the yields of two sweet corn varieties, the Tendermost and the Tenderblonde, are averaged; the regression line is computed as shown in equation (7-26), and the coefficient of linear correlation is evaluated. In this case, it is necessary to use the central value because the sample is too small for other values to be valid; there are five cases for the Tendermost, and four for Tenderblonde.

When the microenvironmental factors which affect crop data are not

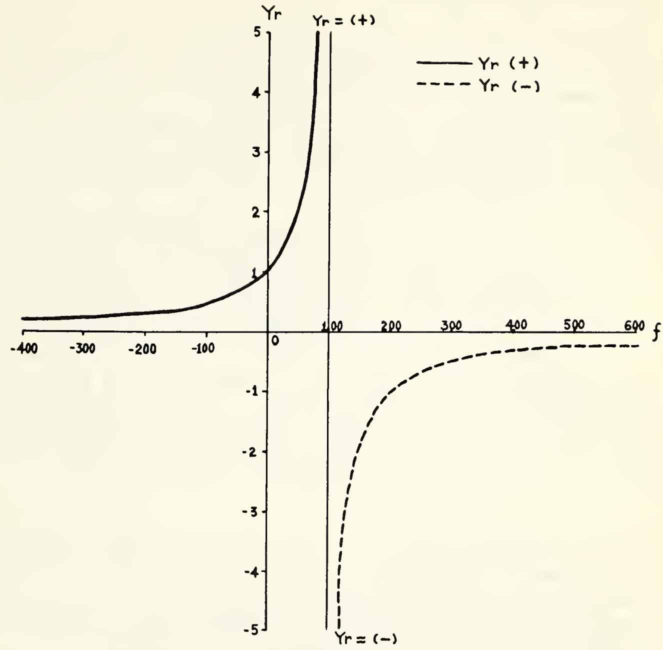

Fig. 8-1. Significance of yield estimates.

available, the statistics of central values again should be applied. This makes possible the test of the crop data in a given area by the environmental factors for that area. This method, which tends to average out the microclimatic influences, has been proved very useful. Furthermore, when the phenological stages of two completely different sets of crop data are similar in calendar dates, the central value should be employed. For example, the planting and flowering dates of peas in Field A may be similar to those in adjacent Field B, but the former may have a much higher yield than the latter. Thus, the central value of A and B should be computed either by the arithmetic mean or by the weighted mean according to the size distribution of the two, because there are no separate environmental measurements available for both of them.

The variabilities of crop data, on the other hand, should be computed in order to find the interrelationships between variables. The standard deviation and the coefficient of variation are the two most fundamental statistical computations. For further statistical operations, the various formulations on probability and tests of distribution have been summarized in Appendix B.

8.1.2 *Environmental data*

Data as transcribed from instruments are usually not adequate for the uses of the agrometeorologist. Just as for crop data, the treatment of environmental data is a necessary step for the forecaster. The environment and its controlling factors have been described in Chapter 2 and further elaborated in Chapter 4. The measurement of environmental factors is mentioned in Chapter 5, and the combination of environmental factors was illustrated in Chapter 7. Thus, the reader should be familiar with the criteria of the crop-rainy day, the evaluation of relative maximum rainfall, the computation of crop-drying days, the summation of the photothermal unit, the estimation of evapotranspiration, and the like. These are parametric treatments of environmental data. In fact, there is no end to data modifications to forms suitable for plant response studies, particularly crop forecasting. In principle, treatment of data should follow physical laws, physiological principles, and phenological sequences. The following check list, which includes items from II, III, and VB of Section 7.5.3, should be useful as a guide.

1. Kind of technique required with respect to class of problem (see Sections 6.4, 7.4, and 7.5).
2. Form of presentation desired (including formulation, tabulation, and graphical solution, such as monographs, maps, and the like. This also includes types of the existing summarization.).
3. Length of record needed
   a. Stabilization of central value (long enough to be representative; see Landsberg & Jacobs, 1951, pp. 978-979, and Wang, 1961, p. 11).
   b. The periodic fluctuations (diurnal, seasonal, annual, and secular)
   c. Completeness of data, e.g., estimation of missing data, as well as techniques for the supplementation, evaluation, and substitution of inadequate data.
   d. The period of coverage of crop and environmental data should be the same.
   e. Normalization of central value, e.g., lengthening of record by means of differences and methods of ratio (Conrad & Pollak, 1950, pp. 232-241).
4. Type of data desired
   a. Choice of factors, e.g., for factors related to soil moisture, considerations are: Rainfall, condensation - sorption, evaporation, transpiration, runoff, penetration, or percolation, capillary action, water table, and the like.
   b. Accuracy of data
      i. Area of representativeness, e.g., the location of instrument or instruments, the area coverage in a spot, an area or a region, the peculiarity of local climate.
      ii. Kind of instrument, e.g., sensitivity, limits, and capacity of instrument.

iii. Recording devices, e.g., visual observation (estimation of human errors), automatic registration (strip chart, punched cards, magnetic tapes, etc.).
iv. Consistency of data, e. g., order of magnitude (temperature ranges of the locality, etc., see also the world extreme climatic records in Section 4.2.1), definitional consistency (both wet-bulb and dew-point temperatures should not be higher than the dry-bulb temperature in the same weather shelter, for instance).

c. Combination of factors
i. Dimensional consistency, see Appendix C, (1).
ii. Physical interrelationship (see Sections 6.4.2 and 7.4.2).
iii. Developing new theory or method for combination of factors.

5. Other considerations on data treatment
a. Information on physical or statistical limitations imposed on the data and their interpretation.
b. The possibility of making environmental analogous operational studies.
c. The efficiency of processing current data.

8.2 ANALYSIS AND SYNTHESIS

Analysis, in crop forecasting, refers to individual sequential relationships of growth and development of a crop with respect to time. Synthesis designates the methods of combining various forecasting systems to reach a forecast which takes time sequences into account.

8.2.1 *Analysis*

There are three steps necessary in the process of analysis: (1) analysis of past historical data, (2) analysis of current data, and (3) prognostication of the likelihood of occurrences.

The ultimate goal of the first step is to discover the quantitative effects of environment on the crop from past records. Both "long-range past" and "immediate past" should be analyzed with respect to a given crop at a given locality. A long-range crop record may be regarded as a time interval of five years or more, covering at least two or three planting sequences in an area. Of course, the longer the period, the better. The environment depends on the types of elements, the seasons of the year, and the geographical localities (Landsberg, 1951; Wang, 1961). Crop and environmental data should cover the same period of years for crop response studies, but this is not necessary for crop forecasting purposes. The "immediate past" refers to the stage of plant growth or development prior to the time of forecast. When forecasting for an annual plant, the seedling stage would be considered the "immediate past," if the forecast was issued at the vegetative stage. This "immediate past" is more important to the forecaster in his decision-making than the "long-range past," because the physiological preconditioning (or predetermination) is sometimes the controlling factor. This means that once the interval (or physiological) factors are set by the environment, they govern the remaining process of development, and the external (or physical) factors have less influence. Many controlled experiments prove that the environmental effects during the seed or seedling stages are revealed in the reproductive or maturity stage of the plant. Fig. 6-4 in Section 6.4.4 indicates that the early spring flowering of a number of native Wisconsin plants is predetermined by the solar intensity of the late winter period.

Section 3.1 shows that the effects of soil temperature on the subterranean ears in the early seedling stage of sweet corn determine the number of days required for maturity. Thus Fig. 3-1 may be used as the first approximation of prediction. Some modifications can be made when necessary during the silking stage, when night temperature of air may be the controlling factor if the temperature is abnormally cold or warm. This illustrates that "immediate past" is more important than "long-range past" as far as developmental problems are concerned. In considering growth problems, "long-range past" may be more significant. Therefore, a forecaster must first be well acquainted with the past history of his crop in a given locality and environment, and especially the relationship between them. Various techniques suggested in Sections 6.4, 7.4, and 7.5 will be useful in the establishment of environment relationships. When these relationships are once established, they should be represented by equations, alignment charts, maps, and tables. This will make the forecast more efficient and accurate. Perhaps half the success in forecasting is determined by the exactness of this analysis. The subjective approach through personal experience, which has often been over-estimated by the field man, is nothing but an intuitional combination of various objective methods. It is based upon the field man's long experience, his present observations, and his own feelings. His judgment can be useful, but may also be dangerous. As far as crop forecasting is concerned, the subjective approach can only be used as a reference, certainly not as a factor in forecasting. But when the current weather and crop conditions have been carefully examined by the field man, his judgment is valuable (see Fig. 8-4 on subjective approach).

Aside from past historical data, the current data, that is current crop and environmental data reported after the "immediate past," should be analyzed. In the case of the first approximation of pea yield by means of the T_D value analysis (Wang, 1962a),[4] the forecaster may consider the daily minimum air temperature during the first 20 days after planting as the current data, and environmental conditions of the

[4]For explanation, see also Sections 4.2.3 and 7.4.2, and Fig. 7-1.

pea seeds in storage as the "immediate past" data. In the case of size and yield prediction of peaches, according to Baker & Davis (1951), the forecaster may consider the "cross-diameter" of peaches selected at random during the first and final stages of development[5] as the current data.

The following conditions must be fulfilled in order to make "current data" analyses: (a) data should be up-to-date — for stations far away from the forecasting center, a good communication system ought to be established (see Sections 5.8.4 and 8.4.1); (b) data should be processed by electronic computer unless only a single station forecast is under consideration (see Section 8.4.1 for details); (c) data should be plotted in various charts, maps, etc. (for detailed procedure, the reader may refer to Section 8.4.2) — Riedat symbols of phenological phases (Fig. 6-7), together with weather symbols in regular surface weather maps, may be used for mapping;[6] and (d) the relationship between the present condition and historical conditions should be established.

Various techniques have been used to accomplish item (d) above. An example of the diagrammatical approach is Podol'skiĭ's (1958) use of the pheno-temperature nomogram for predicting cotton yield in the Gissarskii Valley, U. S. S. R. (see Section 4.2.3 and Fig. 4-15). The thermal grid consists of a long-term mean temperature versus the phenological interphasic period of cotton. His grid describes the thermal regime of the Gissarskii Valley, which is the past historical condition. He made the prognosis possible by plotting the current phenological data on the grid. Wang (1963) has prepared a hythergraph (Fig. 8-2) which is constructed by the accumulated rainfall versus frequency of daily mean temperature at and above 83°F for the flowering period of the tomato in Wyoming, Delaware.[7] Here again the hythergraph indicates the past condition, and current data of temperature and rainfall can be entered in the graph to project the prospective yield of tomato plants in Wyoming, Delaware. This is a two-variable relationship, for rainfall and temperature. A three-variable relationship, such

[5]For detailed information, see also Section 6.4.2 and Fig. 6-3. Of course, there are many other ways of forecasting; for example, Westwood & Batjer (1959) used the fruit weight during pit-hardening to predict the harvest size of Elberta and J. H. Hale peaches.

[6]In Poland, Molga (1958) described the synoptic agrometeorological service system since 1932, including the transcription of phenological events on synoptic maps from the telecode. Their information includes weather, crop, and disease conditions. For details, the reader may refer to Chapter 7, "Agrometeorological Service," pp. 278-324 of Molga's textbook, ***Agricultural Meterology***, Part II, Outline of Agrometeorological Problems. The English version has been published by the National Science Foundation and the Department of Agriculture, in the United States, in 1962.

[7]For details of the Wyoming data, the reader may refer to Figs. 7-4A, 7-4B, and 7-5 in Section 7.4.3.

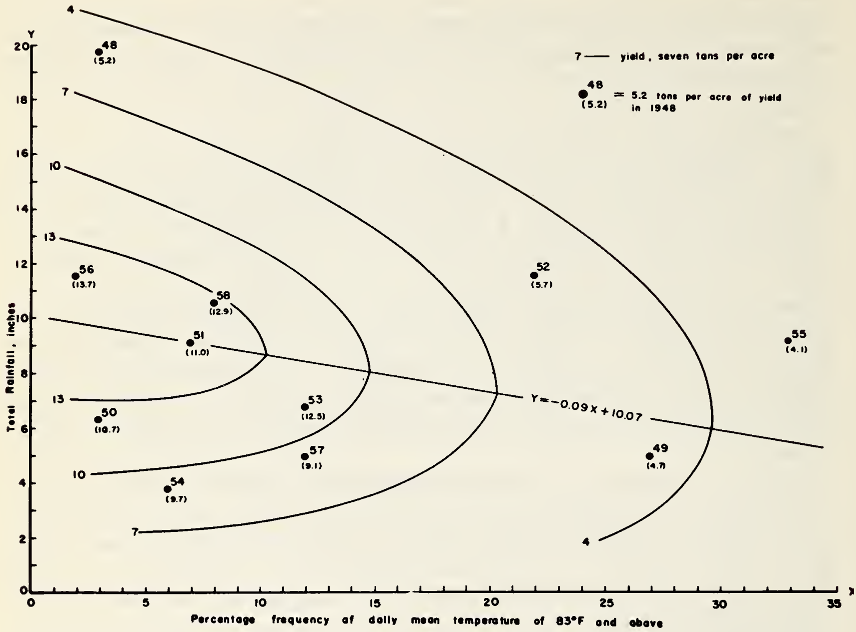

Fig. 8-2. The relationship of rainfall and temperature to tomato yield during blossoming period, Wyoming, Delaware, 1948-1958.

as is shown in Fig. 7-16, can also be constructed.

Since empirical formulas represent the past situation, the substitution of current data into these formulas would be another way of prognosis. Formulas are usually better than graphs, for they can be established with any number of variables and give more accurate results.

8.2.2 *Synthesis*

Combining various forecasting systems obtained through methods of analysis is called synthesis. The ultimate aim of synthesis is to make prediction perfect. There are three considerations in the process of synthesis: (1) time-sequences of the growth and development of a crop in a single locality; (2) space-distribution of the same species and varieties of a crop at different localities; and (3) combination of various analyses according to their predictive accuracy or validity.

(1) Time sequences. When each developmental stage in a given locality has been prognosticated, a combination of all prognoses is needed. Two methods of combination are possible: (a) potential forecast of time series, and (b) multiphase forecast of time series. The word "potential" in the first category designates "existing in possi-

bility, not in actuality," which means that there is a good chance in the making. "Potential yield" is defined as the actual yield that might be realized at the end of the growing season. As an example, early in the season, a crop may be developing nicely with a good outlook for an optimal yield. At this time, the "potential yield" is high. Later, however, a midseason frost or other climatic catastrophe may reduce the potential yield to zero. This illustrates the fact that the potential yield is actually a variable function of time during the growing season.

Section 7.5.2 evaluated the potential yield by combining all environmental factors through a series of partial differential equations as expressed by equations 7-38 to 7-46, in which crop response studies were emphasized. These equations are applicable to all measurable quantities, and can be solved for "potential yield," "potential

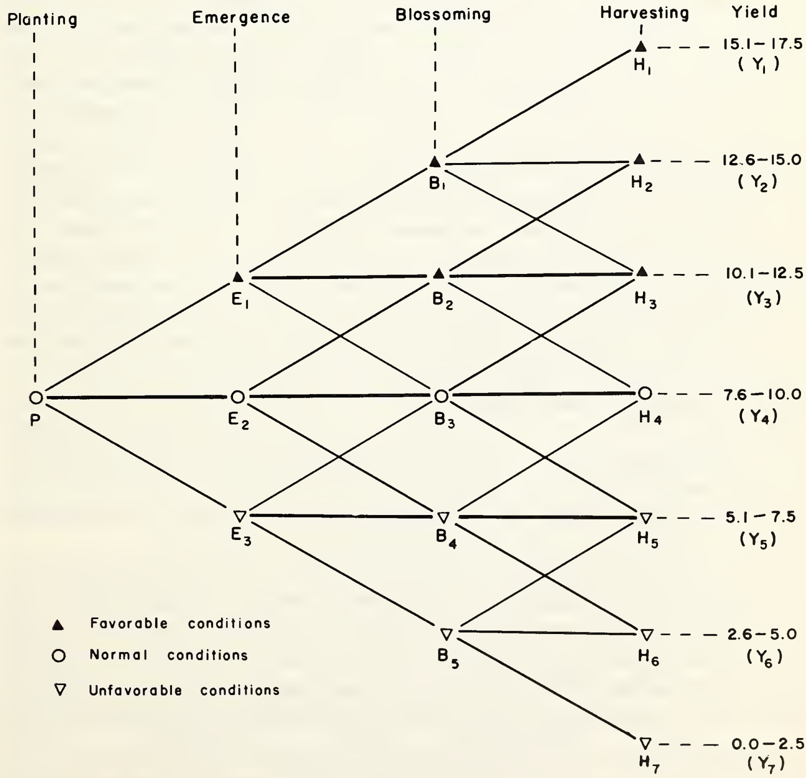

Fig. 8-3. Schematic diagram of a forecasting tree for an annual.

quality," "potential maturity date," etc.

The process of forecasting in terms of time sequence is illustrated by means of a "forecasting tree," and a schematic diagram of the tree for an annual plant forecast is shown in Fig. 8-3. All symbols are clearly explained in the diagram. Subscripts are used to indicate the gradations of performance in growth and development; the lower the numeral, the closer the specific crop will be to the optimal stage. For example, E_1 may refer to a uniform stand and/or a high germinating rate of the crop, while E_3 represents a poor stand and/or a low germinating rate. The last column, which has been chosen arbitrarily, refers to the yield of tomatoes[8] expressed in tons per acre and indicates a class-interval of 15.1 to 17.5 as H_1 (or Y_1), and 12.6 to 15.0 for H_2, etc.

The time series in potential forecasting may be visualized with the aid of the "forecasting tree." For example, a forecaster may start his yield forecast at time of planting (P), basing it upon current soil and weather conditions at P. He may give his first estimation for the yield assuming that the remaining growing season will be normal, i.e., will continue along the straight line of the diagram. This is always risky. In the case of favorable soil conditions for his crop, he may follow the diagrammatic route $P \rightarrow E_1 \rightarrow B_2$ leading to H_3. From the table given on crop yields, he then forecasts a harvest of 10.1 to 12.5 tons per acre. Should the season begin unfavorably, the route would be $P \rightarrow E_3 \rightarrow B_4$, concluding with H_5, an expected yield of 5.1 to 7.5 tons per acre. Likewise, similar procedures could be applied to other phases of development. In other words, potential yield can be predicted at each developmental phase, and the final forecast is issued at the reproductive phase. Potential forecasting emphasizes final performance, such as yield, quality, and maturity date, the projection of which is repeated at each developmental stage, e.g., P, E, and B of Fig. 8-3.

The "forecasting tree" may also be used for multiphase forecast, in which the prediction of yield is reached through successive forecasting of various phases. Stated another way, there are three steps of forecasting involved: (1) forecasting of E at time of P; (2) forecasting of B at E; and (3) forecasting H (or yield) at B.

In time sequence considerations, the first method (potential forecast) overcomes drawbacks in the second method by giving farmers and growers the first prediction of final performance, which they are most concerned with. Presumably, the accuracy of forecasts would increase with time. Nevertheless, the second method, which is more reliable, gives the forecaster verification at each phase of develop-

[8]In the northern U.S.A., tomato growers generally obtain their seedlings from the greenhouse, or more likely from southern states. Therefore, the transplanting phase is needed. However, for most annual plants, this phase is not necessary; thus it is omitted from the "forecasting tree."

ment. Therefore, both methods are needed for crop forecasting in a single locality. Procedures on various phases of crop forecasting are given in Section 8.3.

(2) Space-distribution. Methods on climatic crop response analogues are another consideration in crop forecasting. In analogue considerations, it is assumed that with similar climate and soil type, a farmer would be able to produce similar amounts and quality of crops if cultural practices, species, and varieties of the crop are held constant. By applying this method, various important environmental parameters of the current data could be analyzed in order to make area comparisons of known production with that of unknown production. But the forecaster has to wait until the former area production is known, thereby making reverse comparison impossible. In fact, these two investigations should be pretty close to each other in order to be dominated by a similar type of weather pattern. The drawbacks of this method are: (a) an early yield forecast is most likely impossible; (b) no two localities are exactly identical in either weather or soil type; and (c) not all areas can get a similar region for comparison. This signifies that the analogue method is restricted in use. Also, an early harvesting area can, of course, get no benefit from a late harvesting area.

Despite all drawbacks, the following examples demonstrate some uses of the analogue approach. These are correlation studies on yield of sweet corn and peas for Janesville, Wisconsin, and Rochester, Minnesota. In the case of Victory Golden sweet corn, the mean date of planting for Janesville is June 2, and for Rochester, June 5. The harvesting date for the former is September 4, and for the latter, September 11. The average growing season, in days, and the mean yield, in tons per acre are very much alike in these two localities. They are 94 versus 98 days, for the growing season, and 4.24 versus 4.26, for yield.

When 654 samples of corn yield data for Rochester and 590 for Janesville are classified into 18 class intervals, the class means are comparable, and thus regression equation (8-4) is obtained:

$$\bar{Y}_R = 0.6131\,\bar{Y}_J + 1.316, \tag{8-4}$$

where $\bar{Y}_R$ is the all-class mean yield of sweet corn for Rochester, and $\bar{Y}_J$ that of Janesville. The coefficient of linear correlation is 0.60, the coefficient of determination, 36%, and the significance level, 0.001.

When the yearly mean yield, $\bar{Y}$, of the two localities is compared with the same set of data, a very high correlation results. The r value is 0.93, r^2, 86%, and P, 0.001. The regression equation is

$$\bar{Y}_R = 1.592\,\bar{Y}_J - 2.347. \tag{8-5}$$

The forecaster may make use of Janesville's yield report to forecast yield of corn for Rochester, even if it is only a week or so in advance.

In the case of Early Perfection peas, the mean date of planting is May 12 for Janesville, and May 18 for Rochester. The harvesting date is July 18 for the former, and July 22 for the latter. The average growing season is 67 and 65 days, respectively. The mean yields for the two localities are somewhat different: Janesville, 4060 pounds per acre, and Rochester, 3720. The linear relationship between the two localities is

$$\bar{Y}_R = 0.6109\,\bar{Y}_J + 0.3457, \qquad (8\text{-}6)$$

where Y_R and Y_J are the class means of Rochester and Janesville, respectively. The r value is 0.66; r^2 is 44%; and P, 0.001.

When the yearly mean yields of the two localities are compared, the regression equation is

$$\bar{Y}_R = 0.3885\,\bar{Y}_J + 1.153 \ . \qquad (8\text{-}7)$$

The result is rather poor as far as the linear correlation is concerned. The r value is 0.22; r^2 is 4%; and P, 0.01 .

Analogue methods are applicable under two conditions: (a) in a between—localities comparison of the state of growth at a specific state, as in comparing number of flowers or fruits, or (b) in a comparison between stages at a single locality. These methods can be established only through historical data, as illustrated in equations (8-4) to (8-7).

(3) Coordination of various analyses. This is the last step of the method of synthesis. After completion of all attempts at "time sequence" and "space-distribution" approaches, the forecaster has to make a decision as to which path to follow.

Fig. 3-3, which illustrates the responses of vegetable crops to environmental factors at different phases, can be useful as a guide to combining various forecasts, if the environmental requirements and limits of a specific crop have been determined quantitatively. Thus, emphasis should be placed on seeking "significant elements" and the "significant period." With a knowledge of these, a forecaster would be able to make his first approximation.

By using the coefficient of correlation, r, as the weighted factor, a combination of various forecasts would be possible. This is given in equation (8-8):

$$Q_c = \frac{r_i}{\left|\sum_{i=1}^{n} r_i\right|} Q_i + \frac{r_{i+1}}{\left|\sum_{i=1}^{n} r_i\right|} Q_{i+1} + \dots + \frac{r_n}{\left|\sum_{i=1}^{n} r_i\right|} Q_n \ , \qquad (8\text{-}8)$$

where Q_c is the final (or combined) forecast, Q_1, Q_2, . . . Q_n are the quantities forecast by various approaches, and r_1, r_2, . . . r_n are the coefficients of linear or multiple correlation of each approach.

The correlations can also be any measure of validity tests, instead of r values. The absolute value is used in the denominators to avoid the sign effect. The quantity Q_i can be expressed by yield in tons per acre, quality in tenderometer readings, and the maturity date in terms of calendar days. Where an emergence forecast is made, for example, Q_i can be expressed as the rate of emergence in percentage and/or time of emergence in number of days from planting.

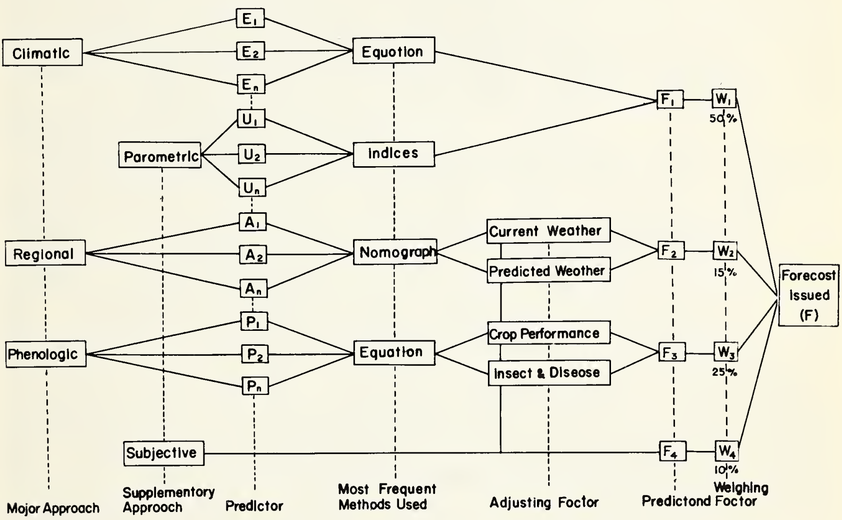

Fig. 8-4. Block diagram on procedures of forecasting.

Since the coordination involves various combinations of possible approaches in association with all available factors, the procedure may be conveniently illustrated by a block diagram, shown in Fig. 8-4. There are five approaches listed, of which climatic, regional, and phenological approaches are designated as major approaches, and parametric and subjective approaches are called supplementary approaches.

In the climatic approach, the symbols E_1, E_2, . . . E_n represent single elements such as relative minimum rainfall, crop rainy days, interdiurnal temperature, and the like, respectively, depending on what is the significant element to be considered. These single climatic elements or predictors are evaluated according to their effects on crop response. In the regional approach, the predictors A_1, A_2, . . . A_n represent the relationship of an unknown area to a known area, as illustrated by equations (8-4) through (8-7). In the phenological approach, the predictors P_1, P_2, . . . P_n stand for the link between events of two different phenological stages without considering direct environmental influences. Expressions of this approach are seen in equations (6-8) through (6-14).

The supplementary approaches function as aids for further adjustment of the three major approaches mentioned above. The parametric approach, which is somewhat similar to the climatic approach, is expressed in terms of predictors U_1, U_2, . . . U_n which represent photoclimatic, thermoclimatic, and hydroclimatic units, respectively (see Section 7.4.2). In other words, these units as a group represent the effect of partially integrated climate on crops. In addition to the parametric approach, another supplementary approach is subjective determination, based upon personal experience, in relation to current crop and weather conditions. All of the above approaches, with the exception of the subjective approach, can be expressed by means of equations, regression lines, alignment charts, or other statistical means (see Appendix B). When two or more predictors are involved in an approach, equations (e.g., equation 8-8), nomographs (e.g., Figs. C-6 to C-10), or indices (e.g., equation 7-28) can be used to combine them. The combination technique can be linear or non-linear. The choice of a specific technique depends upon the nature of predictors to be combined.

With regard to the choice of a predictor, Fig. 3-3 may be used as a guide. The use of two or more similar predictors in one approach or in different approaches should be avoided as much as possible. For example, in the climatic approach, if reliable soil moisture data are available, then rainfall data are not needed.[9] A complete avoidance of the use of similar predictors in two or more different approaches is not always possible or desirable, for sometimes the combined influence of various factors as a group may be an important consideration. For instance, when the photothermal unit (PTU) is employed as a predictor in the parametric approach, the overlapping of temperature and daylength is unavoidable even if they have also been used in the climatic approach. In short, the selection is based upon the association between the "significant period" and the "significant element." The sorters illustrated in Figs. 7-11, 7-12, and 7-13 in Section 7.5.1 would be useful in the determination of significant period and significant element.

Another aspect in the choice of predictor is the concept of "physiological preconditioning." The growth and development of plants are predetermined to various extents by their early environmental conditions. In other words, the growth performance of a plant at any stage reflects the environmental conditions to which it has been exposed during some previous stage of its life history. The time lapse for an effect of certain previous environmental conditions to be revealed at

[9] See Sections 2.2.2 and 4.4 for explanation.

a later stage varies with different species and varieties of the plant. The process is essentially a cyclic phenomenon (see Fig. 3-2). Environment at parental maturation may predetermine the germination rate, and environment at the seedling stage may predetermine the earliness and intensity of flowering, which in turn may predetermine the earliness of parental maturation. As has been discussed before, such phenomena as hardening, photoperiodism, photothermal induction, vernalization (or devernalization), and sometimes dormancy are examples of physiological preconditioning. The advantage of considering the concept "physiological preconditioning" in selection of a predictor is that it makes an earlier forecast possible. Hence potential forecast of the time series will be reinforced. This is especially useful when plant development problems are concerned.

Since climatic and parametric approaches are both environmental in nature, they are usually employed in combination when a forecast calls for the use of both. The combination of climatic and parametric approaches, as shown in Fig. 8-4, results in the predictand, F_1. The symbol W_1 represents the weighing factor which accounts for some 50%[10] of F_1 for the final forecast. In the regional approach, the current and predicted weather (adjusting factors) should be taken into consideration, and thus F_2 is obtained. And the weighing factor, W_2, represents some 15% of F_2 to be accounted toward the final forecast. Likewise, in the phenological approach, the condition of crop performance, as well as the extent of damage by insects and disease, if not serious,[11] should also be considered as adjusting factors. Symbols F_3 and W_3 (or 25 % of F_3) represent the predictand and the weighing factor of the phenological approach, respectively. The subjective determination in conjunction with all "adjusting factors" is represented by F_4, some 10 % of which is designated as W_4.

Finally, the ultimate forecast, F, can be expressed as the sum of all available predictands:

$$F = W_1F_1 + W_2F_2 + W_3F_3 + W_4F_4 . \qquad (8\text{-}9)$$

The value of percentage to be assigned to each weighing factor (W_i) is not a fixed value. The percentages cited above refer to the case where all five approaches are used. Not every forecast requires all five approaches, and when less than five are involved, the percentage of each weighing factor should be adjusted so as to result in a total of 100 percent when combined.

[10]The block diagram (Fig. 8-4) refers to the case where all possible approaches are utilized for the final decision. The percentage of W_i is determined by the number and nature of approaches used. If only one approach is used, then the predictand (F_i) and the final forecast (F) are equal, i.e., W_i = 1 or 100%.

[11]When serious, damage due to insects and diseases alone will determine the fate of crop yield. Thus, the entire procedures of forecasting as illustrated in Fig. 8-4 are not needed.

8.3 CROP FORECASTING

By applying techniques introduced in previous sections, illustrations of emergence-, vegetative growth-, flowering-, maturity-, and yield-forecast are in order.

8.3.1 *Emergence*

For emergence forecast, it is necessary to know the environment of seed storage, as well as air and soil conditions both at the time of, and during the few days immediately following, the planting. Environmental factors involved in seed storage are duration and intensity of light, temperature, humidity, and air composition, which are fairly easy to measure and control. At the time of planting, physical factors significantly affecting the emergence are temperature, moisture, and aeration of soil, while air temperature, air humidity, and other factors in the air are comparatively less significant. This is due to the indirect effects of air physical factors on seeds prior to emergence, except for intense rain. Brown & Hutchinson (1949) indicated that rainfall occurring within a few minutes after the planting of pea seeds often causes a marked reduction in the germination rate. This may be due to the change in seed depth created by droplets, thus affecting the uniformity in germination to a considerable extent. They point out that if the rain does not follow for 36 hours after the seed is planted, germination is rarely reduced to any serious extent. Other mechanical influences include hail, flood, and severe wind.

Emergence forecast, the first step in the multiphase forecasting method as indicated by the "forecasting tree," proceeds with the methods illustrated in the "block diagram" (Fig. 8-4). Considerations are uniformity in stands, rate of emergence, and date of 50% to 75% emergence in the field. The forecast should be issued not later than four days after planting; therefore, constant measurement of soil physical conditions prior to the time of forecasting is important. Specifically, information on soil environmental requirements for germination, such as alternating soil temperature, soil moisture (rate of water intake), and permanent wilting point of soil, are essential (see Chapter 4). Therefore, the historical study of germination-environment relationships in a certain locality is extremely important for the success of forecasting in the locale. A check-list based on the following two conditions can be made on various significant environmental elements: if (a) any element acts as a limiting or retarding factor; if (b) any element acts neither as a limiting nor as a retarding factor. Of course, these two conditions apply to all other multiphase forecasts. Table 4-8 illustrates the limiting factor, the retarding factor, and the optimal range of different vegetable crops with respect to soil temperature. A more elaborate presentation of the relationships of day-, night-, and soil-temperature is given in Figs. 7-2 and 7-3 for tomatoes and corn, respectively. When condition (a) above exists, no germination is forecast. For example, if the ambient temperature is above or below the upper or lower threshold value, respectively, as illustrated in Figs. 7-2 and 7-3, germination will not take place. When condition (b) exists, forecasting is possible by combining all predictors, as shown in Fig. 8-4.

Of the five approaches shown in Fig. 8-4, only the first (climatic approach) is really appropriate for emergence forecast. Sometimes, the regional and subjective approaches, particularly the latter, can also be applied. Equation (8-8) illustrates one method of combining various predictors. For instance, with the following information we are able to forecast the emergence date of a certain crop, expressed in terms of number of days from the date of planting.

From historical facts — correlation of emergence and:

(a) soil temperature at seed level, $r_1 = 0.95$

(b) soil moisture at seed level, $r_2 = 0.50$

(c) soil aeration at seed level, $r_3 = 0.37$

Thus the sum of all the above coefficients of correlation is

$$\left|\sum_n r_i\right| = \left|r_1 + r_2 + r_3\right| = \left|0.95 + 0.50 + 0.37\right| = \left|1.82\right| .$$

The results of prediction derived from each of the above factors are designated as Q_1, Q_2, and Q_3. The values of Q_i are determined on the basis of historically known relationships between each factor and emergence and the current measurement (mean value) of that factor. Thus, for

(a) soil temperature, $Q_1 = 10$ days;

(b) soil moisture, $Q_2 = 5$ days;

(c) soil aeration, $Q_3 = 3$ days.

By applying equation (8-8) to the above values, the ultimate forecast (Q_C) is computed as

$$Q_C = \frac{0.95}{1.82}(10) + \frac{0.50}{1.82}(5) + \frac{0.37}{1.82}(3) = 7.2 \text{ days},$$

and the date of emergence is forecast as 7.2 days from planting. In this case, only the climatic approach of Fig. 8-4 is used, hence $W_1 = F_1 = F = 7.2$ days. If more than one approach is involved, equation (8-9) is used for combination. When equation (8-8) is employed, the validity of each predictor must be carefully examined in terms of order of magnitude. If $Q_1 << Q_2$ and $r_1 >> r_2$, the resulting Q_C would be much distorted. Should this happen, Q_2 must be discarded.

8.3.2 *Vegetative growth*

In forecasting vegetative growth, the rate of growth (particularly that of rapid growth) and the total growth, expressed in height of plants , area of leaves, diameter of stems, and fresh or dry weight of top and roots, are the major considerations for measurement. The calendar dates of the beginning and end of rapid growth are other items to be considered. Environmental factors involved are both climatic and edaphic. By and large, temperature and moisture requirements are comparatively more important than light, for most herbaceous plants during the vegetative period. The choice of significant factors as well as crop measurement depend upon the species and varieties of plants. Since a five-day interval is a suitable time unit for measurement of vegetable parts, unless some means of keeping a continuous record is available, the five-day mean growth rate can be used for growth rate forecasting. Examples of the utilization of vegetative growth forecast are scheduling of irrigation and grazing, and prediction of final product.

When the date and period of rapid growth of the plant are predicted, an irrigation schedule can be planned, on the basis of water requirements of the plant. When the total growth is predicted, scheduling of grazing becomes possible. Also, as soon as the relationship of vegetative growth to the final product, e.g., yield, is established, potential yield can be predicted. Thus, the potential and multiphase forecast (Fig. 8-3) and the procedure of combination (Fig. 8-4) are also used as guides in vegetative growth forecasting.

8.3.3 *Flowering and maturity*

The uniformity or rate of flowering is of general concern to farmers and growers with respect to flowering prediction. The date of first, 50%, and 75% flowering, as well as duration of flowering, are significant in the development of some plants. At this stage, light is comparatively more important than temperature and moisture, provided that the latter two are neither limiting nor retarding factors.

In maturity forecast, the date of maturity should be specified according to the quality requirements of economic significance, which may be expressed in terms of chemical composition, moisture content, and other physical properties. Therefore, relationships between crop quality and environment should be established for an accurate prediction of maturity date. Fig. 3-1 in Section 3.2 is a good example of maturity date prediction for sweet corn, in which the first approximation is based on the soil temperature at the seedling stage with consideration given to physiological preconditioning. Usually, the flowering date and maturity date are closely related to each other. For most crops, number of days between flowering and maturity is nearly constant (see Section 6.4.4a), and it follows that once the date of flowering is predicted accurately a reliable forecast of the maturation date is also possible.

8.3.4 *Yield and quality*

Yield, quality, and maturity dates are the three major final forecasts of interest to most farmers and growers. Of these, yield is concerned with problems of growth, maturity with problems of development, and quality with problems of both. In yield forecasting, the accuracy increases as the growing season progresses. Here again, the first approximation can be made at the seedling stage, followed by confirmation at flowering and maturation. Quality forecast is the most complicated, and depends upon methods of quality determination. As has been mentioned, the determination of quality-environment relationships is essential in preparation for forecasting.

The potential forecast, as illustrated in Fig. 8-3, may be issued at each stage for yield and quality, with adjustments made at each successive stage for improvement in final forecasts. The accuracy of prediction at each stage including the final forecast may be determined by equations (8-1) to (8-3), as illustrated in Fig. 8-1.

8.4 REQUIREMENTS FOR BETTER CROP FORECASTING

Three major criteria for better crop forecast are:

a. Accuracy and reliability in observation of both crop and environment;
b. Efficiency and exactness in communication and processing of data; and
c. Establishment of well-organized forecasting procedures.

8.4.1 *Instrumentation and communication*

In order to have reliable and useful data for crop forecasting, the first consideration is instrumentation and observation. The nature and essentials of agrometeorological instrumentation, as well as the selection of instruments, have been discussed in Sections 5.1 and 5.8. Descriptions and recommendations of various types of instruments have been given in Sections 5.2 - 5.7. In this section, recording devices, observational techniques, and maintenance are the major topics of discussion.

At the present stage, measurements of most crop events and some aspects of the physical environment in large geographic areas are based upon visual observation. In this connection, the completeness of the observational manual and the training and capability of the individual observer determine the accuracy and reliability of the record. As for recording devices, such as strip charts, punch cards, magnetic tapes, the less the human factor is involved, the better. For example, when strip charts are used, the shrinkage of paper, the transcribing of record, and the friction between the recording paper and pen, are all possible error factors. However, in reality, the choice of recording systems is chiefly determined by instruments available and the methods of summary.

Maintenance is dependent upon the number and qualifications of observers, frequency and duration of observation, the accessory and power supply, calibration, replacement and repair of instruments, as well as the recording and communication system. The type of maintenance depends upon the purpose of the experiment and the available funds. Sometimes maintenance is more costly in the long run and more important to a forecaster than the purchase and installation of new instruments. Careful planning for maintenance is necessary for any crop forecasting, so as not to jeopardize the entire program.

Communication systems should be decided upon with reference to the distance between the observational spot and the location of the forecaster, the method of data processing, the recording system, and the frequency of forecast. The ideal communication is a direct link between the recording device and the processing device. In other words, a minimum of steps in the transmitting process is essential from the standpoint of accuracy and efficiency. Communication tools that have been used are teletype, shortwave radio, telegraph, and postal service, of which the teletype is most widely adopted in forecasting programs.

Data processing is done by either hand computation or the use of electronic computer, depending upon the nature of the data. For a large geographical area, covering a number of observational stations, the electronic computer is imperative. For a single station, the forecaster can manage his data by hand, if they are not too voluminous. Methods in the treatment of raw data, analysis, and synthesis for crop forecasting are discussed in Sections 8.1 and 8.2. A well-organized forecasting procedure is particularly important for data processing when a variety of factors is involved. As far as treatment of data is concerned, the check-list presented in Section 8.1.2 is exceedingly important to the forecaster.

8.4.2 *Other considerations*

Aside from factors mentioned in the previous sections, additional factors to be considered are weed conditions, cultural practices, soil types, and other biotic factors. In principle, under the assumption of constancy of biotic factors, they should not be considered as factors in agrometeorology. However, in reality, unless these factors can be controlled, their variation should also be considered as an aid to better forecasting, particularly in large commercial fields. For example, weed conditions may be designated as "heavy," "moderate," or "light," and the relationship between weed condition and yield may be established and applied.

Crop forecasting techniques discussed thus far in the present chapter are more or less restricted to single-locality forecasts. Nothing has been said on forecasting in a large geographical area. As pointed out in Chapter 6, Riedat symbols of phenological phases (Fig. 6-7) can be plotted on daily synoptic charts. The five- or ten-day weather forecast associated with regional characteristics[12] would be an aid to area forecasts. For apples at the time of first pink, a warm spell of 47°-68°F, optimal temperature range, for two weeks' duration, would encourage fruit-set (see Fig. 8-5). Should such a temperature range be predicted, successful fruit-setting is most likely to occur. When

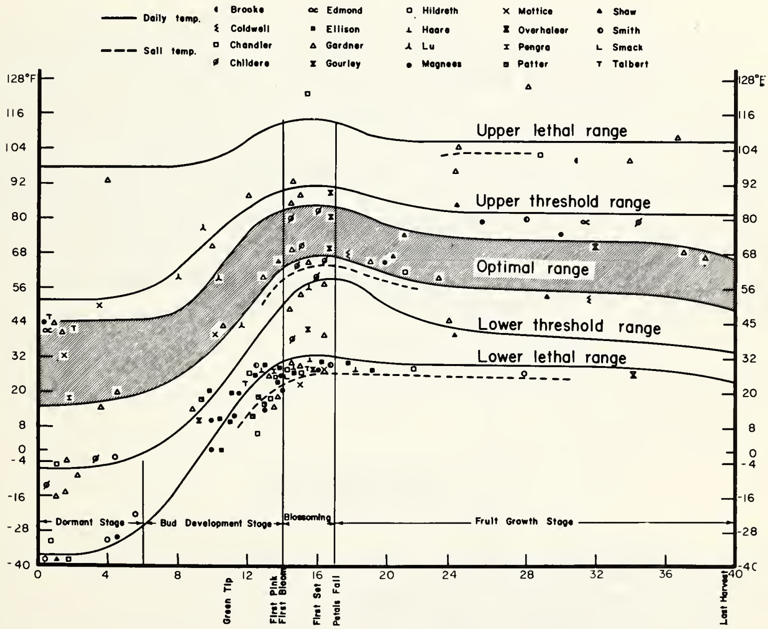

Fig. 8-5. Thermal response model of apple.

a prolonged cold spell of around 32°F is predicted, no fruit-set should be forecast. In view of the possibility of freezing damage of apple blossoms, a low potential yield should be forecast (see Fig. 8-5). In this connection, forecasts for a large geographical area can be made according to the association of regional characteristics and the isophene map: (1) for areas where apples are in their dormant stage (i.e., prior to appearance of green tip), no reduction of yield nor damage to

[12a]The advance of an air mass is always modified by characteristics of the earth surface, such as bodies of water, slopes, forest and soil types, etc. Thus, indices can be prepared according to the areal responses of various types of air masses for a period of 30-40 years.

flowers need be predicted, even though there is a possibility of delayed fruit-setting; (2) for areas where the green tip phase appears (i.e., the area of green-tip isoline), there is a possibility of reduction in yield and delay in flowering, depending upon the duration of the cold spell; and (3) for areas where the first floral isophene appears, a reduction of yield and delay of flowering should be predicted.

The quantitative expressions of the above statement are founded on the historical facts in correlation studies.

8.5 FORECAST ISSUE

The scale and type of crop forecasting determine how the forecast is used. For a small area of a few hundred acres in a single locality, the information can be passed over directly to farmers and growers. For an area the size of a state, forecasts can be issued by various means including newspaper, special bulletin, broadcast, television, telephone, and others. For an early potential forecast, or the first approximation at seedling stage, speed for forecast dissemination is not a problem, but for a multiphase forecast, particularly for those crops with rapid change of phases, a better facility for quick communication is absolutely necessary. Thus, speed, accuracy, and thoroughness are ultimate requirements of a forecaster.

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CHAPTER 9

Weather Forecasting for Agriculture

9.1 THE UTILIZATION OF GENERAL WEATHER FORECASTING

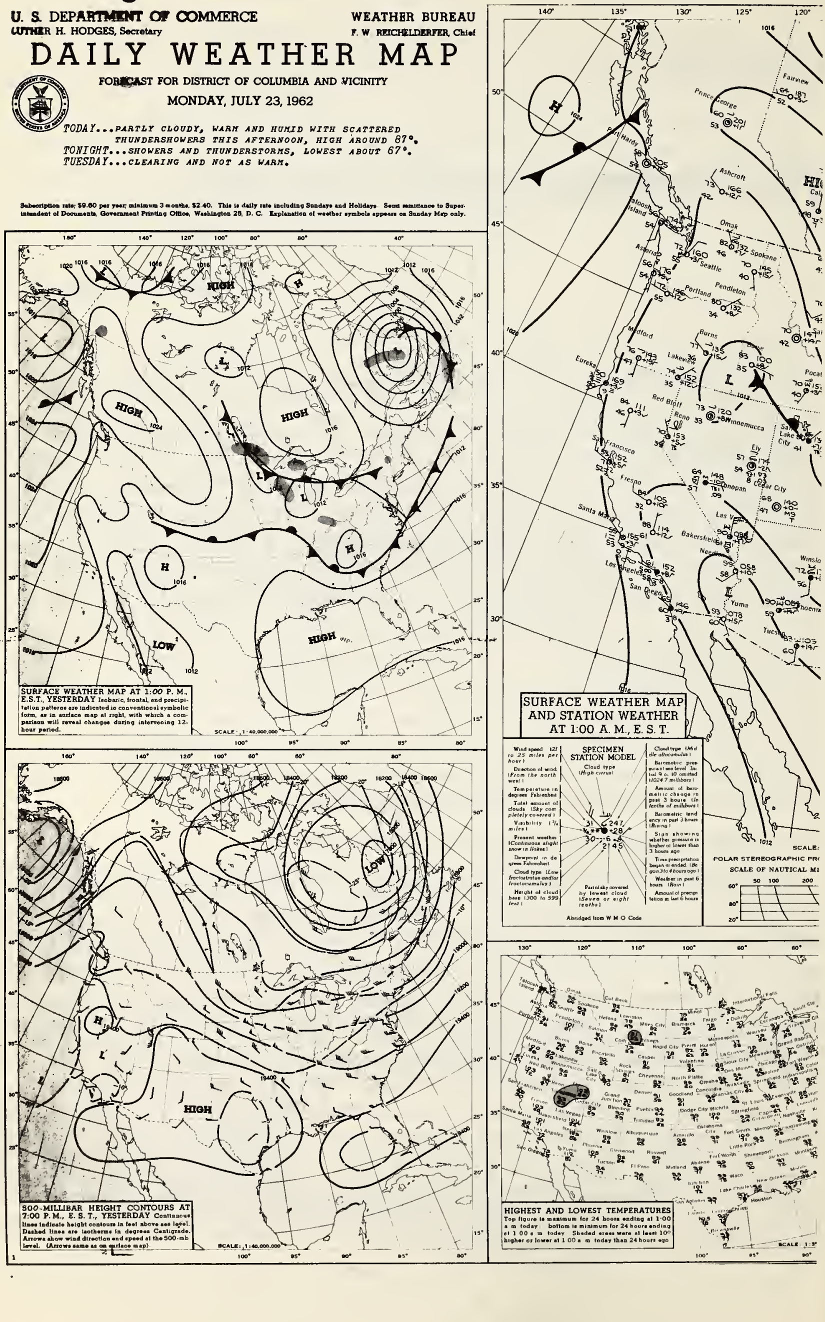
There are several kinds of weather forecast generally issued by national weather services. The U. S. Weather Bureau, for example, makes available to the public the daily weather forecasts, extended weather forecasts, and special warnings. The utilization of weather forecasts for agricultural purposes depends not only on their accuracy and reliability but also on their communication, interpretation, and the usefulness of the specific information to farmers and growers. Forecasts of duration and intensity of warm and cold spells, of soil temperature and moisture, of evapotranspiration, of dew, of solar radiation, of low-level wind, and the like are important for agricultural operations. In addition, warnings of severe weather such as frost, high wind, and heat waves are also important. Needless to say, the utilization of these forecasts or warnings requires an understanding, by farmers and growers, of various forecasting terms.

9.1.1 *Short-range daily weather forecasting*

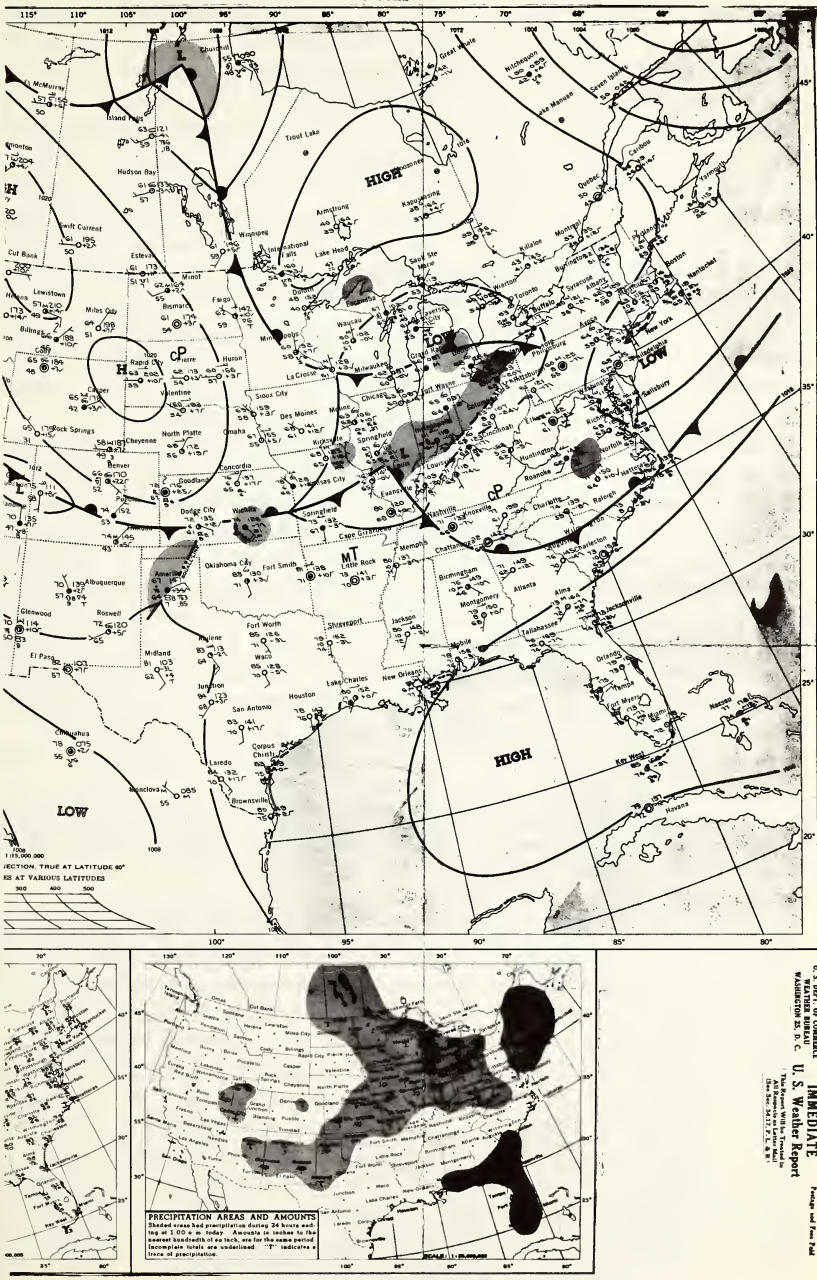
The short—range forecast, commonly known as the daily weather forecast, is a forecast of 12 to 48 hours in advance. It includes daily maximum and minimum temperatures, the state of the sky (cloudiness), wind velocity, humidity, barometric pressure, visibility, and precipitation, if any. Weather maps, known as daily synoptic charts, are prepared several times daily by the weather service, and indicate "high" and "low" pressure centers, type of air masses, frontal systems,[1] and rainfall areas. Specifically, the past and present weather,

[1] A boundary surface of discontinuity between different air masses having different temperature, humidity, and wind velocity is called a front. A system of fronts as it appears on a surface synoptic map is usually indicated by a line which represents the intersection of the frontal surface with the ground. However, a front is three-dimensional, and extends vertically as well as horizontally. It has thickness varying from two or three miles to fifty miles, even though it is not shown on a synoptic map. The types of front are customarily classified as cold, warm, occluded, and stationary.

Fig. 9-1 AN ILLUSTRATION OF



DAILY SYNOPTIC CHART



MONDAY, JULY 23, 1962

U. S. DEPT. OF COMMERCE
WEATHER BUREAU
WASHINGTON 25, D. C.

IMMEDIATE
U. S. Weather Report

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wind velocity, barometric pressure, three—hour pressure tendency, type and amount of cloud, precipitation, etc., are entered for individual stations on the chart (see Fig. 9-1). The three-hour pressure tendency refers to the character and amount of atmospheric pressure change for a three-hour period. The "characteristic" of the change is the direction of the change (i.e., higher or lower) from the initial value as can be seen in the barogram. The "amount" of the change is expressed in tenths of millibars. The synoptic charts are analyzed for the pressure field, wind field, thermal field, moisture field, and the weather pattern of the surface. For the upper air chart, temperature, wind, height contour, and weather pattern are analyzed. The analysis of the upper air weather pattern is made at 850, 700, 500, 300, and occasionally at 200 mb and higher levels.[2] The analyses of various fields are made in terms of isopleths (or isolines) of the individual element. For pressure, it is isobars; for temperature, isotherms; for wind direction, isogons; and for wind speed, it is isotachs.

Pressure tendency analyses, as indicated by isallobars, are useful to the prediction of the movement of highs, lows, ridges, troughs, and fronts. An isallobar is a line of equal change in pressure, and is commonly drawn for the three-hour local pressure tendencies in the synoptic chart. Sometimes the 12- and 24-hour isallobars are also used. In addition, although rarely done in synoptic study, analyses of isohyets, isohumes, and isodrosotherms are made for rainfall, humidity, and dewpoint, respectively. On the basis of these analyses, prognostic charts are usually prepared for the surface and 500-mb level. A prognostic chart is made principally for the expected surface pressure pattern and 500-mb height pattern at a specific future time. In addition, fronts are analyzed for the surface, while troughs and ridges

[2]These are synoptic charts of meteorological conditions in the upper air. In the last 20 years, standard constant-pressure charts have been employed, instead of constant height. When the surface chart of sea-level is used in conjunction with constant-pressure charts of the upper atmosphere, the sea-level pressure is usually converted to the height of the 1000-mb surface known as the "1000-mb chart."

In 1952 the International Civil Aeronautical Organization (ICAO) adopted the so-called "standard atmosphere" for the calibration of pressure altimeter, calculation of aircraft performance, designing of aircraft and missiles, preparation of ballistic tables, etc. It was formulated from the hypothetical vertical distribution of atmospheric temperature, pressure, and density. Some of the pressure height conversions are shown below:

Standard Pressures		Altitudes		Standard Temperatures	
Millibars	Inches of Hg	Feet	Meters	°F	°C
1013.25	29.92	0	0 (sea level)	59.0	15.0
1000	29.53	370	110	57.7	14.3
850	25.10	4780	1460	41.9	5.5
700	20.67	9880	3010	23.7	-4.6
500	14.76	18280	5570	-6.2	-21.2
300	8.86	30050	9160	-48.1	-44.5
300	5.91	38660	11790	-67.0	-55.0
100	2.95	53170	16210	-67.0	-55.0

are used for the 500-mb chart. The U.S. Weather Bureau publishes a daily surface and 500-mb chart for the current weather maps. Some of these maps are made available to the general public through newspapers and television. Fig. 9-1 illustrates a U. S. Weather Bureau daily synoptic chart, containing surface and 500-mb maps. The prognostic charts and many other weather analyses, such as the jet-stream analysis, are transmitted by facsimile equipment via radio or wire from Washington, D. C., to individual weather stations.

Problems in the utilization of daily synoptic charts for agricultural purposes are: (a) lack of correct understanding of the technical information issued; (b) difficulty in interpretation of large-scale prediction for local weather conditions; (c) insufficient length of forecasting periods; (d) lack of specific information of interest to farmers and growers; and (e) lack of a satisfactory degree of accuracy in forecast.

While there is a prescribed standard, practical consensus on the meaning of various weather forecasting terms, particularly those of a general descriptive nature, is not found even among forecasters, and there is also misunderstanding by the general public. For instance, words used in precipitation forecasts, such as "moderate," "light," "heavy," and "scattered," lead to confusion, unless specified with quantitative expressions. Moreover, since the present technique of forecasting is far from perfect, recent trial attempts to express the forecast in the form of a probability value are strongly endorsed. The forecaster may, for example, present his forecast as "chance of rain 60% today and 90% tonight."

In the study of weather forecasting for agriculture in the semiarid areas, Palmer (1956) called forecasters' attention to the differentiation in regional and seasonal variation. In the Western Great Plains of the United States, for example, neither the minimum temperature forecast nor the sporadic and sprinkling shower forecasts during the summer is of consequence in raising cattle or in growing wheat. But the daily forecasts of time and intensity of rainfall, drought, and duststorm are highly valuable. During the winter, forecasts of snow depth, wind velocity, and lowest temperature are of importance to agricultural operations. During the spring, a "medium-range" forecast of 10 to 14 days in advance on rainfall would be helpful in the selection of plantings, such as the choice between corn and sorghum, while a long-range forecast of rainfall would be useful to determine the summer feed for cattle. In the event of drought, for example, the climatological forecast should give the probability of the beginning and the end of the drought period, as well as its intensity. Andrews (1954) also emphasized the wet and dry spells, and further noted the usefulness of wind, humidity, and dew information. Dust and hail storms, effective rainfall, and evaporation are other important items of concern to farmers and growers. For pathological applications, forecasting the duration and intensity of fog and dew as well as relative humidity, are essential. The above items are rarely, if ever, included in the daily weather forecast issued by the weather service (see Fig. 9-1).

Aside from the official weather forecasts, amateur forecasting from local weather observations has been practiced by farmers for centuries. Such forecasts, based upon personal experience and weather lore, are often accurate for predicting very short-range weather, i.e., for a period of a few hours to a day. However, heavy reliance upon unscientific methods alone could hardly prove satisfactory for effective farm operation, and one should have some scientific knowledge of weather, particularly in the interpretation of daily synoptic maps. A few scientific rules of thumb for local forecasting follow.

1. Fair weather and associated weather elements — A drop, followed by a sharp rise, in barometric pressure and an increase of cloud heights after the passage of a cold front is a commonly observed sign of fair weather. Changes in cloud type and amount, as well as changes in wind speed and direction, are other signs of significance. The wind must be interpreted in relation to other weather elements in the light of recent developments. Fair weather can be recognized by descending air currents in the downward movement of smoke from chimneys, which indicate a location within an anticyclone. Under the condition of successive days with calm clear skies, a large diurnal temperature variation usually occurs, with high daily maximum and low daily minimum temperatures. An increase in relative humidity commonly precedes formation of fog, dew, or frost. Good visibility is generally associated with a cold air mass in the prevailing westerlies, while poor visibility is generally associated with a warm air mass.

Above all, changes in cloud type, amount, height, and in wind speed and direction accompanied by barometric changes are the most useful and reliable weather signs for the amateur forecaster. This also holds true for the prediction of stormy weather.

2. Stormy weather and frontal system — The development of stormy weather can be predicted from increasing cloudiness, lowering of cloud heights, and changing cloud types. Particularly, the sequential change of cloud types is a good indicator. The first sign of a warm front coming toward any particular place is the appearance of high clouds[3] (cirrus, cirrostratus, and occasionally cirrocumulus), which are sometimes indicated by halos,[4] and cold air from the southeast. As the front approaches closer, the middle clouds[5] (altostratus and altocumulus) are noted. Rain or snow usually begins from the altostratus cloud and is intensified with the low clouds[6] (stratus and nimbostra-

[3,5,6]A classification of cloud types can be obtained from any standard textbook of meteorology. See the Glossary (Appendix A) for detailed definitions.

[4]Halo phenomena are produced by the refraction and reflection (for whitish halos) of the sun or the moonlight that enters the prism surfaces of ice crystals of high clouds (e.g.,

tus). Usually the first sign of a cold front is the appearance of either cirrus or altocumulus clouds accompanied by warm air from the south or southwest. This is followed most often by stratus clouds in the winter and clouds of the cumulus type in the summertime. When cumulonimbus clouds appear, rain might occur. The most vigorous squall condition is noted with the passage of the cold front and the shifting of the wind direction to the west or northwest. The use of clouds in forecasting is nothing new. Brooks (1951) and Rossby (1941) have made a comprehensive summary of the subject.

Aside from cloud conditions, a continuous drop in barometric pressure, a shift in wind direction, and the upward movement of smoke from chimneys, in general, indicate the approach of a cyclone, with cloudy or rainy weather. However, a gradual rising and lowering of barometric pressure may or may not indicate stormy weather. The increase in wind speed which is always associated with the increase of pressure gradient may cause a more intense storm.

Changes in temperature, accompanied by changes in relative humidity, may also be an indicator. In the warm sector of a cyclone, during the summer, an increase in temperature and humidity might be a token of more thunderstorm activity. A lowering of temperature and increase in humidity during early evening in the early spring or late fall may be a sign of frost formation during the night. Or it may be a sign of dew and fog formation, if no freezing temperature occurs. A continuous lowering of temperature during the time of cold front passage may indicate the coming of a cold air mass, and persistence of cold air for a period of several days.

9.1.2 *Extended weather forecasting*

The extended weather forecast has been defined by Namias in 1957 as a forecast beyond 48 hours, up to geological epochs including the ice ages. According to this definition, it includes the "medium-range forecast," covering three or four days to two weeks, and the "long-range forecast," covering monthly, seasonal, annual, up to millennial periods. At the present stage, however, the extended forecast has at best shown promise in prediction of a period of only a few days to a month. The Extended Forecast Branch of the U.S. Weather Bureau, for example, makes twice-monthly issues of an Average Monthly Weather Résumé and Outlook, commonly referred to as the 30-day outlook. A series of the past and outlook charts covering both the United States and the northern hemisphere are made for monthly mean temperature and precipitation classes, and 700-millibar contours. The normals and limits for monthly mean temperature and precipitation for individual stations in the U. S. A. are also published. The upper two maps of

cirrus) with an average elevation ranging from 20,000 feet up to the base of the tropopause. The halo of 22°, the most common of all halo phenomena, for example, has a coloring display of red inside and blue outside.

Fig. 9-2a indicate the outlook for July, while the lower two are the observed conditions for June 1962 in the U. S. A. For the July 1962 prognosis of the northern hemisphere, the top map of Fig. 9-2b indicates the mean 700-millibar contours; the middle, the temperature anomaly; and the bottom, the precipitation. Based on the period 1921 to 1950, the climatological quantities for temperature and precipitation for the month of July are shown in Fig. 9-2c; these define necessary forecasting categories for both temperature and precipitation. For example, the top map of Fig. 9-2c gives the temperature class limits for Chicago for the month of July as

74.6
-0.9 • 0.5
-2.7 2.4

where 74.6°F is the normal temperature. The temperature range from (74.6 - 0.9) to (74.6 - 2.6) is categorized as "below normal," and that of (74.6 - 2.7) and below, "much below normal." Similarly, the "above normal" temperature ranges between (74.6 + 0.5) and (74.6 + 2.3), and "much above normal," upward from (74.6 + 2.4). In the case of precipitation (see the bottom map of Fig. 9-2c), the class limits are:

3.65
•
2.49

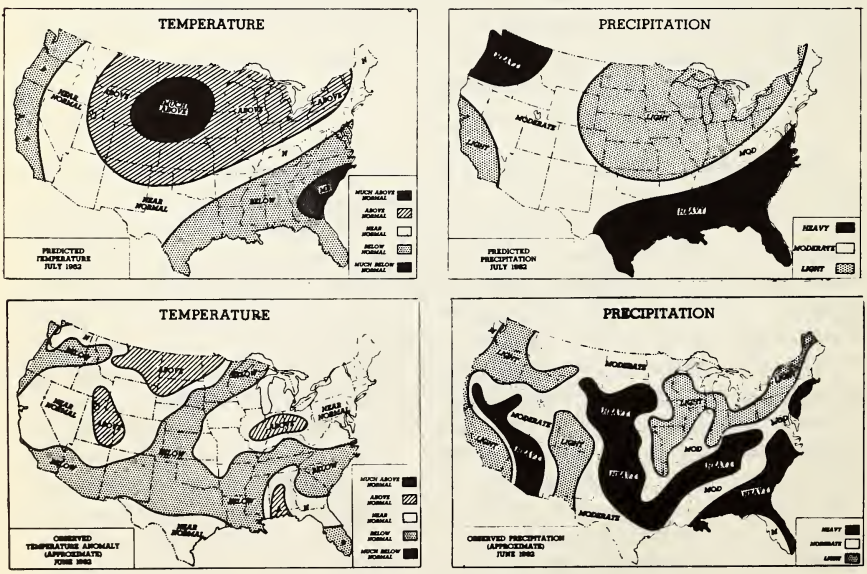
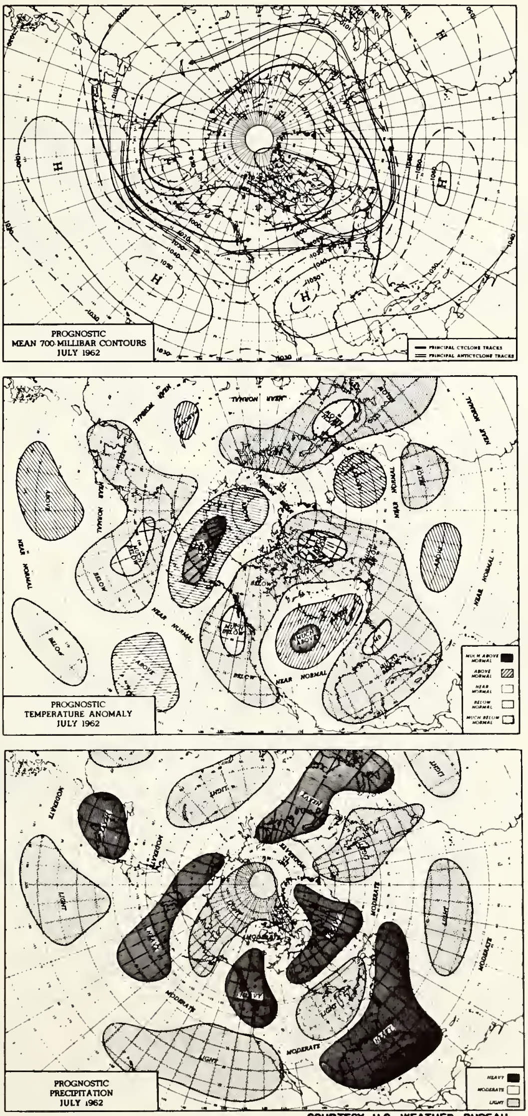


Fig. 9-2a. Extended weather forecast on temperature and precipitation.
Courtesy U. S. Weather Bureau

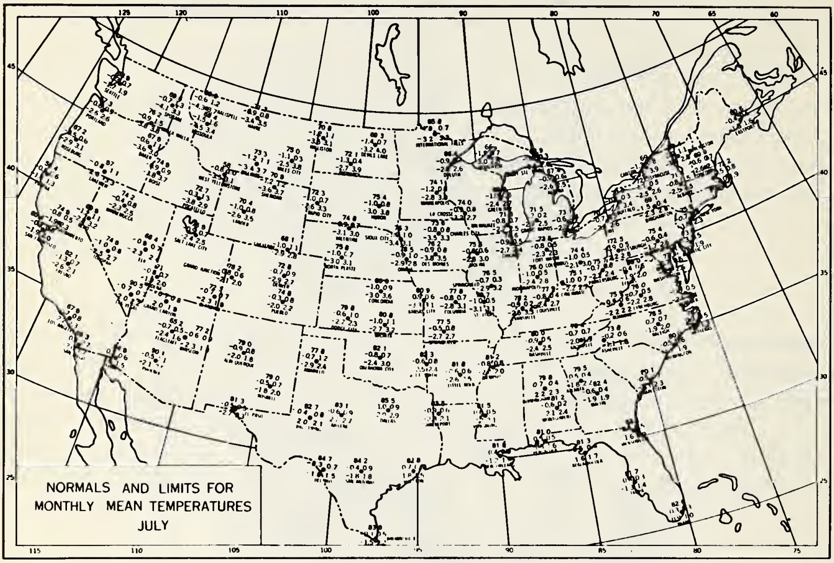
Fig.9-2b EXTENDED WEATHER FORECAST FOR THE NORTHERN HEMISPHERE

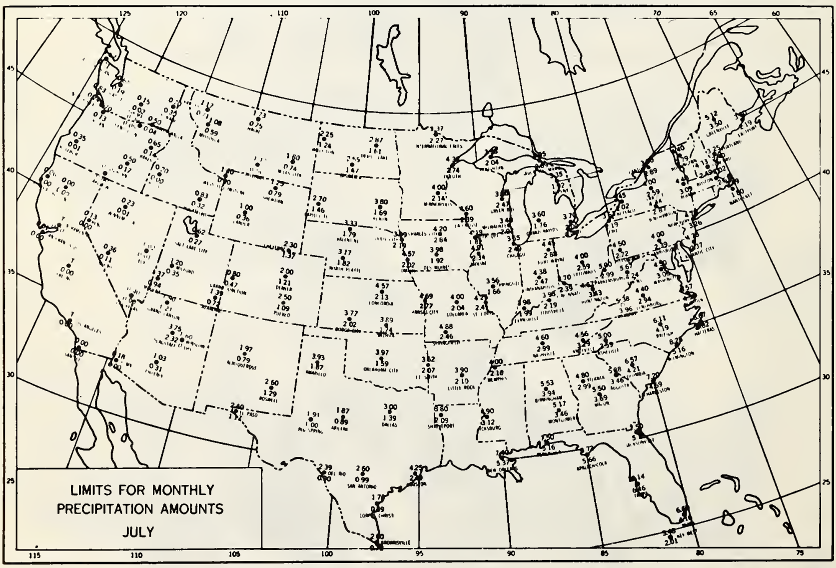
OUTLOOK FOR JULY 1962



COURTESY U.S. WEATHER BUREAU

Fig. 9-2c NORMALS AND LIMITS OF TEMPERATURE AND PRECIPITATION, U.S.A.





COURTESY U.S. WEATHER BUREAU

In Chicago, the precipitation total of less than 2.49 inches, during the month of July, is classed as "light," from 2.49 to 3.64 inches, as "moderate," and 3.65 inches or more, "heavy" rainfall. Note the different limits and normals at different stations and for different months.

For agricultural uses, seasonal and annual forecasts are desired, although no promising and reliable techniques have yet been achieved. Willett (1951) in his study of weather forecast problems, investigated the accuracy range of short-range forecasts. On a 50 percent probability level of verification, the accuracy range was found to be 90-95 percent for an 18-hour forecast, 70-90 percent for a 20- to 48-hour forecast, 70-75 percent for a two- to seven-day forecast of mean temperature anomaly, and 60 percent for rainfall forecast. When the forecast period extended beyond seven days, the verification was found to lie in the range of 50 to 60 percent. He concluded that the unsatisfactory progress in weather forecasting since 1914 could be attributed to (a) lack of trained personnel, (b) too heavy reliance on personal experience and, in turn, subjective interpretation, (c) multiplicity of forecasting tools and techniques, and (d) failure in appropriate utilization and correct understanding of the essentials in the forecasting problem. These problems apply to both short—range and extended weather forecasts.

Byers (1959) pointed out that basic difficulties encountered at the present stage of weather forecasting are due to (a) infrequent measurement of the vertical motions of air that produce weather, and (b) the difficulty in detecting acceleration and intensification of perturbations (cyclones, anticyclones, troughs and ridges). Moreover, height contour analysis of the upper charts are based mainly upon the geostrophic wind assumption even though the weather is not produced by the geostrophic wind but by ageostrophic wind.

The techniques used in extended weather forecasts are quite different from those of short-range forecasting (Namias, Baur, & Elliott in Compendium of Meteorology, 1951; Also Namias, 1953). Namias developed statistical, analogue, and physical methods in his extended forecast on the basis of general circulation and physical laws. He converted mean circulation patterns into temperature and precipitation. He established simultaneous relationships between component parts of the general circulation by means of the evolution of flow patterns. Baur, working on the assumption that individual cyclones and anticyclones are steered by general circulation along fairly well defined paths, used broad—scale features of the general circulation for his forecasting. His method, known as "Grosswetterlegen," is an empirical establishment on the basis of long-term statistics. Elliott, on the other hand, emphasized a weather-type analysis. Obviously, extended weather forecasting can be improved only by a better understanding of the physical principles of general circulation, and with the aid of proper instrumentation. The recently developing technique of satellite weather observation holds promise for extended forecasting.

The paleoclimatological approach to the long-range weather prediction, with the aid of the periodicity of climatic cycles through the observation of tree rings, sunspots, silt deposits, and long–term weather statistics, is expressed in terms of warmer or cooler, wetter or dryer. The foundations of these techniques are rather primitive and crude, and their predictions are as yet unavailable for verification.

The applications of extended forecasting to agriculture are, notably, for planning effective agricultural production or merchandising campaigns, for effective utilization of irrigation, and for hydroelectric and drought-control facilities. At the present stage, however, the agrometeorologist is forced to satisfy himself with a very restricted utilization of extended forecasts.

9.1.3 *Interpretation for weather forecasts for farming*

The effective interpretation of weather forecasts for farming operations depends upon (a) the period of forecast (short-range and extended), and (b) the interpreter's knowledge. It is essential that an interpreter be equipped with sufficient knowledge in synoptic meteorology; therefore, some public education in such matters is desired (see also Landsberg, 1940; Sherrod & Neuberger, 1958). With the distinction between long- and short-range forecasts and types of specific forecasts, microclimatic characteristics should be carefully considered. Specific forecasts, such as frost warning, fire weather forecast, and harvesting-period forecast, are discussed in the following section.

9.2 SPECIAL AGRICULTURAL WEATHER FORECASTS

Specific forecasts are costly but are much in demand because, as mentioned above, both short-range and extended forecasts consisting of only general weather information for a large geographical area do not meet all the needs of specific agricultural operations. Specific weather forecasts for vegetables, fruits, forests, insects, diseases, and animals, such as warning of weather hazards, scheduling of planting dates, and programming of chemical spraying, are required.

9.2.1 *Frost warnings*

The frost-danger warning for crop protection is nothing but a forecast of the ambient minimum temperature in crops, irrespective of the actual occurrence of frost. Therefore, to be of satisfactory use to agriculture, the minimum temperature profile or the distribution of temperature with height should be forecast according to species and varieties of crops.

Methods of frost forecast depend upon synoptic patterns and microenvironments. The classification of frost types presented in Section

4.2.2 may be simplified for forecasting purposes as radiative, advective, and their combination. In the event of radiative frost, nocturnal radiational cooling is the major process concerned in the forecast. It occurs during calm and clear nights. The intensity of minimum temperature varies with the amount of infrared radiative heat loss from the ground. From the synoptic standpoint, information on current temperature, humidity, dewpoint, cloudiness, air mass type, wind speed and direction are necessary for prediction (Allen, 1939; Biéler, 1953; Horning, 1955; Jacobs, 1940; and Kopáček, 1956). From the microclimatic point of view, more information is needed, such as soil heat storage, soil thermal conductivity, nocturnal radiation, net radiation, topography, and cold air drainage of the specific locality (Geiger, 1942; Brunt, 1934; and Donaueschingen, 1953). No attempt is made here to describe the methods by which the predictions are made, and the reader may refer to the references cited above. Advective frost is a result of the replacement of warm air by cold air brought by horizontal wind movement from colder regions. For the forecasting of advective frost, the synoptic approach is extremely important. A combination of radiative and advective frost, for example summer frost, on the other hand, is caused by processes of evaporative cooling, cold air drainage, and so forth. Summer frost is also determined by the soil types, topography, vegetation, and current weather patterns (for detail, see Section 4.2.2). The frequent formation of summer frost in cranberry bogs in the north central area of the U.S. is obviously a problem of local effect.

The U.S. Weather Bureau operates a special Frost Warning Service in several agricultural areas for citrus fruit, tobacco, cotton, and cranberries. Federal-state cooperation has made frost warning service especially valuable to these areas. This type of service should be carried on by all weather forecasting organizations in the vicinity of intensive farming areas.

9.2.2 *Fire weather forecast*

Fire weather may be defined as the state of the weather with respect to its effect upon and kindling and spreading of forest fires (Huschke, 1959). Fire-inducing conditions include low humidity (i.e., 40% or less) and lack of rainfall (i.e., 0.01" or less) during preceding days, and high wind speed (i.e., 13 mph or more) on the day in question (Landsberg & Jacobs, 1951). The values assigned to the above factors are not an absolute scale and may be modified by (a) types of forest—deciduous or evergreen, (b) fuel moisture — the specific measure of moisture conditions in the forest, (c) seasonal stages of foliage, (d) the build-up index — the cumulative effects of precipitation and evaporation, (e) the humidity and speed of air movement in the forest, and (f) the maximum temperature above the forest floor. Based upon the above considerations, a graphical aid, known as the burning index,

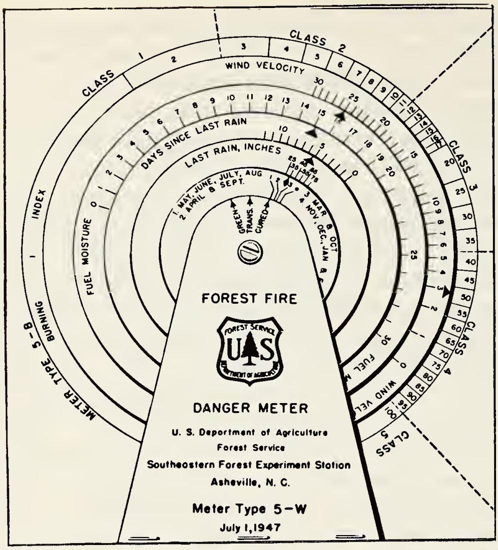


Fig. 9-3. Forest fire danger meter. **Courtesy U. S. Forest Service**

is used to forecast the degree of forest fire danger. For the convenience of the forecaster, the graphical method is converted into a slide-rule known as a fire-danger meter (see Fig. 9-3; also Hayes, 1949). Using the three climatic elements, relative humidity, weighted precipitation, and wind speed, Landsberg & Jacobs (1951) have made a four-months (January to April) statistical summary of forest fire days for a period of four seasons (a total of 480 days) in the following categories: good-fire day (R. H. $\leq 40\%$, precipitation ≤ 0.01, and wind speed ≥ 13), poor-fire day (R.H. $\geq 60\%$ and precipitation ≥ 0.05), and indifferent-fire day.[7] The latter is designated as the state of weather

[7]Other systems of categorization are presented below:

According to relative air humidity and litter moisture content as measured by air psychrometer and litter-covered hygrometer, the generalized indices are:

Degree of fire danger	Relative humidity, percent	Litter moisture content, percent	Causes of fire
I. No danger	Above 70	Above 26	Most causes inoperative
II. Possible danger	60-69	19-25	Lightning fire, incendiary fire, etc.
III. Slight hazard	50-59	14-18	Campfire, debris burning fire, etc. *
IV. Moderate hazard	40-49	11-13	Smokefire, etc.
V. Dangerous	30-39	8-10	Railroad-fire, saw-fire, spontaneous combustion, etc.
VI. Extremely dangerous	Below 29	2- 7	Danger from all causes.

*Hereafter, the "higher" degree of fire danger includes all previous causes.

According to the index of combustibility used in the U.S.S.R., we have

$$g = \sum_{n=1} T \cdot d$$

that would neither contribute to nor retard the fire hazard. The results of their studies are given in Table 9-1.

TABLE 9-1. Fire Occurrences and Fire Danger Class

Fire Class	Total Days	Total Fires	Fires Per Day
Good-fire day	110	226	2.05
Indifferent-fire day	224	193	0.86
Poor-fire day	146	32	0.22

The last column of Table 9-1 shows that the frequency of fire incidence in the good-fire days was over nine times that in the poor-fire days. However, the total number of fire days in the latter two classes is 225 and that for good-fire days is 226. This signifies that one-half of the occurrences of forest fire are classified under "poor" and "indifferent" hazard days, when protective measures are not as intense as on good-fire days. This suggests that the classification can be improved by (a) thorough understanding of the sources of fire, and (b) the investigation of factors other than the three climatic elements listed above. The improvement of forecasting, prevention, and control techniques should be established through experimental tests.

As to the causation reported, the main categories are lightning fires and man-caused fires. Self-combustion[8] as a source of forest fires is rather rare. It has been reported, however, that during the hot dry season in Australia, when "blow-up" conditions are reached, spontaneous combustion may occur, especially in the eucalyptus forests. The Australian Forestry Service therefore broadcasts three times a day on fire weather conditions during the summer when fire risk is high. In Sweden, it is estimated that one-third of the fires are caused by lightning strikes. In the United States, according to the Pacific Northwest report, lightning was found to be the most serious contributor. In 1961, 3064 out of 5651 total cases were lightning-fires, the highest lightning fire rate recorded since 1908 for the Pacific Northwest area. For the entire forest regions of the western United States, the number of lightning-caused fires was estimated at 6000 annually (Critchfield, 1960).

where T is the air temperature in degrees Centigrade, d is the saturated vapor pressure deficit in millimeters (both measured in the weather shelter at 1:00 pm local time), and n is the number of days since the last rainfall. This index is tabulated as follows:

Degree of fire danger	Index of combustibility
I. No danger	300
II. Slight hazard	301-500
III. Moderate hazard	501-1000
IV. Dangerous	1001-4000
V. Extremely dangerous	Above 4000

For further elaboration on fuel moisture, see Table 9-2.

[8]This is the spontaneous combustion resulting from chemical heating through decomposition of forest fuel. As soon as the temperature reaches the kindling point, fire occurs.

TABLE 9-2. Burning Index Class

Class	Burning Index Values	Class	Burning Index Values
0	0	6	25-35
1	1b-1a	7	36-48
2	2-3	8	49-63
3	4-8	9	64-80
4	9-15	10	81-100
5	16-24		

Burning Index Value Table No. 1

(Use this table in the spring and until July 15, provided herbs and grasses have not already reached the curing or dead stage.)

Wind Speed	Fuel Moisture Stick — Percent												
	3	4	5	6	7	8	9	10	11	12	13-15	16-25	Over 25
0- 3	15	11	8	5	2	1a	1a	1a	1b	1b	1b	1b	0
4- 6	21	17	13	9	6	3	2	1a	1a	1a	1b	1b	0
7- 9	30	25	19	15	10	6	3	2	2	2	1a	1b	0
10-12	40	34	28	22	16	11	6	3	2	2	2	1a	0
13-15	53	45	38	32	25	19	14	8	4	3	2	2	0
16-18	66	57	49	42	34	27	20	13	7	3	3	2	0
19-27	90	77	67	57	45	38	28	20	12	4	4	3	0

Burning Index Value Table No. 2

(Use this table in early summer after herbs and grasses reach the curing or dead stage, and in all cases after July 15 to end of season.)

Wind Speed	Fuel Moisture Stick — Percent												
	3	4	5	6	7	8	9	10	11	12	13-15	16-25	Over 25
0- 3	19	15	11	8	5	2	1a	1a	1a	1b	1b	1b	0
4- 6	26	21	17	13	9	6	3	2	1a	1a	1a	1b	0
7- 9	35	30	25	19	15	10	6	3	2	2	1a	1b	0
10-12	48	40	34	28	22	16	11	6	3	2	2	1a	0
13-15	61	53	45	38	32	25	19	14	8	4	2	2	0
16-18	75	66	57	49	42	34	27	20	13	7	3	2	0
19-27	100	90	77	67	57	45	38	28	20	12	4	3	0

Courtesy U. S. Forest Service

The speed with which fires spread, and the depth to which they burn, are determined by the wind speed and direction, the amount and intensity of rainfall, the condition of the vegetation and litter, and the temperature and dryness of the forest air. These factors are, of course, independent of the way in which forest fires start.

Experiments, under controlled environments and in the natural field, are required to study the causes and spread of forest fires, even though they are rather expensive. It has been reported that such an experimental test on forest fire spread has been done in the United States and Sweden. Naturally, it will require measurements of the horizontal and vertical distribution of meteorological elements in both surface and upper air prior to and during the experiment, as both micro- and macro-meteorological effects are influential in forest fire hazard.

In addition to the meteorological elements, knowledge of other factors is required, such as the degree of inflammability of forest materials. Forest litter dries much faster under a broken canopy than under an unbroken canopy. In the latter case, drying time is lengthened by as much as a week. The moisture content of litter can be as low as three percent. At 10 percent, it is hazardous, but above 25 percent there is no fire danger. The determination of moisture conditions under the canopy is therefore important. This may be done by the use of a fuel moisture indicator. This instrument consists of wooden sticks placed on the forest floor where they are freely exposed to the weather. These sticks are periodically weighed in the field on a scale which is calibrated to give an index of fuel moisture content. The scale of the Pacific Northwest Forest and Range Experiment Station indicator (see Fig. 9-4) ranges from 0 to 50 percent, representing the moisture content of the set of sticks. These half-inch diameter wood dowels are exposed to the free air at six inches above the ground. When these sticks are oven-dried, they weigh 100 grams, and the scale indicates 0 (i.e., the zero reading). When moisture is absorbed by the sticks, their weight increases, as do the scale readings.

From the wind speed (mph) and fuel moisture content (%) records, the burning index (or B.I. value) can be obtained from Table 9-2. The burning class, as shown at the top of Table 9-2, is made from the B.I. values. The higher the class, the greater the chance of fire occurrence. This is one of several methods used in different parts of the United States to determine fire danger. The U.S. Forest Service is working on the development of one system for all of its lands.

The U.S. Weather Bureau administers a Fire-Weather Service in close cooperation with fire protection organizations. Meteorologists at fire-weather centers specialize in issuing forecasts and warnings for individual forest areas. Information about expected lightning, temperature, humidity, and wind is used to determine future fire danger. This in turn makes possible correct actions to prevent many fires

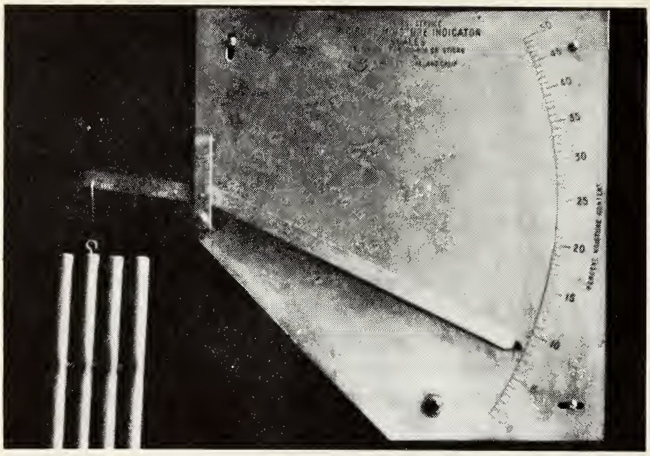


Fig. 9-4. Fuel moisture indicator. Courtesy U. S. Forest Service

from occurring, as well as keeping small many fires that do occur. Traveling forecast offices are used at the scene of large forest fires in the West to provide forecasts which assist fire officials in determining the strategy to be employed for rapid and economical fire control. Operations based on fire-weather forecasts include deployment of manpower and equipment, aerial reconnaissance, manning lookout towers, opening and closing of areas to the public, shutting down logging operations, issuing burning permits, controlled burning, and slash disposal.

9.2.3 *Planting and harvesting weather forecast*

Weather forecasts for planting and harvesting are much alike. They depend upon types of crop as well as methods and time of planting or harvest. The forecast is made in terms of probability on such items as (a) dry and wet spells, (b) cold and warm spells, and (c) weather catastrophes such as severe wind, thunderstorms, dust storms, and hail. It is important that these forecasts specify duration, intensity, and size (or total amount) of the event. For example, in the forecasting of wet spells, we should know the type (i.e., rain, snow, or hail, etc.), duration (including time of beginning and ending), frequency (e.g., number of crop rainy days, etc.), and total amount as well as the geographical area of coverage. These are, as has been pointed out in Chapter 7, the major determining factors for planting and harvesting time.

Although weather forecasts for planting and harvesting are much alike with respect to the items covered, there is a conspicuous difference between the two. Due to the difference in farm operations, and seasonal changes, it is desirable for the planting weather forecast to be made more extensively, frequently, and for longer periods. Thus, the extended forecast may be considered as a powerful tool, provided the accuracy is high. The short-range forecast can be an aid in the determination of the planting schedule, which involves the time, acreage, and species of plant. As to harvesting weather forecasts, the following items are essential: For extended forecast, we have dry and wet spells, warm and cold spells, and severe storms. For short-range forecast, we have types of weather (e.g., clear, cloudy, and overcast), amount of sunshine, air and soil temperatures, air humidity, the amount, duration, and intensity of rainfall, and the like.

Most of the studies on planting and harvesting period forecast are given elsewhere in this textbook. Forecasting of yield, quality, and maturity date of a crop are discussed in Chapter 8; extended weather forecast, its limitations and possibilities, has been presented in Section 9.1.2; and details and illustrations on statistical forecasting will be explained in Section 9.3.

9.2.4 *Insect and disease forecast*

This type of forecast covers the outbreaks of diseases (fungi, viruses, bacteria) and insects (pests and beneficial) for both plants and animals. In this section, the discussions are restricted to the topics of plant diseases and insects, since the treatment of the entire subject is beyond the scope of this volume. Forecasting of insect pests is important in its relation to prevention and control programs. The items of pest forecast may include expected relative abundance, expected period of increase or decrease, time of peak infestation, beginning and peak periods of hatching, and the period of rapid growth and development of plants, particularly their flowering. The latter item is just as important as the others, though indirect, because plants are hosts to insects and diseases. In this connection, the stages of development of plants as related to the degree of infestation, should also be considered.

Environmental factors used for the study of plant pests are temperature, relative humidity, dew, rainfall, fog, cloudiness, light, wind, snow cover, and even frost penetration. Among them, temperature, relative humidity, and rainfall are the more popularly used elements. When wind is used, the synoptic weather pattern is generally concerned. The parameters used are rather simple and crude. They are heating-degree-days, growing degree-days, and monthly mean values of humidity and rainfall. When temperatures are employed, the daily mean, maximum, and minimum, as well as day- and night-temperatures, have been specifically concerned.

Improvements can be made as increased knowledge permits the introduction of additional environmental factors, e.g., net radiation, air composition, soil aeration, soil moisture, and temperature, and derived climatic parameters (see Section 7.4.2). A few studies have been made on soil temperature and moisture, but, to the best of our knowledge, none on net radiation.

The types of forecast may be classified according to the life history and ecology of insects and diseases as (a) long-term warnings, (b) medium-term warnings, and (c) short-term warnings. This classification is independent of the two major types of the general weather forecast.

(a) Long-term warnings. This refers to a period of several months in advance. For certain pathogens and insect pests, the environmental factors during the winter, particularly thermal factors such as air and soil temperatures, are crucial to survival, and the severity of these pests can be forecast only after the winter is over. Some illustrations of diseases are given below.

In his study of corn blight, Kangieser (1956) found that in Massachusetts the development of bacterial wilt and Stewart's leaf blight, *Bacterium Stewartii*, of dent corn and sweet corn are related to the previous winter's temperatures. If the sum of average temperatures of December January, and February was less than 100° F, the wilt on sweet corn was not likely to occur; if the sum was more than 85°F, dent corn was attacked by the leaf blight. Therefore, southern Massachusetts' bacterial wilt and Stewart's leaf blight tended to build up to epidemic proportions after several mild winters.

Volcani (1958) has conducted infection experiments on corn by inoculating *Erwinia Carotovora* into the collar and stem of very young plants under extremely humid conditions. It was found that the optimal temperature for infection was between 79° and 82°F; no infection at 98° and 41°F; slight infection at 46°F. Based on these findings, a forecast of the possibility of this type of bacterial disease in corn is possible under humid conditions at the early stage.

For insects, Wheeler (1955) has adopted an approach similar to Kangieser's, in his forecast of corn flea beetle outbreak on Massachusetts farms. He predicted the survival probability of the insects over the winter as "high" for the total average temperatures at 90°F and above, "some" for 85-90°F, and "none to low" for 80-85°F.

Pratt (1955) analyzed the monthly data on insect and mite populations in 130 representative citrus groves in central Florida for a period of four years. He found that the monthly mean temperature for December had a direct effect upon the life span and mortality of insects and mites, and an indirect effect on the abundance and efficiency of parasites, predators, and diseases. At the same time, these pest outbreaks were inversely correlated with the rainfall. By means of temperature and rainfall observations in December, he claimed that he could make forecasts, particularly of the economic significance of the peak infestations during the month of May or June.

It has been reported that in the southern states of the U. S. A., 95% of the hibernating adults of cotton boll weevil die during the winter.

However, the incidence of pests is considerably less in high latitudes and altitudes, because of lower temperatures as well as the absence of host plants.

Evenhuis (1958a, 1958b) has observed the mortality of the woolly aphid, *Eriosoma Lanigeram*, and its parasite, *Aphelimus mali*, a serious apple pest, for the two years 1956-57 in the Netherlands. He found that the woolly aphid is much more susceptible to low temperatures than is its parasite. He also found that at temperatures of 64°F and above, the amount of both the host and parasite is greatly increased. In 1956, almost all woolly aphids were killed by the severe frost in February, and a small infestation by the woolly aphid as well as a low rate of parasitism was seen the following autumn. It was extremely mild during the winter of 1956 and many aphids survived. At the beginning of 1957, the ratio of parasites to aphids was still very low. In the summer of 1957, however, the parasite recovered completely with respect to its host and in September 1957, parasitism reached 68 percent.

On the basis of such findings and the observation on the severity of the immediate past winter, it is possible to predict the degree of infestation in terms of an equation or an alignment chart. The choice of parameters for the evaluation of severity depends upon the species and varieties of insect pests or pathogens, the lethal effects of climatic factors, and/or climatic units, and characteristics of the local environment. It may be the summation of air and soil temperatures, frost depth, or intensity of insolation, as has been discussed previously in Section 7.4.2.

(b) Medium-term warnings. This refers to a period of more than two days but less than a month in advance. In this type of forecast, the synoptic approach is a useful tool. Wellington (1958; see also Section 3.3.1) discussed the prediction of tent caterpillar outbreaks in terms of synoptic conditions in Canada. Meteorological factors accompanying the insect outbreak are moderately low air temperatures associated with intermittent sunshine and occasional showers. Unfavorable weather for the tent caterpillar, on the other hand, includes both extremes — hot and dry, as well as cold and wet.

Craigie (1945) studied the relation of meteorological factors to the development of wheat stem rust in western Canada, particularly in Alberta, Saskatchewan, and Manitoba, during 1916-1938. He found that the development of rust in each of these areas is not an independent local phenomenon, but is related to the wind movement. According to his observations, it first appears in the Red Valley, Manitoba, in late June or early July. Then it spreads to Saskatchewan and Alberta, where it appears a month later. Southerly winds over Manitoba during June 12 to July 20, accompanied by high humidity, rainfall, and dew frequency with attending high temperatures, appeared to correlate positively with great rust prevalence. Thus, with knowledge of synoptic conditions and with measurements of dew frequency, solar intensity, air humidity, and number of spores present, a rust-weather forecasting may be possible.

Potato blight weather forecasts, as well as potato blight-weather relationships, are a very popular and important subject of investigation. As early as 1916, Erwin made a correlative study of the late potato blight epidemics and climatic conditions in Iowa. To name a few other recent researchers on this subject, we have Bourke (1953-1962), Raeuber (1957), Šikić (1956), and Uhlig (1957). A brief summary of their findings is in order.

Bourke has made forecasts of potato blight in Ireland (see also Section 6.2.2) for a number of years, with the primary objective of determining the optimum times for preventive spraying. His study is based mainly upon synoptic weather patterns with modifications of microclimatic influences. His forecast technique has been adopted by the Irish Meteorological Service for their Blight Warning, and it has been used with success since 1952.

"Blight weather" has been defined experimentally in the laboratory in various countries, and has been summarized by Bourke (1959) as

> The necessity for a period of at least 10-12 hours of saturated air within the crop cover, at temperatures of the order of 50° to 59°F, for the formation of blight spores . . . that the spell of high humidity required to be followed immediately by a period of several hours during which free moisture was present on the foliage of the host plant in order to permit germination of the spores and reinfection of the host.

The synoptic situation associated with blight weather has been indicated in Section 6.2.2, and an illustration of the synoptic approach to blight weather is given below, with the 1958 blight weather in Ireland as an example (see Figs. 9-5 and 9-6). The blight attack of 1958 in Ireland, which was considered the worst in the present century, has been described by Bourke (1959):

> Early June showed abnormally high rainfall in most parts of Ireland. From June 13th to 18th, however, was generally dry, but it would have been premature to advise spraying unless it could confidently be said that the weather would soon revert to moist, warm conditions. Fig. 9-5(a) shows the surface weather chart of June 17th. A broad south-westerly current of maritime tropical air covered much of the Western Atlantic, and it was clear that, although the anticyclonic ridge would give fine spraying weather for another day or two, an influx of warm moist air into Ireland was inevitable, and was likely to persist, or recur with short interruptions, probably to the end of the month.

The shaded area of Fig. 9-5b indicates the area which was expected to be affected by the first wave of maritime tropical air in Ireland. Accordingly, the first spray warning for potato blight in Ireland was broadcast on June 17, 1958. Fig. 9-5c shows the actual situation and the effective duration, expressed in days of blight weather, at each station. Obviously, the first spray warning was well timed, although

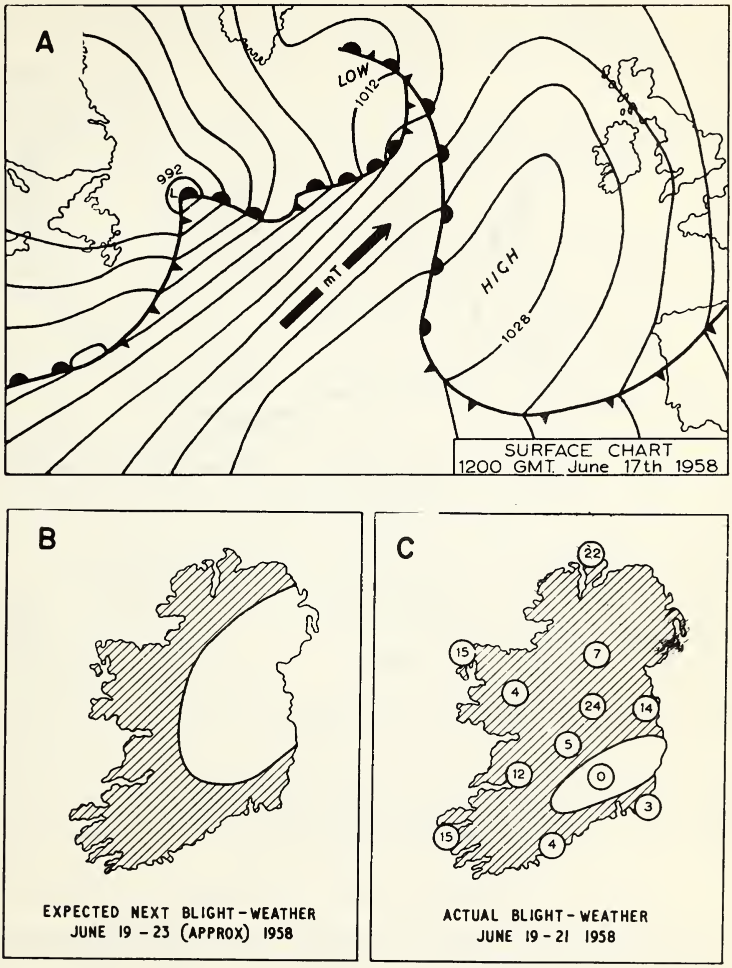
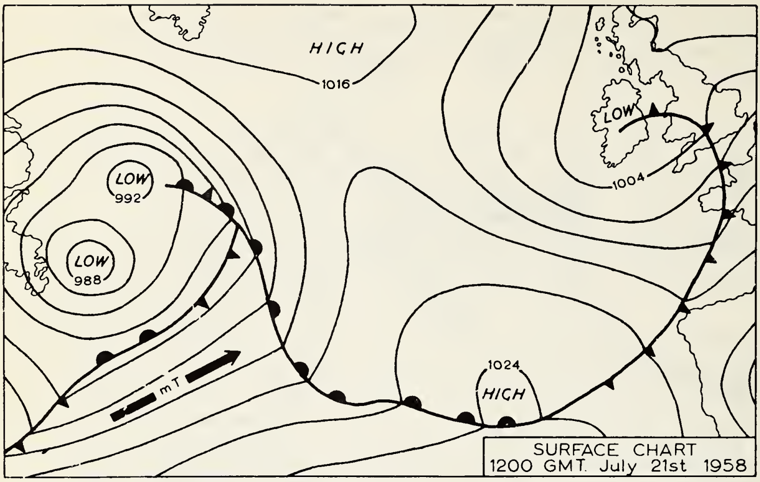


Fig. 9-5. Potato blight weather analysis, 1. Courtesy Bourke, 1959

the area predicted was somewhat off position. In Fig. 9-6, the top map is the surface synoptic chart on July 21, and the bottom map is the 300-mb chart of the previous day. A glance at the upper and surface synoptic conditions shows that the Atlantic High will move toward Ireland in a day or two, but the low pressure center will follow shortly afterward by the "upper air steering." Thus, another spray warning was issued on July 21, stressing that the 1958 blight attack in Ireland was expected to be the worst in many years. This forecast was well justified by the fact that poorly sprayed crops were completely destroyed by mid-August in that year.



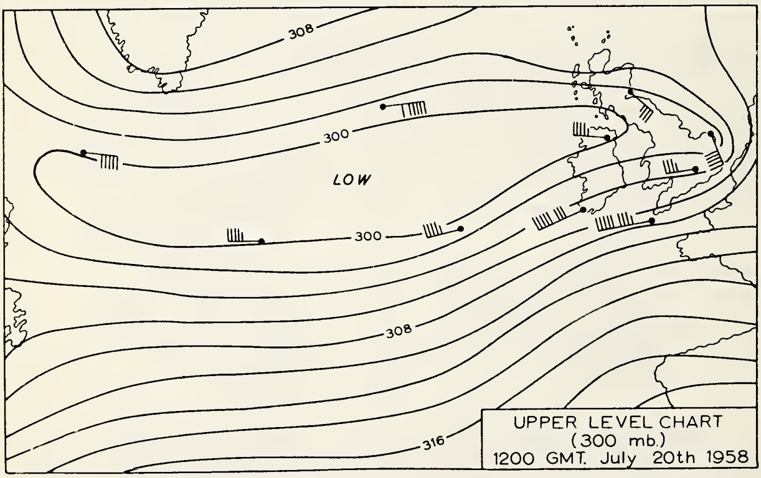


Fig. 9-6. Potato blight weather analysis, 2. Courtesy Bourke, 1959

Raeuber (1957), after examining the validity of the potato blight warning service in Gross-Lüsewitz, Germany, achieved an improvement by measuring spore catches with a specially designed spore collector. Emphasis was placed on the combination of phenological and microclimatical approaches, and such factors as atmospheric pressure, wind, humidity, temperature, light, and general weather were examined. Uhlig (1957) also examined the potato blight warning service carried out by the German Weather Service during 1954-56. He made various recommendations on the developmental sequence of potato blight, on the criteria of favorable blight weather conditions, and on the comparison of biological and meteorological observation on a large geographical area.

In Slovenia, Yugoslavia, Šikić (1956) reviewed various meteorological indices pertaining to minimum temperature and relative humidity in the prediction of potato blight. These indices have been verified by him in Slovenia through experiments.

In addition to potato blight, there are many prediction studies of various other plant diseases. For example, there are the following: the application of synoptic techniques to the dispersion of cereal rust spores, by Bourke (1958); the outbreaks of sporulation of brown rot of apples, ***Selerotinia fructigena***, by Byrde (1956); the spread of bruzone disease of rice, by Vámos (1954; see also Section 6.2.2); and many others. Byrde's findings are particularly worth mentioning. He discovered that a slow-moving, shallow low-pressure system, or a moist southwesterly air stream of tropical or subtropical origin was associated with the outbreak of brown rot of apples in England. Such weather conditions are similar to those favorable to the spread of potato blight.

The main advantages in the use of the synoptic approach are as follows: (a) It furnishes information on the future development of weather. Concepts such as cyclogenesis, upper air steering, and blocking action give clues, a few days in advance, to a major weather change. (b) It permits delineation of the geographical area of coverage of the stormy weather, generally in terms of changes in tracks and high and low intensity. And (c) effective and economical use can be made of already existing data.

Aside from the synoptic approach, the statistical approach is employed as a useful tool. For example, Salmon (1951) in Japan formulated the outbreak of rice stem borer ***Chiro simplex*** (the destructive moth) as

$$X = 23.3 - 0.537y + 0.457z, \qquad (9\text{-}1)$$

where X is the date of moth emergence, expressed in number of days before or after May 31; Y, the mean temperature in March in Centigrade; and **Z**, the date of first blossoming of cherry. His empirical formula was valid in Gumma Prefecture, Japan. Naumova (1951) in U.S.S.R. studied the intensity of mildew development in summer wheat and found the air temperature to be the most important factor of those considered. Damage caused by the mildew was less in earlier plantings when germination of the plant began at lower air and soil temperatures.

(c) Short-term warnings. This refers to a period of less than two days in advance. This type of warning can be useful in a small farming area where the facilities for preventive measures are available.

A majority of the research on pest control has been devoted to the short-term warning. To cite a few of the recent works, Poliakov (1956) in the U. S. S. R. made a forecast study of the onset of various pests, in which he used the daily mean temperature and the depth of ground freezing for the appearance of insect pests and rodents, respectively. Tinker (1952) studied the effect of maximum and minimum air temperatures on the boxelder bug, ***Leptocoris trivittatus***, in Minnesota. He used the temperature summation with a threshold temperature of 20°C, and found a correlation between the heat sum and the behavior of the bug. In 1959, Bowen & Kennedy investigated the effect of high soil temperature on legume bacteria. They found the maximum temperatures of the legume bacterial growth to be 31 to 38.4°C for clover, 32 to 32.7°C for peas, 36.5 to 42.5°C for medic, and 30 to 42°C for tropical legume of Rhizobium. They also found that 40°C is the lethal temperature for the bacteria of clover and peas.

From the results of studies such as the above, warnings may be made in terms of favorable or unfavorable environments, such as daily mean temperature, depth of ground freezing, heat sum, soil temperature, etc.

9.2.5 *Spraying weather forecast*

Whether the application of liquid or solid chemicals is made for the purposes of insect control, disease control, weed control, or fruit-thinning control, there are basic problems, such as spraying weather, effectiveness of treatment, and avoidance of hazardous effects of the chemical application on the specific crop and those surrounding it. The spraying weather forecast tends to relieve such problems.

(a) Spraying weather. To ensure the maximum effect of spraying, ideal spraying weather has to be defined. While the type of chemicals, method of spraying, and kind of operation (or the purpose of the spraying), as well as the phenological aspects of plants and pests, are important considerations, the present section emphasizes the meteorological aspects of spraying weather.

Ideal spraying weather may be defined as a combination of the following meteorological elements with suitable specifications:

(i) Vertical and horizontal winds. The horizontal wind speed, measured at a height of five or more feet above the ground of the field to be treated, should not exceed five mph for most spraying operations. In other words, the lower the wind speed, the better the concentration of the chemical on the area to be covered. At wind speeds of 10 mph, the operation is affected appreciably; at 20 mph, it becomes very difficult, and at 30 mph, it is practically impossible. It should be pointed out, however, that these figures are conditioned by vertical wind and/or atmospheric turbulence above the field. For instance, on certain days, even when the horizontal wind speed is above

5 mph, spraying may be done without causing appreciable concentration of toxics on susceptible crops of nearby fields. At other times, the horizontal wind speed can be as low as 2 or 3 mph and yet the turbulence may cause drifting of fine spray particles for a considerable distance. The effect of turbulence is seen not only in the spreading of the chemical particles, but also in the rate with which they will settle from the air. Of course, for large heavy spray particles, slightly higher wind and/or turbulence would be permissible, and vice versa for small and light spray particles. Studies of turbulent eddy transfers belong to the realm of micrometeorology and microclimatology. Theoretical and experimental investigations in this subject are numerous (see also Section 5.5.3, for turbulence measurement), and valuable studies have been presented by Brooks (1947), Latimer et al. (1947), Lowry (1951), Priestley (1956), Railston (1954), Schultz et al. (1956), Smith (1951), Sutton (1955), Vehrencamp (1955), and Waggoner et al. (1958). Particularly worth mentioning here is the formulation of equations by some of these authors, on the rate and distribution of maximum concentration of the spray particles. In principle, knowledge in atmospheric pollution control should be applicable to the chemical spraying operation (see Section 5.6.4 for air pollutant measurements). In conclusion, vertical and horizontal wind profiles and atmospheric pressure are of paramount importance to the determination of spraying weather.

(ii) Temperature and solar radiation. During the day, spray particles tend to move upward with the convective current and then drift sideways with the horizontal wind, reducing the concentration greatly. At night, the reverse condition exists: the convective current ceases and descending air usually prevails. Moreover, when the chemicals are falling at or below the temperature inversion level, and when the wind speed is under 5 mph, the particles are usually trapped and are not likely to drift far. It follows, therefore, that the best time for spraying is at night or in the early morning, provided it does not start within 30 minutes after sunset, when the surface soil temperature is still too high. Also, it should not be continued beyond five hours following sunrise, and no spraying is recommended when the air temperature within 10 feet of the ground reaches 80°F, due to high evaporation loss of the chemicals (see Section 4.3.2). Kennerly (1952) has reported heavy evaporation loss of airplane-sprayed chemicals at high temperature and radiation.

(iii) Humidity and precipitation. When the air surrounding a crop is saturated with water vapor, some condensation of moisture on the leaves is likely to occur, usually in the form of dew. Dew can act as a "sticking agent," particularly for dust particles. This again suggests night or early morning as the best time for spraying. Drifting fog or rain, on the other hand, acts as a "washing agent," particularly rain occurring within two or three hours after spraying. Rain occurring two to three hours previous to spraying may dilute the chemicals, but the effect is not serious.

(b) Effectiveness of treatment. Generally the above weather factors affecting the economical use of chemicals will naturally determine the effectiveness of treatment, depending upon the part of the plant treated. For example, turbulence, although an unfavorable factor for the effectiveness of insecticides, in that it reduces the concentration of chemicals on the top of the leaf, will usually promote the work of fungicides by distributing the chemicals to the underside of the leaf, where fungi grow. Moreover, the duration of treatment and change in weather during or following treatment will influence the effectiveness of chemicals used.

(c) Avoidance of hazardous operations. Reports on crop damage brought about by wind drift of spray particles are numerous, and have led to spray control legislation in California and some other states. In any spraying operation, drifting of material which is poisonous to neighboring crops, or animals and human beings, should be prevented insofar as possible. It is clear that turbulence, wind direction, and wind speed are the major factors in such considerations. In addition, the topography and obstructions (e.g., wind shelters, forests, and houses) should also be taken into account.

In conclusion, the spraying weather forecast is essentially a short-term forecast. It combines macrometeorological aspects with the micrometeorological operation. Smith (1951) has studied the forecasting of micrometeorological variables as related to large-scale weather patterns. His technique is recommended for spraying weather forecasting.

9.2.6 *Livestock weather forecast*

Problems of weather influence on livestock, particularly grazing animals, are generally discussed under the topics of livestock introduction, production, and feed supply, breeding, reproduction, and infective and parasitic diseases.

Livestock introduction associated with acclimatization is a subject of applied climatology. It is regional in nature, and therefore a knowledge of physiological response in animals (see Section 3.3), in combination with regional climatological statistics, would determine the possibility of introduction. Areas where a certain livestock fails to acclimatize and maintain a satisfactory production level are not suitable for the introduction of that specific livestock. Weather forecasts relating to the introduction of new varieties or species to a certain area are essentially long-range predictions, and are made in terms of climatological probability.

The quality and productiveness of livestock depend upon the quality and amount of feed supply, which in turn is affected by the weather. Hence both short-range and extended weather forecasts may be said to have an indirect relation to the productivity and nutrition of livestock. Sometimes, a favorable weather for plant growth and development can cause a disease outbreak, provided that these plants are appropriate food for pests.

As has been mentioned previously (Section 3.3.2), high temperature and intense light of long duration reduce the reproductive capacities of animals through reduction of fertility, semen quality, and sperm production. On the other hand, the fertility of both male and female animals is greatly increased by cool air, low light intensity, and short day-length. These responses, of course, vary with varieties and species of animals. It follows, then, that a knowledge of the effect of weather on livestock is necessary for an estimation of the rate of reproduction.

Although there are a number of valuable findings available from studies of animal-weather relationships, particularly from laboratory experiments, little, if any, is known of actual use of such findings in forecasting livestock weather. Nevertheless, some systematic techniques have been developed for animal disease prediction.

Facial eczema, a seasonal disease of sheep, cattle, and horses, is caused by a fungus, ***Sporidesmium bakeri***, which is saprophytic on ryegrass. In New Zealand, this disease is most frequently observed in an autumn following a hot, dry summer; the outbreak begins with a new growth of dried-up pasture after a rainfall of 0.5 inch or more. It has never been observed in a late, cold autumn, and rarely after a cool, wet summer. The warning system maintained by the New Zealand Department of Agriculture is based on the weekly temperature deviations from the normal of the preceding week and the rainfall during November through April (New Zealand's summer and autumn). Mitchell et al. (1959) attempted to improve the accuracy of warning by considering soil temperature, soil moisture, and minimum grass temperature. They defined the first approximation of the outbreak as either 62.5°F or more above average November soil temperature at 8-inch depth, or 1.5-inch soil moisture deficit by the end of November. The average December soil of 65°F or more, with no soaking rain, or minimum grass temperature of 54°F and above with adequate rainfall are considered more definite signs of outbreak.

Grass tetany, another sheep and cattle disease, causes a drop in the magnesium content of the blood of grazing cattle and sheep, and is characterized by suddenly developed tetanic convulsions, frequently causing death without symptoms of disease. Allcroft (1947) found that this disease has a marked seasonal rhythm, with low magnesium levels occurring during the following weather conditions: (1) mean minimum temperature below 42°F, (2) heavy rain and wet soil, (3) wind force between 6 and 8 on the Beaufort scale preceding the wet spell, (4) an occurrence of hail, sleet, or snow, and (5) little sunshine. Thus cold, wet, and windy weather forecasts could be a guide to occurrence of clinical cases of grass tetany in grazing cattle and sheep.

Some fundamental considerations in animal disease forecasting, as pointed out by Allcroft (1947), Mitchell et al. (1959), Ollerenshaw et al. (1959), and Crawford (1962), are (1) more reliance upon field tests rather than laboratory experiments, (2) environmental effects on fodder plants and host plants, as well as poisonous plants and toxic fungi, (3) immunological status of the population of animals at risk, and (4) the species of animal as related to the kinds of diseases.

9.3 SOME RECOMMENDATIONS FOR OPERATIONS FORECASTS

Weather forecasts for agricultural uses besides those already mentioned may be classified as "operations forecasts," which may be concerned with warm and cold spells, wet and dry spells, and severe weather such as hailstorms, tornadoes, and thunderstorms.

9.3.1 *Warm and cold spell*

The Extended Forecast Branch of the U. S. Weather Bureau issues monthly mean temperature predictions. The information is given in such general terms as "normal," "above normal," "much above normal," and the like. Such predictions, if accurate, could serve as guides to planning farm operation. For example, a forecast of "much below normal" temperature in spring will allow farmers and growers to select short-season crops for planting, since the frozen soil could hamper plowing and seeding, and cause a delay in planting. Or, change of feed crop from corn to sorghum may be necessary if summer is predicted as hot and dry. In autumn, harvest of an immature crop may be required if an early frost has been predicted. In winter, when planning animal house heating, severe weather warnings should be taken into consideration. However, extended forecasts in such general terms often conceal daily anomalies which have important effects upon the responses of plants and animals; they indicate neither a specific point of occurrence nor a specific temperature.

Combining probability climatological forecasting with extended forecasting is more promising for effective farm operations provided the following conditions are satisfied: that the climatological data were accurately observed and covered a sufficient length of time; that the observation site was representative; that a short-term probability of the single climatic element (namely, one- to five-day interval) has been computed; and that the short-term daily weather forecasting is considered when appropriate.

Various attempts have been made at probability forecasting of daily maximum and minimum temperatures, particularly the minimum temperature forecast. Other subjects relating to minimum temperature forecasting are frost forecast, frost penetration forecast, minimum soil temperature forecast, and the like.

For illustration, a brief account of probability statistics on warm and cold spells during the growing season in Wisconsin is given below. Wang (1958) has prepared an IBM computing program on the occurrence of warm and cold spells during May through October for a period of 25 to 50 years at six selected stations in Wisconsin. He defined a warm spell as a period of no more than two months' duration during which the daily maximum temperature remains at or above a certain specific temperature level. The temperature levels used are 0°, 32°, 40°, 50°, 60°, 70°, 80°, 88°, 96°, 104°, and 112° F. Similarly, a cold spell is defined as a period when the daily minimum temperature remains at or below a certain level. The levels used for the minimum temperature are 0°, 16°, 24°, 28°, 32°, 40°, 50°, 60°, 70°, 80°, and 90°F. The time spans of spells, cold or warm, are 1, 2, 3, 4, 5, 6, 7, 10, 14, 21, 30, and 60 successive days. An overlapping or cumulative system is adopted for the computation of the occurrences of spells. In the five-successive-day spell, for example, if the daily maximum temperature is at or above 80°F, it is counted as five cases of one-day warm spells, four cases of two-day warm spells,[9] three cases of three-day warm spells, two cases of four-day warm spells, and one case of a five-day warm spell at or above 80°F. The results for Darlington, Wisconsin (1901-1951) are listed in Table 9-3, in which the frequency distribution of warm (or cold) spells is expressed in the units of "per year," "per 10 years," or "per 100 years." For example, in the first row (104°) of Table 9-3a, the first figure is interpreted as "there have been only five cases in 100 years of 104° warm spells of one day or more duration in the months of May and June at Darlington, Wisconsin." Also, in the last row of Table 9-3a (32°), the last figure indicates there have been 12 cases in 10 years of 32° warm spells of 60 days' or more duration in the months of September and October at the same station.

There are many methods, of course, for the computation of warm and cold spells. Whatever method is employed, the forecaster should consider the statistical results in conjunction with the current weather conditions in making the probability forecast. To be sure, neither extended nor probability forecasts fully satisfy the requirements of farm operations. More research in this area is urgently needed.

[9]The first case is the first two days; the second case is the second and third days, and so on until the entire four cases are counted. Note the overlapping, such as the second day being counted in both the first and second cases. This overlapping system has been found more effective in crop response studies than the non-overlapping system.

Table 9-3a. Frequency Distribution of Warm Spells During the Growing Season at Darlington, Wisconsin, 1901-1951

	May-June												
Period	1	2	3	4	5	6	7	10	14	21	30	45	60
Temp. °F													
104	5/100	2/100											
96	90/100	41/100	21/100	11/100	7/100	2/100							
88	62/10	38/10	23/10	14/10	94/100	62/100	41/100	5/100					
80	22/1	16/1	11/1	86/10	67/10	52/10	41/10	20/10	78/100	7/100			
70	43/1	36/1	31/1	26/1	23/1	20/1	17/1	12/1	71/10	34/10	13/10	9/100	
60	56/1	52/1	48/1	45/1	42/1	39/1	37/1	31/1	24/1	17/1	98/10	30/10	18/100
50	60/1	58/1	56/1	54/1	52/1	50/1	48/1	43/1	37/1	29/1	19/1	78/10	57/100
40	61/1	59/1	57/1	55/1	54/1	52/1	50/1	46/1	41/1	32/1	22/1	11/1	99/100

	July-August												
Period	1	2	3	4	5	6	7	10	14	21	30	45	60
Temp. °F													
112													
104	14/100	5/100	2/100										
96	31/10	17/10	97/100	64/100	44/100	32/100	23/100	9/100					
88	18/1	12/1	76/10	51/10	36/10	27/10	22/10	12/10	51/100	5/100			
80	45/1	38/1	32/1	27/1	23/1	19/1	17/1	11/1	72/10	36/10	13/10	28/100	
70	61/1	58/1	55/1	52/1	50/1	47/1	45/1	39/1	33/1	24/1	15/1	56/10	48/100
60	62/1	60/1	58/1	56/1	54/1	52/1	50/1	45/1	39/1	30/1	21/1	10/1	15/10

	September-October												
Period	1	2	3	4	5	6	7	10	14	21	30	45	60
Temp. °F													
96	31/100	14/100	5/100										
88	25/10	15/10	92/100	52/100	31/100	24/100	16/100						
80	10/1	67/10	44/10	30/10	19/10	14/10	11/10	52/100	21/100				
70	29/1	23/1	18/1	14/1	12/1	96/10	78/10	43/10	19/10	28/100			
60	47/1	42/1	38/1	34/1	31/1	28/1	25/1	19/1	13/1	57/10	11/10		
50	57/1	54/1	52/1	49/1	47/1	45/1	43/1	38/1	31/1	22/1	13/1	32/10	14/100
40	60/1	59/1	57/1	55/1	54/1	52/1	51/1	46/1	41/1	32/1	23/1	11/1	10/10
32	61/1	60/1	58/1	57/1	55/1	54/1	52/1	48/1	42/1	34/1	24/1	12/1	12/10

Table 9-3b. Frequency Distribution of Cold Spells During the Growing Season at Darlington, Wisconsin, 1901-1951

	May-June												
Period	1	2	3	4	5	6	7	10	14	21	30	45	60
Temp. °F													
80	61/1	59/1	57/1	55/1	54/1	52/1	50/1	46/1	41/1	32/1	22/1	11/1	99/100
70	60/1	58/1	55/1	53/1	51/1	49/1	47/1	42/1	36/1	27/1	17/1	70/10	48/100
60	50/1	44/1	39/1	35/1	31/1	28/1	26/1	19/1	13/1	69/10	21/10	5/100	
50	30/1	22/1	17/1	13/1	10/10	76/10	59/10	26/10	78/100	7/100			
40	12/1	63/10	33/10	18/10	97/100	62/100	37/100	2/100					
32	32/10	92/100	30/100	11/100	5/100	2/100							
28	16/100	11/100											
24	16/100												

	July-August												
Period	1	2	3	4	5	6	7	10	14	21	30	45	60
Temp. °F													
80	62/1	60/1	58/1	56/1	54/1	52/1	50/1	45/1	39/1	30/1	21/1	95/10	14/10
70	59/1	55/1	51/1	48/1	44/1	41/1	39/1	31/1	24/1	15/1	78/10	28/10	34/100
60	37/1	27/1	20/1	15/1	11/1	83/10	63/10	29/10	12/10	30/100	2/100		
50	12/1	50/10	23/10	97/100	48/100	38/100	18/100	5/100					
40	94/100	34/100	7/100	2/100									
32	5/100												

	September-October												
Period	1	2	3	4	5	6	7	10	14	21	30	45	60
Temp. °F													
80	61/1	60/1	58/1	57/1	55/1	54/1	52/1	48/1	42/1	34/1	24/1	12/1	12/10
70	61/1	59/1	58/1	56/1	54/1	53/1	51/1	47/1	41/1	33/1	23/1	11/1	11/10
60	56/1	51/1	48/1	45/1	42/1	40/1	38/1	32/1	26/1	18/1	10/1	28/10	9/10
50	42/1	35/1	29/1	25/1	21/1	19/1	16/1	10/1	54/10	14/10			
40	24/1	16/1	12/1	85/10	64/10	48/10	37/10	14/10	38/100	5/100			
32	11/1	60/10	34/10	18/10	10/10	57/100	35/100						
28	57/10	24/10	11/10	54/100	21/100	5/100	2/100						
24	27/10	87/100	26/100	5/100									
16	33/100	2/100											

9.3.2 *Wet and dry spells*

Wet and dry spells have already been defined in Section 4.4.1a. However, the best definition should be related to the amount of available soil moisture required by a specific plant. When the soil moisture is excessive, a retarding effect is produced, and the period is called a wet spell. When there is too little soil moisture, a limiting effect appears, and the weather is called a dry spell. In the extreme cases, a wet spell becomes a "flood," and a dry spell a "drought.. Since soil moisture has not been adequately measured, rainfall is commonly employed instead.

Wet and dry spell forecasting is similar to that described in the previous section. Since rainfall forecasting is a popular subject of research, literature citations are numerous. Subject areas covered include flood prediction, drought prediction, the probability approach to dry or wet spells, and rainfall frequency, as well as the rate of evapotranspiration.

9.3.3 *Severe weather*

In meteorology, "severe weather" refers to any strongly disturbed state of the atmosphere affecting the earth's surface, and may be generally termed "storm." The study of storms will vary in its emphasis according to the interest of the investigator. For a hydrologist, "storm" alludes primarily to the space- and time-distribution of rainfall over a given region. For an agriculturist, a "storm" is a transient occurrence identified by its most destructive or spectacular aspects, such as hailstorms, rainstorms, snowstorms, and windstorms. Some notable storms occasionally happen, as blizzards, icestorms, sandstorms, and duststorms in rather localized areas. For a synoptician, a "storm" is a complete individual disturbance identified on synoptic charts as a combination of various meteorological elements, such as pressure, wind, clouds, and precipitation of all kinds. Emphasis is placed on its initiation (or area of development), its direction and rate of movement, its intensity, and its dissipation.

The size of storms may range from as small as tornadoes and thunderstorms to as large as extratropical cyclones, with tropical cyclones (or hurricanes) in between. In view of the various dimensions of circulation patterns, namely general circulation, secondary circulation, and tertiary circulation, the size of disturbances may be global, of the area of a few states, or restricted to a specific locality. Considering the temporal variability of the atmospheric flow over the entire earth resulting from seasonal changes and from the effects of transient cyclones and anticyclones, the general course of easterlies and westerlies would be modified, and the strength of "storms" associated with them will be either intensified or weakened. The secondary circulation involves the tropical cyclone (or hurricane), the extratropical cyclone (or extratropical storm), and the anticyclone. The tertiary circulation consists of local wind, tornadoes, dust devils, thunderstorms, etc. In this section, the forecast of severe weather will be illustrated by that of tornadoes and hailstorms. The physical mechanisms for the formation of hailstorms, thunderstorms, and tornadoes are somewhat similar in nature. For detailed information on forecasting of storms other than tornadoes and hailstorms, the reader may refer to textbooks on synoptic meteorology.[10]

Tornadoes have long been recognized as a product of certain specific large-scale synoptic situations (Finley, 1885), with a short-term effect.[11] Due to their frequency, severity, and large geographical coverage, much attention has been paid to tornadoes, and particularly to tornadic forecast. Many publications on tornadoes and related storms are available and have been collected and reviewed by Koschmieder (1943) and Kramer (1950). Enormous reports have been published on the disastrous effects of tornadoes on agricultural production, but only a few studies have been executed on the relation of tornadoes and agricultural industry.

In the United States, much research on tornadoes, particularly on forecasting, has been done by Fawbush and his Air Force collaborators in the Weather Bureau Severe Weather Forecast Center, Kansas City, since 1948. A brief review of their work is in order.

In 1951 Fawbush and his collaborators made an extensive investigation of tornadoes in the United States prior to 1949. They found that tornado situations developed only when the synoptic situation met all of the following six conditions:

(a) a layer of moist air near the earth's surface must be surmounted by a deep layer of dry air;

(b) the horizontal moisture distribution within the moist layer must exhibit a distinct maximum along a relatively narrow band (i.e., a moisture wedge or ridge);

(c) the horizontal distribution of winds aloft must exhibit a maximum of speed along a relatively narrow band at some level between 10,000 and 20,000 feet, with the maximum speed exceeding 35 knots;

[10]See S. Petterssen, 1956, Weather analysis and forecasting, 2nd ed., Vol. I, Motion and motion systems, 44 pp., and Vol. II, Weather and weather systems, 284 pp., McGraw-Hill Book Company, Inc.; W. J. Saucier, 1955, Principles of meteorological analysis, University of Chicago Press, 438 pp.; P. D. Thompson, 1961, Numerical weather analysis and prediction, The Macmillan Co., 170 pp.; C. L. Godske, T. Bergeron, J. Bjerkness, & R. C. Bundgaard, 1957, Dynamic meteorology and weather forecasting, American Meteorological Society, 800 pp.

[11]The duration of tornadoes was studied by Battan (1959) in terms of their path length and speed of movement. It was found that the average duration is of the order of four minutes. Battan recognized that a reported duration of more than 16 minutes should raise the suspicion that more than one tornado funnel may have been involved. When over 40 minutes, it is pretty sure that more than one tornado funnel exists. Most frequently, tornadoes travel less than one mile. The individual tornado vortex is about two miles in diameter, and its upper limit is about 20 miles. However, Battan's observations are challenged by Fujita's later report that the lifetimes of well-known tornadoes are mostly 40 minutes (cited from Byers, 1962).

(d) the vertical projection of the axis of wind maximums must intersect the axis of the moisture ridge;
(e) the temperature distribution of the air column as a whole must be such as to indicate conditional instability;
(f) the moist air layer must be subjected to appreciable lifting.

With the above empirical rules it is possible to forecast the development of tornado conditions about eight hours in advance.

The seasonal occurrence of tornadoes and tornado days, as well as their geographical distribution, have also been examined. The primary maximum in the United States was found to be about 600 miles east of the mean ridge of the Rocky Mountains, with a secondary maximum about 100 miles east of the mean Appalachian ridge. In the U.S., over two-thirds of all tornadoes were reported during March through July, with about one-seventh falling in the period from October through February.

In 1954, Fawbush & Miller classified the tornadic air mass in the U.S.A. According to 286 pertinent soundings, they were able to identify three kinds of tornado-producing air masses. Type I is the most common, while Type II and Type III are rather rare; the characteristics are given in Table 9-4.

Aside from the Fawbush & Miller technique, the local heating approach (Whiting, 1957), the Showalter tornado index (1953), the jet-stream method (Lee & Galway, 1956), the radar technique (e.g., AMS Committee on Radar Meteorology, 1955; Staats & Turrentine, 1956; Schuetz & Stout, 1957); the aircraft weather reconnaissance (e.g., Beebe, 1957), Sferic detection (Jones, 1952; Dickson, 1956), and the meteorological television satellite (Hoecker, 1960; Whitney & Fritz, 1961) are valuable recent detection developments or establishments in tornado forecasting. No attempts are made here to describe these methods; however, it appears that the scientific observation of tornadic development, as by radar and satellite vehicle methods, is a very promising approach. It has been found that the identification of the first intense and cumulus-convective activity is possible on the satellite photograph by the appearance of the isolated bright cloud mass. Such a cloud mass indicates the area of tornadic development. Caution must be taken, however, that the interpretation of such clouds or cloud mass is done in the light of geographical location. That is to say, the climatological region and the existing synoptic situation should be scrutinized as potential producers of severe local storms such as tornadoes and hailstorms. In the use of the radar technique, the tornado is frequently detected on the Plan Position Indicator scope in the shape of a "figure 6" in the southwest sector of the storm. However, this particular pattern has not been noted in all radar-observed tornadoes.

Hailstorms are sufficiently common to most agricultural areas that related preventive measures are presented in Section 12.4.1. The techniques of hailstorm forecasting are somewhat similar to those of tor-

Table 9-4. Comparison of the Weather and Occurrence of the Three Tornado-Producing Airmass Types

	Type I (230 soundings)	Type II (38 soundings)	Type III (18 soundings)
Most common region	Great Plains	Gulf Coast	Pacific Coast
Vertical air structure	Dry over moist stratum, conditionally and convectively unstable	Warm, moist, conditionally unstable	Cold, moist, conditionally unstable
Weather sequence changes	Rapidly	Slowly	Slowly
Mammatus associated	Always	Seldom	Nearly always
Associated severe weather	Thunderstorms, windstorms, hailstorms	Thunderstorms	Thunderstorms, windstorms
Height of Wet-Bulb-Zero above terrain	Near 8,000 feet	High	Low
Most common type of associated front	Cold	Warm	Cold
Vertical wind shear, with altitude	Increase and veer	Decrease and veer	Increase and veer
Probable vertical current in tornado core	Downrush	Uprush	Downrush
Number of tornadoes in system	Often in families or groups	Usually isolated	Usually associated with funnels that do not reach ground
Speed of tornado	Usually rapid	Usually slow	Usually rapid
Path of tornado	Often long and wide	Short and narrow	Short and narrow
Life of tornado	Long	Short	Very short

Fawbush & Miller, 1954

nado forecasting. Dynamic considerations, air mass identification, radar, and aircraft weather reconnaissance, are used in hailstorm forecasting. From the amateur's standpoint, the appearance of cumulonimbus clouds is usually associated with lightning, thunder, or hail. With cumulonimbus virga, thunderstorms and sometimes hailstorms are expected, but with cumulonimbus tuba or mammatus, tornadoes might be observed. Tornadoes, squall lines, thunderstorms, and hailstorms are all initiated by extremely strong uprising convective currents, as has been pointed out previously.

The size of hailstones is of particular interest to farmers and growers in relation to crop damage. Fawbush & Miller (1953) sought to forecast hailstone size with a so-called "hail-graph." In their study of 274 upper-air soundings where hailstones of noticeable size were observed, 91.6 percent indicated a wet bulb freezing level located between 5,000 and 12,000 feet above the terrain. The concentration of larger hailstones was detected near the 8,000 foot freezing level. Also, the Showalter Stability Index Computation Chart, which was originally used for thunderstorm forecasting, can be used for the prediction of hailstone sizes. His index has been proved by several investigators to be a useful tool.

In southern France, Dessens (1960) claimed that the presence of a jetstream at 6,000 and 12,000 meters is a factor which transforms a thunderstorm into a destructive hailstorm, and that large shears in vertical wind speeds are conducive to the formation of hail. However, Ratner (1961) found from his climatological analysis that Dessens' theories do not apply in the United States.

In the United States, the theoretical and experimental study of local storms has been greatly stressed, particularly after the large thunderstorm project directed jointly by the Air Force, Navy, National Advisory Committee for Aeronautics, and Weather Bureau, in 1946-47. In recent years, various models of severe convective systems, such as hail-cloud and tornado-system models, have been developed and verified with varying degrees of success. Research in modeling, together with other predicting techniques, has made a great contribution to severe storm forecasting. A brief summary of some outstanding studies is in order.

By combining the photograph taken from a high altitude aircraft with Tiros (the television satellite) and radar echoes, Fujita[12] presented a three-dimensional picture of the surface severe weather conditions in terms of the anvil outline, convection cores, temperature breaks, and pressure oscillations. In the study of mesometeorology, he found that the entrainment rate of a convective system varies inversely with the diameter of the system. He and Newton introduced the concept of "nonhydrostatic pressure effects" for the better understanding of models designed by various investigators, namely Browning & Ludlam's model. Newton emphasized the importance of horizontal differential advection. From aircraft data, Malkus developed methods to compute vertical air movements and determined turbulent exchange in terms of heat, moisture, and momentum between the ocean surface and the air above it. Her theoretical model on warm-core systems of hurricanes, known as "warm towers of hurricane," as well as her extensive investigations of cumuli, contributes a great deal to severe weather research. Byers has differentiated two convective systems: (a) the self-perpetuating type, such as the warm-core hurricane prevailing over the tropical ocean, and (b) the self-destructive type, such as the cold-core severe storm prevailing over the continent. This explains why the

[12]Detailed information on the studies cited in the remainder of this chapter can be obtained from the following sources: Bull. Am. Meteorol. Soc., Vol. 42, No. 5 (May 1961), pp. 360-370; Vol. 42, No. 12 (Dec. 1961), pp. 840-851; Vol. 43, No. 6 (June 1962), pp. 239-242; and the monograph entitled "Conference on Severe Storms," Feb. 13-15, 1962, Norman, Oklahoma (to be published by the A. M. S.).

former may last for days, the latter only a few hours.

Vonnegut & Rathbun indicated that tornadoes, being highly electrified, may be triggered or intensified by electrical and/or magnetic field effects. Kasemire reported that more radio statics (sferics) are received from tornado areas than from ordinary thunderstorm areas. The Vortex Laboratory at the University of Oklahoma Research Institute is designed to study the effect of electrodynamics on vortices, in order to determine means of predicting and controlling possible effects, as reported by Wilkins. Both theoretical and experimental studies on the electrostatic field and the coalescence of water drops have been conducted by Lindblad & Semonin of the Illinois State Water Survey.

On the subject of hailstorms, List, Hallett & Douglas have revealed on various occasions the nature of the updraft as compared with the dry and wet growth of the hailstone. As far as the amount and intensity of rainfall are concerned, there is no indication of a good correlation with hailstone size. Water storage of hail clouds is another aspect of investigation. The Atlas satellite data have shown that small dry hail scatters less than wet hail, up to a diameter of the order of magnitude of wavelength in microns. From this point up, the opposite is true. In other words, according to the conventional definition of hailstone (i.e., 5 mm or more), dry hail is a better scatterer than wet.

As indicated in Section 5.4.6, Schleusener & Jennings, in their observation of the impact damage of hail on the hail indicator, found that the stone of less than half an inch diameter has the greatest impact. Based upon measurements of hailstone density and drag coefficients, Foster has constructed a new hailstone terminal velocity table, in which the vertical wind velocity is computed from horizontal wind convergence. By incorporating his equation for the vertical wind velocity with the buoyancy equation, it would be possible to predict hailstone size.

As mentioned earlier, the contributions of such studies as these are very important to the improvement of severe storm forecasting, but they are by no means complete. Also vitally important is the improved instrumentation which makes possible accurate and reliable observation of the physical characteristics within a storm.

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CHAPTER 10

Water Management

In this chapter and the following chapters, emphasis is placed upon various applications of the concepts introduced thus far. Application is the final goal of the agrometeorologist, for without it the science of agrometeorology cannot be complete. Water management is a common major application which includes conservation, irrigation, and drainage. It has long been recognized that water is the major determining factor in agricultural production. Of all environmental factors, such as carbon dioxide, temperature, light, and wind, water has been the most effectively controlled in the natural field. For improvements in the management of water, agricultural engineers are concerned with the duration, intensity, and time of irrigation, as well as with methods of water drainage. Soil scientists deal with water conservation and erosion control through soil management. Agronomists and horticulturists attempt to improve cultural practices so as to prevent the loss of moisture by evaporation and runoff. Plant breeders develop hybrids suited to dry farming. Hydrologists study the formation of water, it's behavior and its utilization, and meteorologists investigate the origin and formation of water. All these aspects of the water management problem should be considered by the agrometeorologist. Although the actual field application is mainly in the hands of the engineer, the role of the agrometeorologist is to facilitate effective planning of water management, particularly in relation to the improvement of agricultural crop production.

The topic of water has been dealt with in various previous chapters, and a brief review is in order. Water as a physical medium of plants and animals has been described in Section 2.1.1c, and its physical processes in Section 2.2.2. The responses of livestock and domestic fowl to the presence of water have been discussed in Section 3.3.2b, and the responses of crops to air humidity and to soil moisture have been investigated in Sections 4.3 and 4.4, respectively.

The movements of water and its vapor were presented in Section 4.5.2, and the measurements of water were given in Section 5.4. Section 6.4.1 deals with phenological events and water relationships, and Sections 7.4 and 7.5 treat hydroclimatic units and methods of analysis and synthesis with respect to the hydrofield. Prediction of crop events as related to moisture was covered in Chapter 8, and forecasting of rainfall, dew, fog, relative humidity, and soil moisture has been mentioned in Chapter 9. The present chapter deals with agricultural management of water in its three phases.

The water economy of a farming area can be controlled mainly (1) by reducing the loss of water, or (2) by supplying water to the area. The loss of water can be reduced by mulching, sheltering, fencing, and, more effectively, by chemical suppression of evaporation. Addition of water, on the other hand, is achieved primarily by various methods of irrigation. Another aspect of water management is the control of excess water by drainage. The major purpose of drainage is to improve soil aeration by increasing the rate of infiltration and percolation. Fig. 4-21, "The Hydrologic Cycle," describes various processes of water loss and gain in a layer of soil. Water loss from farm land takes place through evaporation, transpiration, percolation, runoff, and drainage; water gain, through precipitation, irrigation, capillary action, seepage inflow, condensation, and sorption. The reader should keep in mind all of these processes of gain and loss when considering methods of water management.

10.1 MOISTURE CONSERVATION

In principle, the purpose of soil water conservation is either to minimize the escape of water from a given area, or to collect water from natural sources and direct them to that area. This also holds true for the conservation of water in plants.

10.1.1 *Mulching*

In a broad sense, mulches are all those substances which cover and are allowed to remain on the soil surface in order to accomplish certain agricultural purposes. In a narrow sense, mulches are those materials generally used for the prevention of water loss caused by evaporation from the soil surface and by transpiration from weeds. The application of mulches is a common practice in agriculture.

Mulching is also practiced for the reduction of surface runoff, soil erosion, capillary effect, and soil moisture depletion. Other effects of mulching, either beneficial or harmful to crops, are the stabilization of soil temperature, wind speed reduction, attenuation of radiation, and fertility reduction. In short, mulching alters the physical and chemical properties of at least the topsoil and sometimes the subsoil. Its influences depend upon the physical environment of the area concerned, the type of material used, and the method of application. Further discussion of effects of mulching on soil moisture, evaporation, runoff, infiltration, and the like will be given in Section 11.1.4. The influences of mulching on the radiation field are described in Section 11.1.1; that on wind in Section 11.1.3; and that on the thermal field in Section 11.1.2.

Both natural and artificial materials are used in mulching. Snow cover is a good example. Sod and other plants may also be designated as natural mulches. A number of artificial materials are commonly employed for mulching: paper, polyethylene sheet, stubble (or straw and plant residue), manure, aluminum foil, sawdust, litter, and even soil. When soil is used for mulching, it is called dust or soil mulching; when organic matter is employed, it is organic mulching. Dust or soil mulches act as a thermal insulator, reduce capillary action, and in turn keep surface soil moisture from evaporating. An organic mulch is a good absorber of short wavelength radiation, and also a good insulator of the heat exchange between air and soil. The term "ground cover," instead of "mulch," is generally used in non-agricultural literature. It may include the application of coloring materials to alter the albedo of the soil surface, and application of chemicals to suppress evaporation from the soil surface. The latter practice will be discussed in Section 10.1.4. Increasing the infiltration rate of various types of soil by mulching is an effective farm operation when drainage is needed; this will be discussed in Section 10.3. Following are some examples of research done on mulches.

Smith, in 1931, discussed at length the effect of paper mulches on soil temperature, soil moisture, and yield of a number of crops. Duley & Russel (1939) considered stubble mulching as a method of rainfall and soil moisture conservation, and in 1942, they studied the effect of stubble on soil erosion and runoff. Kenworthy (1953) in Michigan investigated depletion of soil moisture in a mature apple orchard under the soil mulch system. Turk & Partridge (1941; 1947) also investigated the effects of various mulches on the moisture loss from soil. McCalla & Duley (1946) observed the maximum and minimum soil temperature of straw mulched cornfields at 1" depth. They reported that when two and eight tons of straw were used per acre, the weekly mean maximum temperature dropped from 88°F to 80°F and 74°F, respectively. The minimum temperature for both cases was found to increase from 61°F to 68° F. The effects of crop residues on erosion control and grain yields under Idaho dry-land conditions have been studied by McKay & Baker (1946). Mooers et al. (1948) made a comparative study of wheat straw, farmyard manure, and the *Lespedeza sericea* hay for the conservation of soil moisture and the production of nitrates. Goodman (1952) described the effectiveness of precipitation in orchard mulch. Denisen et al. (1953) studied the effect of summer mulching on the yield of everbearing strawberries in terms of soil moisture and temperature.

In summary, mulching is considered beneficial to crop growth with respect to (a) reducing evaporation and transpiration, (b) decreasing runoff and percolation, and in turn increasing infiltration, (c) promoting sorption and condensation, and (d) preventing soil compaction from the impact of precipitation. Mulching can be quite harmful when the activity of soil microbes is restricted either by lowering of temperature or by depletion of nitrogen; in the latter case, the bacterial activity is concentrated more in the organic mulch than in the soil itself.

10.1.2 *Shelterbelt*

A shelterbelt (shelter hedge or windbreak) is usually a belt of trees or shrubs so planted to serve as a wind barrier. By and large, a series of shelterbelts, if designed to give protection to crops over a large area, should be maintained at intervals of about 25 times the height of the trees. In the U. S. A. the general practice is to plant a moderately dense belt of conifers and deciduous trees 15 to 30 feet wide, containing at least three rows of trees perpendicular to the direction of prevailing winds. Weeds may be used as a shelter hedge for the protection of vegetable crops, and are just as effective as trees or shrubs, or even more so, depending upon the adaptation of weeds to the locality concerned. Sometimes a fence, a wall, or other obstructions are also used as shelter hedges.

The microclimate of the sheltered area is very much different from that of unsheltered areas, and as far as the moisture condition is concerned, it is greatly affected by wind and temperature.

The wind, both vertical and horizontal, together with turbulence, is the first factor to be considered in the study of the microclimatic effects of a shelterbelt. Bates, in 1911, presented nine diagrams of "efficiency curve" for various classes of windbreak. He found, from his study of cottonwood groves, that with wind speeds of 5, 10, 15, and 20 mph, the protective efficiency of the grove was higher with increased wind speed. Also, it was found that the size of the protected area had much to do with differences in the protective efficiency at wind speeds of 5 to 10 mph, but made little difference at wind speed of 15 to 20 mph. When both the size of the protected area and the wind speed are held constant, the protective efficiency was found to be proportional to the height and density of the windbreak. Denuyl (1936) observed the wind-reducing effects of windbreaks in relation to their size, and found that with a four-row Norway spruce windbreak, wind speed of 5 mph was reduced by 96 percent, and that of 10 to 30 mph was reduced by 50 to 80 percent. With a one-row windbreak, on the other hand, a reduction of 60 percent was observed for 5 mph wind, but only 50 percent for 20 mph wind.

The relation of penetrability of the shelterbelt to the wind patterns of the sheltered area has been observed by Panfilov (1936) as shown in Fig. 10-1a. In this figure, the abscissa is the distance from the belt (or trees) expressed as a multiple of the height of the belt, h. Thus, 5h, 10h, and 15 h designate 5, 10, and 15 times the height of the shelter belt, respectively. The ordinate is the wind velocity in the sheltered area expressed as a percentage of that on the open steppe. This is known as the "relative wind velocity." Four types of shelterbelt are classified as (a) open throughout height of the belt — Curve I; (b) dense throughout height of the belt — Curve II; (c) medium density below and dense above – Curve III; and (d) medium density above and open below – Curve IV. In Curve I, the structure of the shelterbelt is partially penetrable by wind, and is the least wind-reducing of all types. In Curve II, the structure is almost impermeable to wind, and the greatest reduction occurs at the foot of the belt, diminishing rapidly as the distance from the belt increases. In Curve III, the structure is slightly permeable to wind. The greatest reduction occurs on the windward side, and a considerable reduction also takes place on the leeward side. In Curve IV, the greatest average reduction is on the leeward side, with practically no reduction on the windward side. Nägeli (1946), in his study of 12 shelterbelts, classified them into four density types: open, moderately penetrable, dense, and very dense. His findings are somewhat similar to Panfilov's (see Fig. 10-1b and Fig. 10-1c). He emphasized that the wind patterns are chiefly determined by the height of the belt.

Sneesby (1953) in England emphasized the value of shelterbelts in the reduction of wind erosion. Staple & Lehane (1955) and Staple (1961) in Canada made a thorough investigation of shelter effects with

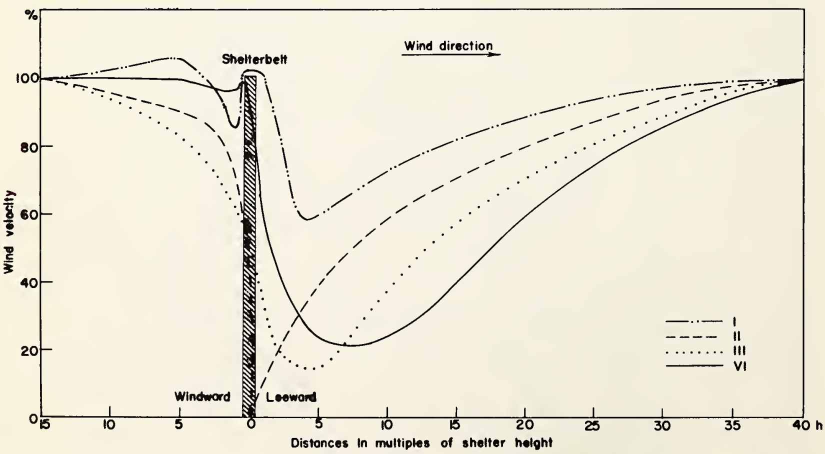

Fig. 10-1a. Wind patterns of different structures of Russian shelterbelts. After Panfilov, 1936

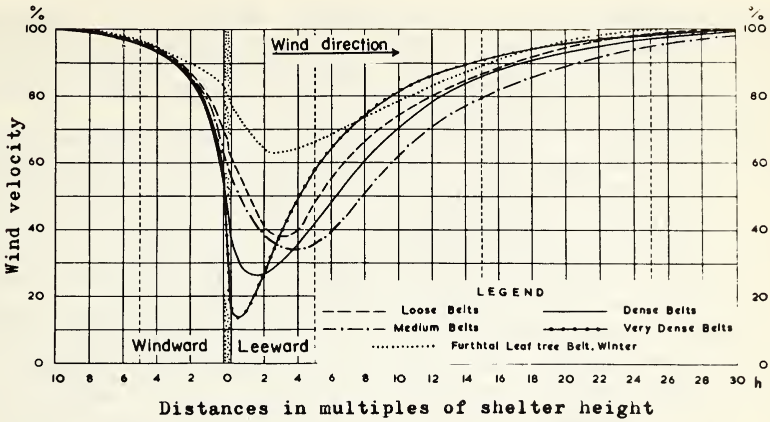

Fig. 10-1b. Wind patterns of different structures of Swiss shelterbelts.
After Nägeli, 1946

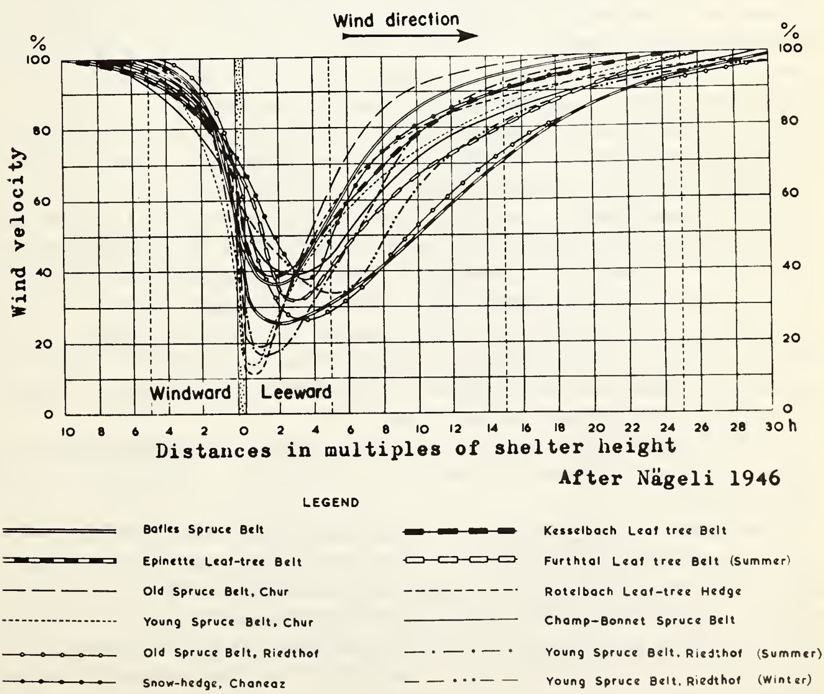

Fig. 10-1c. Wind patterns of twelve different shelterbelts in Switzerland.
After Nägeli, 1946

special attention to wind and evaporation. In the U. S. A., Woodruff and his collaborators (1952, 1953, and 1959) made a series of wind-tunnel experiments on shelterbelt, and in 1956 he developed formulas for the computation of shelterbelt effects.

There has been little disagreement in the literature, concerning the influence of shelterbelts on the microclimate of the protected area. As far as the wind is concerned, the variability of the influence depends upon (a) wind speed and direction, (b) density and height of the shelter, and (c) the topography of the locality. Major topics of interest in the study of windbreaks or shelterbelts are (a) the reduction of wind speed, expressed in percentage terms, in both windward and leeward directions (measured from the shelterbelt in terms of multiples of the shelter height, such as 2h, 5h, etc.), (b) the effects of shelter on various wind speeds, in different directions, and (c) various side effects of windbreaks on other microclimatic factors associated with wind, such as wind erosion, snow accumulation, and soil drifting. It has been reported in western Canada that soil drifting is absent under most of the well-planted shelterbelts.

The temperature, including that of air, water, and soil, as well as temperature gradients associated with them, are also modified considerably by shelterbelts. With regard to the effect of shelterbelts on water temperature, Japanese workers have shown a particular interest in the topic in relation to rice growing, as indicated by various studies, such as Asai's report (1952) on the increase of water temperature as affected by windbreaks, and the study by Abe et al. (1960) on the effect of windbreaks on the yield of rice.

On soil temperature, we have Smal'ko's observation (1951) in the U.S.S.R. on the change of air and soil temperatures by a system of tree shelterbelts. Fekete & Gavenčiak (1956) investigated the effect of a one-row closed shelterbelt on the freezing of soil layers. Since neither wind nor temperature is the central topic of discussion in the present section, the remaining portion of the section will deal with the effect of shelterbelts on moisture, particularly in relation to various aspects of moisture conservation.

The moisture field of the sheltered area may be discussed under the topics of evaporation, transpiration, air humidity, precipitation, and soil moisture.

Woodruff (1954) measured with filter papers the evaporation of protected areas under systems of 10-row belt, a defoliated 10-row belt, and a solid wall, and found evaporation reductions of 46, 26, and 26 percent, respectively, at a distance 18 times the height of the barrier. At an earlier date, Bates (1911) also used filter papers to measure evaporation in a sheltered field, and found that the reduction varied from 40 to 90 percent at various distances from the shelter. By using the Canadian four-foot tank, Staple & Lehane (1954) and Staple (1961) measured the free-water evaporation of wheat field and open field, both sheltered by caragena, 8 to 10 feet high, during the period 1951-1955. He found a reduction of 5 to 13 percent at varying distances from the barrier. Woelfle (1938) indicated that the evaporation rate is almost proportional to the square root of the wind velocity when all other climatic conditions are constant. The rate decreases significantly near the shelterbelt, with least evaporation within the belt. More or less similar findings were reported by Nägeli in 1943. In Japan, Iizuka (1950) found that for average conditions in four shelterbelts, evaporation rates at leeward distances of 1h, 5h, and 10h were 40, 60, and 80 percent, respectively, of the open ground evaporation. Bodrov (1935) concluded that dense shelterbelt is less effective for evaporation reduction than a penetrable belt. This is due to the intense turbulent mixing leeward of dense barriers, rapidly transporting water vapor from the sheltered area, and thus promoting further evaporation. IUdin (1950), in his study of the influences of shelterbelts on turbulent exchange, claimed the importance of optimal width of the belts for the best result. Jensen (1954) made an extensive investigation of the aerodynamics of the shelterbelt and effects on microclimate and crops. He formulated that transpiration in plants as affected by shelterbelt is a function of wind speed and vapor pressure deficit, thus

$$\text{Transpiration} = (3.7 + 0.5\,U^{0.8})\,d\,, \tag{10-1}$$

where U is the horizontal wind speed in meters per second, and d is the vapor pressure deficit in mm of mercury. Symkiewietz (1924) observed the bending influence of the wind on transpiration of crops. He concluded that there is an increase of transpiration as influenced by the alternating contraction and expansion of the intercellular space, facilitating the exit of saturated air and the entrance of dry air. Since wind movement is greatly reduced by the shelterbelt, less bending movement of leaves, and in turn less transpiration, is to be expected within the sheltered area. Satoo (1952) claimed that the wind reduces water content of shelter-tree leaves more on the windward margin than on the leeward edge of the belt, due to lesser transpiration in the latter than in the former. The above studies, and most of the other studies on evaporation, are based on the measurement of free-water evaporation, obtained by pan evaporimeter or atmometer. For future work, more measurements on the actual evapotranspiration need to be encouraged. Measurements of transpiration in the natural field are rather complicated, but not those of evapotranspiration (see Section 5.4).

Although relative humidity is not as good a parameter as other moisture parameters, many more studies are found on this topic. Nägeli (1943) found that in daytime there is an increase in the average relative humidity of sheltered regions. His finding more or less confirms an earlier conclusion by Kreutz in 1938, on the measurement of relative humidity within plots, screened by artificial windbreaks. Since an artificial windbreak contributes no vapor pressure to the air, Kreutz' finding can be taken as an indication that an increase of relative humidity is caused by reduced air movement. Kas'Yanov (1950) compared the monthly relative humidity of a sheltered area with that of an open steppe. The results are given in Table 10-1. A glance at these results shows that almost always the relative humidity is two to four percent higher in a sheltered area than in the open steppe, with an order of magnitude of three. Bodrov (1935) studied the influence of shelterbelts on weather and variation in air humidity. He pointed out that during the hour of sunset in dry and warm weather, the moisture deficit would drop an average of 15 percent over a distance of 3/5 mile from the shelter belt. However, a fall of moisture deficit as great as 50-60 percent was observed near the belt. During the morning hours, the moisture deficit rises an average of 20 percent over 3/5 mile from the belt, and at noon, the belt begins to produce a favorable effect.

Table 10-1. A Comparison of Relative Humidity in the Sheltered Area and the Open Steppe

	Year	April	May	June	July
Sheltered Area (a)	1946	66.4	55.6	42.6	54.1
	1947	68.6	65.0	51.0	47.0
	1948	63.0	53.0	41.5	50.0
	Mean	66.0	57.9	45.0	50.4
Open Steppe (b)	1946	63.7	51.6	38.6	51.6
	1947	65.3	63.0	39.0	44.0
	1948	60.0	49.6	39.3	47.2
	Mean	63.0	54.4	42.3	47.6
Mean Departure (a) minus (b)		3.0	3.5	2.7	2.8

After Kas'Yanov, 1950

Since relative humidity is a function of air temperature, wind, transpiration, and evaporation from both the vegetation and the shelter itself, as well as the soil moisture of the surface layer, it is highly variable with respect to time of day, season of the year, and various weather conditions. With this in mind, it appears that the moisture content of the air would be better represented by dew point than by relative humidity.

Little work has been done on the efficiency and variability of rain distribution in the sheltered area. However, it is common knowledge that light rainfall is intercepted by the crown of trees, resulting in practically no rain under the crown and adjacent to the belt. Heavy rainfall, when accompanied by wind, will give increased precipitation to the sheltered area, due to reduced wind speed and turbulences. Thus, the wind speed, wind direction, and intensity of precipitation are the major factors to be investigated. Studies on precipitation are important in their relation to soil moisture, and will be discussed separately in the following section.

10.1.3 *Snow fence*

A "snow fence" usually denotes an open, slatted board fence of about 4 to 10 feet height, placed on the windward side of the area to be protected, although any shelterbelt can act as a snow fence as well. A wild fence[1] which is used to reduce eddies around the snow or rain gauge is also a snow fence on a small scale. In this section, the effects of snow fence or shelterbelt on precipitation in the form of snow, rain, dew, and even fog drip, are discussed in relation to the soil moisture.

The snow fence is used to accumulate more snow with a minimum of drifting in the area concerned. It secures a uniform snow cover for winter crop protection, and uniform soil moisture for spring planting after melting. With a snow fence, the moisture loss either diminishes or is minimized, depending upon the depth of snow cover.

Also, the melting snow in the spring is more or less evenly distributed, the ground becomes more receptive to percolation, and in turn, runoff and erosion are greatly reduced. Gorshenin (1946) found that the depth of ground freezing varied inversely with the depth of snow cover, being shallower around the belt and increasing in depth with greater distance from the belt.

According to Staple's report (1961) in western Canada, in the sheltered areas under systems of 20- to 23-foot maple, ash, and caragena shelterbelts, the size of major snowdrifts ranged from 12 to 60 feet in width and 18 to 27 inches in average depth, with some tapering off toward the center of the field. At the time of thawing this will bring about six to nine inches of water, an ample supply of moisture for the area of accumulation. However, due to the tendency for snow to accumulate on a certain spot, the intended benefit of snow fence is greatly reduced by an uneven distribution of soil moisture. As the shelter trees grow, the pattern of snow accumulation, and the pattern of soil moisture distribution will be greatly affected. Stoeckeler & Dortignac (1941), in their study of the growth and longevity of shelterbelt, found that all snowdrifts are trapped within 30 to 80 feet on the leeward side of the first shrub row at least eight feet high. With

[1]A device used to minimize eddies around the rain gauge and to maintain a steady flow of horizontal air in the vicinity of the receiver. It is usually a wooden enclosure about 16 ft. square and 8 ft. high, to insure a representative catch of rain or snow.

one or more rows of densely growing shrubs, five to eight feet of drifts was generally observed. Bekker (1947) concluded that the length (or distance) of drift (L) is proportional to the height of the fence (h). When expressed in units of feet, it is

$$L = \frac{1}{k}(36 + 5h), \qquad (10\text{-}2)$$

where k is the function of fence density, being 1.00 for a density of 50 percent, and 1.28 for a density of 70 percent. Comparing a solid fence with an open fence, Pugh (1950) found that the former causes the drifts to accumulate on both sides of the fence, while the latter produces an accumulation mainly on the leeward side. Also, the drift is short and deep for the former, long and shallow for the latter. With an open fence, for snow of 0.2 specific gravity and wind velocity up to 25 mph, no effect was observed on either the length of drift or the maximum depth. But for snow of 0.3 specific gravity accompanied by wind velocity of 10 to 25 mph, the maximum depth was generally located further away from the fence; there was no effect when the wind was less than 10 mph. When the wind exceeded 27 mph, the drift became short, and when 34 mph was reached the drift became stable. It is generally recognized by various investigators that a 50 percent open fence is the optimum density for distribution of snowdrifts.

In a mountainous area, the accumulated winter snow can be reserved by a dam in a valley so as to control the supply of melting snow

Fig. 10-2. Snow water supply from mountain for potato irrigation near Teton, Idaho. After Donnan & Sharp, 1962

Fig. 10-3. Thawing snow in the valley near Ketchum, Idaho.
Courtesy U. S. Soil Conservation Service, 1962

according to various situations and needs. In Teton, Idaho, for example, the snow is captured in large reservoirs (see Fig. 10-2). It is withheld from the spring runoff and used in summer for irrigation of potatoes. Fig. 10-3 shows the thawing snow from mountains moving slowly to the valleys near Ketchum, Idaho, for summer irrigation. The reserving of snow for summer irrigation and spring flood control is an important moisture conservation practice.

As far as rainfall is concerned, an interception zone with little or no rainfall, known as the "rain shadow" zone, is developed on the leeward side of the shelterbelt. It is interesting to note a contrasting pattern between the rainfall accumulation and snowfall accumulation, which is confined to a more or less narrow marginal strip around a dense, wide shelterbelt. In general, the higher the belt, the wider the rain shadow zone. In 1947, Lammert observed a rain shadow zone about 100 ft. wide to the leeward of a dense poplar belt 132 ft. high and 66 ft. wide. In 1952, Kreutz indicated that the distribution of rain in the sheltered area depends upon the wind velocity. With low wind, the distribution is fairly uniform near the belt, but with high wind this uniformity is disturbed.

Shelterbelts also exert a considerable influence on dew and fog. Steubing (1952) reports the dew collection from the sheltered area as 200 percent of that from the open area. The heaviest dewfall was observed over a distance of 2 to 3 h on the leeward side of the hedge. The difference in dewfall between the sheltered area and the open area depends upon weather conditions, particularly the wind. In weather favorable to dew formation, the difference is small, whereas in windy weather the difference is large.

With regard to fog, Kashiyama (1953) observed the interception of one millimeter per hour of sea fog (0.3 gm per cubic meter moisture content) on the windward side of a belt $6\frac{1}{2}$ ft. high and 43 ft. wide, under a wind velocity of 3.4 meters per second, in the coastal fog-belt of Japan. Other researches on physical processes and effects of dew and fog are numerous; some of them have been mentioned in Section 4.4.1c.

When trees or weeds are employed as shelterbelt or snow fence, the sapping of soil moisture by their roots must be anticipated. Reports from the U.S.A., Canada, and elsewhere show that tree roots of the shelterbelt extend one to two times the tree height; thus the suppression of crop yield is to be expected (Bates, 1911; Staple, 1961). With the growth of the shelterbelt trees, this effect is expected,. in general, to become more intense. Nevertheless, sapping by tree roots is partly offset by snow accumulation and reduced evaporation; thus the result is not so conspicuous.

According to all available literature, soil moisture is appreciably higher in the sheltered area than in the unprotected area. Masinskaja (1950) observed that, during the entire growing season, 25 to 30 percent higher soil moisture was found between 10 and 12h leeward. At a greater distance from the belt, the difference decreases up to a distance of 20h, where no significant difference exists between protected and unprotected areas. Around the belt, or in the rain shadow zone, it is 20 percent less. In 1952, Kreutz reported that during May through September, the average soil moisture of the protected area was 10.48 percent, and that of the unprotected area was 6.38 percent.

For estimating the total available water in a sheltered area, the water budget concept is a useful tool. The gain of water to the area is brought by precipitation (snow and rain), condensation (dew and fog), irrigation, and capillary action; loss takes place by evaporation, transpiration, percolation, and runoff. A balance between the gain and the loss is the available water in the soil. L'vovich (1950; 1954) of the USSR, for example, studied the water balance of irrigated fields in the sheltered area. Fig. 4-21 shows various processes related to water budget, and section 10.2.2 presents the procedure of the water budgeting method.

The usefulness of the shelterbelt or snow fence, or of any other artificial device for moisture conservation, can be evaluated by various microclimatic factors, such as air humidity, evapotranspiration, amount of precipitation, and soil moisture. However, from the practical agricultural point of view, it should be emphasized that the actual crop response is the best yardstick in the final analysis.

There are numerous reports concerning the favorable effects of shelter on crop yields, particularly on field and vegetable crops. Although a certain decline in production occurs within a narrow strip bordering the belt,[2] this strip ordinarily extends no more than 0.5 h in width; therefore, an increase in the average yield of the entire sheltered area is usually seen. Some examples of such reports are arranged chronologically in Table 10-2.

For fruit crops, many reports as to the benefit of shelterbelt indicate not only the reduction of wind damages, but also the prolongation of the ripening season, thus leading to higher yield. As to forestry, the benefits have been summarized by Caborn (1957) as follows:

(a) The use of shelterbelts may allow the planting of areas which are otherwise too exposed for economic forestry. This practice would facilitate establishment of the forest; Petrie (1951) has recorded the silvicultural desirability of establishing marginal and internal belts of wind-resisting species some years before the planting of the main species, with the object of having a certain amount of shelter in readiness.

(b) Microclimatic conditions produced by shelterbelts within their zone of influence are generally more favourable for the growth of trees; possible disadvantages such as frost may be minimised by means of penetrable belts.

(c) Protective margins and internal belts will reduce damage by strong winds and promote forest conditions more favourable for regeneration immediately behind the plantation margins.

(d) Shelter margins, designed specifically for protection, should occupy a smaller area than would normally be occupied by deformed and retarded trees if the main timber species were planted to the edge of the forest area; this would imply an increase in the productive area of the forest (see Robinson & Watt, 1910).

[2]The decline in productivity in the narrow strip is due to lack of light by shading and lack of moisture by either root competition or "rain-shadow" effect.

Table 10-2. Examples of Shelterbelts' Influence on Crop Yields

Year	Crop	% Increase in Yield*	Specifications, if any	Investigator
1911	Corn	45%	At 4h to 5h, sometimes up to 12h leeward	Bates (USA)
1935	Wheat	Average increase 4.5 bu. per acre	None	Rudolf & Gevorkiantz (Russia)
1940	Hay	100-300%	None	Ignat'ev (Russia)
1940	Oats	25-28%	Five-row shelterbelts	Kucheryavykh (Russia)
1941	Grass	34%	None	Nägeli (Switzerland)
1942	Cereals	27%	None	Nägeli (Switzerland)
1943	Beets	23%	On the west shelter	Andersen (Switzerland)
1943	Cabbage	13%	On the west shelter	Andersen (Switzerland)
1943	Lupins	49%	On the west shelter	Andersen (Switzerland)
1944	Potato	21-24%	On the west shelter	Geete (Germany)
1949	Grain	25%	Eucalyptus belt, 10 m high and 30 m wide	Savi (Italy)
1954	Various crops	7-18%	Central half of a U-shape enclosure 60' wide protected by snow-fence 8' high	Jensen (Denmark)
1961	Wheat	1.1 bu. net per acre	Caragana hedge 7' to 10' high	Staple (Germany)

*Percentages of yield exceeding the unprotected area.

10.1.4 *Suppression of evaporation*

Since the escape of water vapor from the surface of plants, soils, and water is a process of evapotranspiration, control of evaporation by physical and chemical means is another aspect of water conservation. Much more research and actual field practice have been accomplished on the suppression of evaporation from free-water surface than is the case for reduction of transpiration from plants and of evaporation from soils. The suppression of free-water evaporation is extremely important to areas where irrigation is needed and where fresh water supply is limited for man and animals. The climate of such areas is characterized by little rainfall, high evaporation, and low runoff. For example, Eaton (1958) found that in the Great Basin and the Colorado Basin of the U.S., evaporation dissipates almost one-sixth of the available water supply. Hobbs (1961) estimated an annual evaporation of two to three feet of water from lakes and reservoirs in Canada. Evaporation control is important even in humid areas such as in rice paddies and where farming is done with cultural solution. In the United States, several organizations are engaged in research on evaporation suppression, among them the U.S. Bureau of Reclamation, the U. S. Geological Survey, the Southwest Research Institute, and the Illinois State Water Survey Division.

Chemical compounds used for suppression of evaporation, known as suppressors, suppressants, or retardants, are available in the form of solids, liquids, or emulsions. Sometimes certain plant materials are also used as suppressors.[3] There are many types of chemicals used as suppressors, under a variety of trade names; they are essentially fatty alcohol. To name a few, we have Adol 62 (1-octadecanol, U. S. P.), Adol 11 (1-dodecanol saturated with coconut), Siponol L 5 X (1-dodecanol saturated with 62% C_{12} and 23% C_{14}), Stearyl alkanol (1-octadecanol), X—69 (polyoxyethylated tallow alkanols) and OED (Oxyethylene docosanol), with suppressing power of 68, 65, 61, 58, 51, and 85 percent, respectively.[4] As to chemical structure, each individual molecule of suppressor contains a hydrophylic (water attracting) and a hydropholic (water-repelling) group in its molecular structure. The adhesive force between the hydrophylic (or hydroxyl) group[5] of the molecule and the water is greater than the cohesion between molecules of the suppressor, and therefore the latter separates from the mass and moves across the water to form a film of one molecule thickness (or one ten-millionth of an inch), known as a monomolecular or simply monolayer film. Spreading continues from the source until the monolayer becomes condensed with molecules closely packed, exerting the equilibrium surface pressure, or simply film pressure, of about 40 dynes per centimeter. Any useful suppressor should have a minimum film pressure ranging from 17 to 20 dynes per centimeter, as has been generally accepted.

[3]Duckweeds, water lilies, and other plants have suppressing effects, while bulrushes were found to double reservoir water losses.

[4]These percentages are based upon individual investigators' reports. They are by no means an indication that one chemical is better than the other, for the methods of application and the local environmental conditions differ considerably. For details, the reader may refer to Cruse & Harbeck's Evaporation Control Research, 1955-58, U. S. Dept. Interior, Washington, D.C., 45 pp. The OED compound was reported by Mihara & Nakamura (1961) of Japan.

[5]It can be a carbonyl, carboxyl, amine, amide, or nitrate group instead of hydroxyl group.

The choice of suppressor depends upon a number of factors. The chemical characteristics should be odorless and nontoxic to every beneficial animal and plant, not hazardous to human health, and non-detrimental to the biological balance of the reservoir, including the free exchange of O_2 and CO_2. Its physical requirements include relative imperviousness to water vapor, and the ability to form a continuous film over the water surface, self-restoring when broken. Above all, it should be inexpensive and in a form which can be readily utilized. In addition, weather influences on the suppressor are another major consideration, particularly to agrometeorologists. Among various meteorological factors, the wind velocity (vertical and horizontal), the vertical vapor pressure, the solar intensity, and the temperature of the surface water, as well as that of the water-air interface, are the main topics of discussion. For example, in 1957, Boon & Downing reported that the suppressive efficiency of cetyl alcohol (hexadecanol) on the water surface depends on the intensity of solar radiation, wind velocity, relative humidity, the rate at which films are replaced, and the biological activity.[6] High solar intensity contributes to high film temperature and to increased convective current and turbulences, thus resulting in a higher rate of evaporation. In this connection, the albedo of the film is a factor to be investigated; an increase in the albedo tends to lower the rate of evaporation. As for the effect of wind, particularly high speed wind, it not only accelerates the evaporation of the film, but it also breaks the film surface and tends to blow fragments of the film in one direction. Using kerosene for dispersing cetyl alcohol, Grundy (1957) found that a light breeze is helpful in spreading the monomolecular film. He noticed particularly the rapidity of film spreading with the first drop of suppressor to as far as 100 feet from the point of dosing. On the other hand, Cruse & Harbeck (1961) found the effect of wind to be quite different. They made an experiment with hexadecanol film on lake water under the 10 mph artificial wind tunnel, and found that the change in rate of spread is too small to be of any practical significance, if the point source dosing is adopted from the upwind side of the lake of over one acre size. They also found an eventual piling up of the film on the downwind shore, with resulting losses. Mansfield (1956) has designated the evaporation of suppressor as a function of an L/A factor, where L is the perimeter of the solid particle of a suppressor in contact with the water surface, and A is the surface area to be covered. He claimed that the L/A ratio should be 0.0025 centimeters per square centimeter for normal conditions. Since evaporation of the monomolecular film is also a function of the

[6]Bactericidal and bacteriostatic activities shorten the life of monomolecular films. For example, Cruse & Harbeck (1960) found that the addition of 0.6 ppm cupric sulfate pentahydrate ($CuSO_4 \cdot 5H_2O$) to a 10-foot water tank increased the life span considerably. Although the method is not practical for a large water surface for reasons of safety and cost, it proves that biological action is significant.

volatility of the suppressor, it appears that the temperature of the film also needs to be considered.

Mihara & Nakamura (1961) reported their observation of shallow flood temperature of rice paddy fields covered by oxyethylene drocosanol, that the temperature is 5° to 7° higher on a clear day, and 2° to 3°C higher on a cloudy day, than that of free water. Using pans of three feet in depth, buried in the ground, Roberts (1958) also found that the surface temperature of water treated with hexadecanol is always higher than the untreated surface. At the warmest time of the day, when evaporation is greatest, the water beneath the monolayer surface was 2° to 5°F warmer than the plain water surface. For this temperature measurement, he anchored a hook gage to the side of the evaporating pan and attached the temperature sensing element to the hook gage, so that the sensing element could be lowered precisely to the surface of the water.[7] His finding is shown in Fig. 10-4.

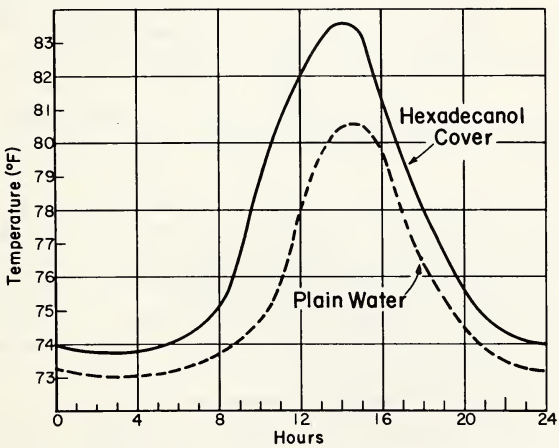

Fig. 10-4. Diurnal temperature of water with and without hexadecanol cover. After Roberts, 1957

Considering the various aspects involved in the relationship between environment and suppressor, when conducting such studies, specification should be made as to the size of the water surface, the physical and chemical properties of the suppressor, and the method of application. Various considerations and methods described in Section 9.2.5 can be referred to with regard to the spraying.

Suppression of evaporation from the soil surface and of transpiration from the plant surface are ideal methods for conserving soil moisture, but they are still in the experimental stage. Although experiments were started as early as 1885, and several research projects are now

[7]Through personal communication.

available, large-scale application of the technique has yet to be performed, due to the lack of substantial proof of the favorable outcome of such application. There is always a possibility of complication in the method, due to the permeability of living cell membranes to water, the variation in concentration of soil solution, and many other factors. The variation in the rate of transpiration and evaporation depends upon the combined mechanisms of physiological functions of plants and the physical or chemical properties of soils when the experiments are conducted in the greenhouse.

In the past, the use of chemicals to bring about changes in the rate of transpiration has been tested by many researchers, with varying degrees of success. Burgerstein (1885) found that soil solutions containing one part of camphor per 1000 had an accelerating effect upon the transpiration of most plants. Ricome (1903) found that soils containing 0.06 to 0.08 percent of NaCl showed an increase of transpiration in wheat. Similar findings were reported by Burgerstein (1904), for corn plants. It was found that with solutions of 0.1 and 0.25 percent $Ca(NO_3)_2$ and $MgSO_4$, the transpiration rate of corn is accelerated, but that stronger solutions (0.5 and 1.0 percent) retard the transpiration rate. Spraying with Bordeaux mixture has been observed to prolong the life of the potato plant for 25 days and to increase the yield of tubers 100 bushels per acre over that of unsprayed plants (Miller, 1938). The transpiration rate of plants, either increasing or decreasing, depends upon the composition of the mixture, and the age, species, and variety of plant. Tilford & May (1929) observed that the application of Bordeaux mixture and copperlime dust to the leaves of potato plants lowered the leaf temperature by 2° to 4°F, depending upon the composition of the mixture. However, when the leaves were sprayed with a 4-4-50 Bordeaux mixture plus lampblack, the temperature was 5°F higher than that of unsprayed leaves.

The use of monomolecular film on plants and soils for the purpose of suppressing evapotranspiration is a very recent development. Roberts (1961), from laboratory tests on the germination of hybrid corn, found that the mixed cultural solution of octadecanol and hexadecanol at various concentrations exerted no effect on the rate of germination. The same mixture in powder form was introduced to the sterilized soil of potted corn plants, and the examination of four-week-old seedlings revealed that the water requirement for growth of the treated plants was only 60 percent or less of that for untreated plants. He used the same powdered mixtures on corn planted in vermiculite, and measured the water loss of the plants at the three-leaf stage (in weight per unit weight of plant material) during various hours of the day. The result is shown in Fig. 10-5. The plants grown in the radioactive hexadecanol solution indicated that the radioactive isotopes had traveled

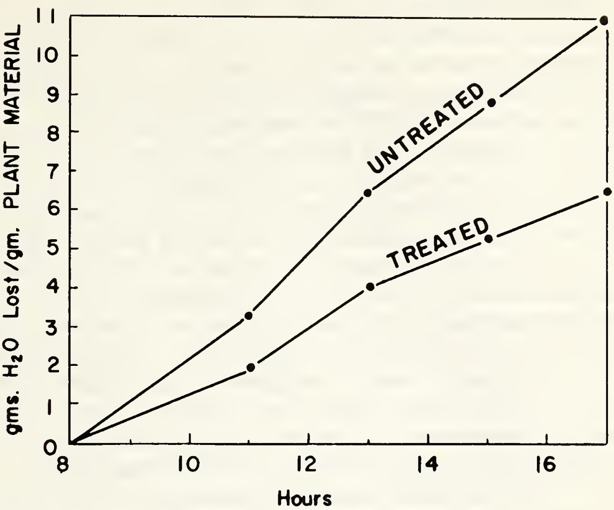

Fig. 10-5. A comparison of water loss from treated and control plants.
After Roberts, 1961

through the root structure to all parts of the plant, including the leaves. A great concentration of hexadecanol was shown in the root structures by radioautographs. With the application of monomolecular film, a blocking action on water movement appeared to take place in the root by reducing the stomatal opening and thus restricting the translocation of water in the plant tissue. It is assumed that the stomatal transpiration from leaves and the lenticular transpiration from fruits and woody stems would be reduced by the film deposited at the stomate water vapor interface, for the film will still have the ability to permit passage of oxygen and carbon dioxide across its surface but will inhibit the escape of water molecules.

Roberts also made a field study on the application of flaked hexadecanol to hills of corn during the knee-high stage. A harvest of 125 bushels per acre was reported from this experiment. There are favorable reports from various commercial firms in several countries, concerning the increase in the yield of crops by the reduction of transpiration. However, only through experimental verification can the validity of these reports be established. The environmental factors which govern the transpiration process, such as evapotranspiration, solar intensity, wind, leaf temperature, soil moisture, and temperature, should be examined carefully.

10.2 IRRIGATION

So far, the discussion has been concerned with the subject of "moisture conservation" in soils, air, and reservoirs. Another phase of water management is the various techniques of irrigation. The aim of moisture conservation is to keep the available water in a given area from escaping, whereas irrigation puts additional water in that area, from reservoirs. Irrigation had been used for combating drought in the past. However, it has been acclaimed recently for achieving maximum production in humid regions as well. In arid regions, the agricultural season is often confined to a warm dry period, and therefore irrigation is desperately needed for dry farming.[8] In dry farming practice, a combined study of the choice of drought resistant crops to fit the environment, and the modification of environment by irrigation and soil conservation to fit the crop is essential. In semi-arid and subhumid climates, irrigation makes possible larger yields, better quality, and a greater variety of crops. In humid regions, it is useful in time of drought. Whatever regions are under consideration, climate, or rather environment, is a major factor to be investigated. Contributions to a full understanding of factors governing the need for irrigation and decisions on irrigation are now made mostly by agrometeorologists; thus agrometeorological techniques have been introduced in nearly every large irrigation project.

10.2.1 *Factors in irrigation*

The stress upon the efficiency of irrigation design with respect to maximum production and minimum cost necessarily lead to the consideration of the physiology of plants and the physics of an environment of both air and soil.

Concerning the effect of irrigation on the physiological aspects of crops and vice versa, criteria may be established according to the species and varieties of crops. However, the over-all considerations may be grouped as (a) rapid vegetative growth stage, (b) the minimum moisture requirements, (c) the absorption and transpiration ratio, (d) the direct and indirect effects of irrigation water, and (e) the ecological aspects of growth and development of plants.

For illustration, corn plants are used to show some of the physiological aspects of irrigation—crop relationship. Holt & Van Doren (1961) found that the water requirements for corn grown in western Minnesota are greatest in the period from tasseling to kernel formation and henceforth drop sharply. Denmead & Shaw (1960) demonstrated that the reduction in corn yield in Iowa, from moisture stress during the vegetative, silking, and kernel stages was 25, 50, and 21 percent,

[8] The UNESCO's Arid Zone Programme, established in 1951 under the supervision of the Advisory Committee on Arid Zone Research, emphasized the climatological approach in dry farming projects.

respectively, indicating the silking stage as the most critical period for moisture stress. They explained that moisture stress in the vegetative growth stage has an indirect effect on corn yield by reducing the assimilatory surface area, while moisture stress after the ear emergence has a more direct effect through reducing assimilation in the critical period. Robins & Domingo (1953) indicated that a soil moisture deficit for one or two days during the tasseling stage reduced yield by as much as 22 percent. Leonard et al. (1940) reported the highest efficiency of irrigation as occurring during the tasseling stage in Colorado. These and many other similar findings stress that the more rapid the weight or volume increase of the plant, the higher are the plant's water requirements. Kiriakov (1938) has in fact defined the critical period of corn as the interval from 15 days before to 15 days after tasseling. Corn has an extensive power of recovery from early season setbacks by drought, if not critical, and the yield will not be affected if adequate irrigation is supplied at a later period. Hybrid corn is generally more drought resistant than inbred corn. Haynes (1948) pointed out that although the availability of soil moisture did not affect the amount of water transpired per unit plant dry matter, the quality of vegetative growth was greatly affected within the soil moisture range from near saturation to near permanent wilting. Weaver (1927) reported that hot wind sweeping over the level prairie may cause serious injury in a single day by promoting an extensive transpiration, even if the soil ordinarily has an adequate supply of water. Jenne et al. (1958) showed that dry matter, phosphorus, nitrogen, magnesium, and potassium of mature corn grown under inadequate soil moisture were significantly decreased below those obtained under adequate moisture conditions throughout the growing season. All these findings and many more indicate that various physiological factors in plants are significant for irrigation design.

With regard to the physical aspects, factors such as solar intensity, precipitation and condensation, wind velocity, air and soil temperature and moisture, soil types, and topography should be considered jointly. Although none of the single environmental elements is a dominating factor for irrigation, the concept of significant elements associated with significant periods (see Section 3.2), and the method of combining factors (see Section 7.5) are also applicable in irrigation design.

In macroclimatic considerations, precipitation is taken as the gain in soil moisture, and evapotranspiration as the loss. When precipitation exceeds evapotranspiration, no irrigation is needed; when the reverse situation exists, irrigation is needed to make up the shortage. This simple scheme is subject to a serious criticism when applied to a small farming area. In the first place, neither precipitation nor evapotranspiration is accurately measured. Secondly, irrigation water is different from rain water in many ways. For example, irrigation water is subject to the "oasis effect," and thus evaporation is great, particularly in sprinkling irrigation. Rain water, on the other hand, is susceptible to dissipation due to the great variation in intensity, duration, and time distribution. Factors in the dissipation of rainfall are infiltration, percolation, runoff, interception, and the like.

In microclimatic considerations, factors such as vertical vapor pressure and temperature gradient above and under the ground, as well as soil type and topography, should also be taken into account. Onchukov (1959) investigated the scheme of diurnal vapor migration in the upper soil layer. He found that vapor within the soil moves at night toward the soil surface. Vapor moving from the warmer and deeper soil layers encounters cold soil layers and condenses on its way up; that which has not been condensed passes through the soil surface and escapes into the free atmosphere. Intense evaporation begins at sunrise when the soil is warm, and the surface layer becomes unsaturated. The reverse condition occurs at night. Fesko & Strugaleva (1959) reported that deep plowing with turning of sod favors the accumulation of winter and summer precipitation in the soil, and secures a better distribution of water along the soil profile during irrigation. They stressed the benefit of deep plowing, particularly on light and medium silt loams, for releasing the compaction of soil caused by rainfall and irrigation. Taylor & Slater (1955) pointed out that soil moisture capacity is influenced by the degree of dryness before irrigation, as well as by soil structure and texture.

The studies mentioned above are only a few indications of possible influences that biological and environmental factors exert on the need for irrigation. Descriptions of decisions made in irrigation design will follow in the next section.

10.2.2 *Irrigation decision*

Major problems involved in the irrigation decision are (a) the demand for irrigation, (b) methods of irrigation, (c) scheduling of irrigation, and (d) irrigation operations. From the agrometeorological viewpoint, these respective problems may be solved, to some extent, by the following schemes.

In order to determine the need for irrigation, a knowledge of the effects of irrigation on crops in a certain area, with specification of soils, climate, and seasons of the year, is imperative. In other words, possible profits to be gained from irrigation with respect to survival of crops, increase in yield, improvement in quality, and/or change in maturity date need to be carefully examined in reaching a decision. Other aspects, such as the cost of installation and maintenance, including land leveling, also need consideration, but they are mainly problems of engineering. When effects of irrigation on crop production are concerned, techniques such as methods of analysis and synthesis (see Section 7.5) should be consulted, and thus factors other than moisture should also be considered.

The choice of irrigation methods, such as sprinkler irrigation, subirrigation, and surface irrigation, including flood, furrow, and corrugation, may be made according to species and varieties of crops, soil types and topography, cropping systems, soil management, and microenvironmental conditions. Factors to be considered are evapotranspiration, precipitation, runoff, infiltration, etc., as has been mentioned in Section 10.2.1.

For sprinkler irrigation, water and air temperature, wind velocity, evaporation, solar radiation, and the like, must be taken into account. The advantages of sprinkler irrigation may be summarized as almost complete freedom from erosion and runoff, general applicability to all types of soils, and minimum drainage even on sandy soil. However, there are disadvantages, too. In a hot windy climate, for example, the loss of water by evaporation is large. Also, on soils of low water intake or of poor infiltration, this type of irrigation is inefficient. Mather (1950) claimed that 20 percent of the sprinkler-irrigated water is lost through evaporation. For remedies, he suggested a rapid irrigation of a large quantity at a time, and a large area application. Quackenbush & Shockley (1955) reported the distortion of the sprinkling pattern by high wind, resulting in an uneven distribution of water. They found that fine-textured clay soils absorb water at a rate as low as 0.1 inch per hour, while coarse-textured sandy soils have an absorption rate as high as 2.0 inches. Thus, erosion and runoff can be serious in some instances, depending upon soil types, cropping systems, soil management, and kind of sprinkler used.

With subirrigation, evaporation loss and wind effect are minimized, even though transpiration cannot be controlled. The problems of runoff, infiltration, percolation, and even erosion can become quite serious if the choice of area is inappropriate. The criteria for the selection of area include free lateral underground movement of water, rapid capillary rise, and an impervious layer with substratum. In fact, subirrigation is an artificial water table by itself. In such practice, a large quantity of water can usually be supplied, and it is applicable to all crops. However, when precipitation is high, the drainage is a serious problem, particularly with sandy soil.

As to surface irrigation, border irrigation (a type of flood irrigation), for example, is well adapted for all close growing crops and is used for some row crops, such as cotton. It can also be applied to all soils, but has some limitations on slopes. For annual crops, the slope may be as much as 3 percent, and for sodded pastures, up to 8 percent. Good leveling with no more than 0.3 percent cross slope is

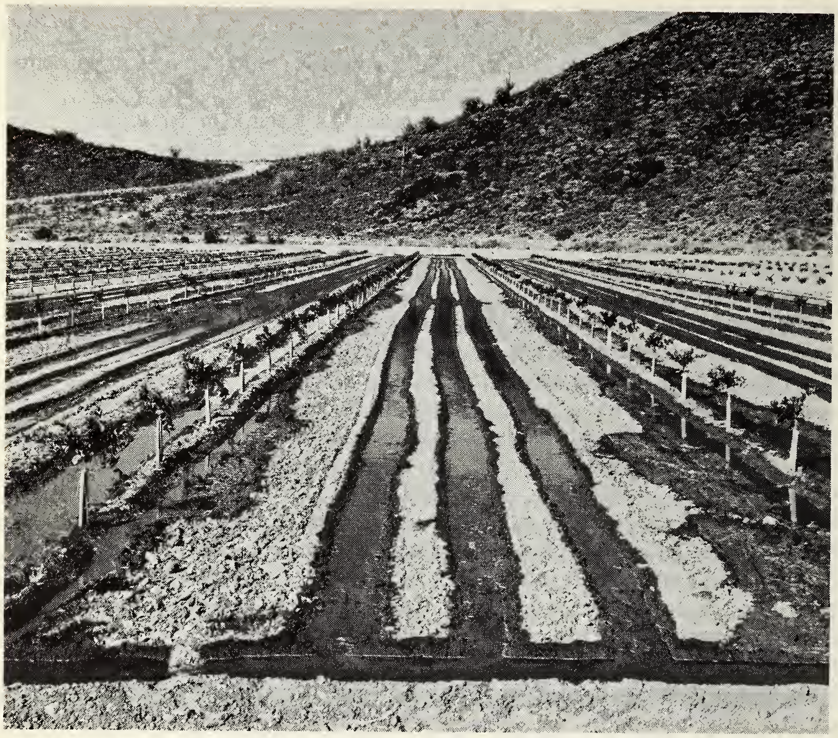

Fig. 10-6. Furrow irrigation in Phoenix, Arizona.
Courtesy U. S. Soil Conservation Service, 1957

preferable. Furrow irrigation is limited to a slope up to 3 percent in the direction of irrigation, but for row crops a 10 percent slope could be permissible. Fig. 10-6 shows an application of furrow irrigation in the New River Soil Conservation District in Phoenix, Arizona, where young orange trees are grown with lettuce in between. Light, medium, and fine textured soils can be used for both furrow and corrugation irrigation. The latter can be applied to a slope as great as 12 percent for semipermanent crops, but for annual crops, 8 percent is the limit. Fig. 10-7a shows irrigation with plastic siphons in Nebraska in which a 1" siphon is used for each row and a $1\frac{1}{2}$" or 2" siphon may be used to divide between two and three row irrigation. Fig. 10-7b shows the first irrigation of corn field with 10" gated pipe near Waco, Nebraska, after detasseling of female rows.

In the past decade, agrometeorologists have made special contributions to the scheduling of irrigation by introducing methods of climatic evaluation. In macroclimatic evaluation of irrigation need, the major concern has generally been with precipitation and estimated potential

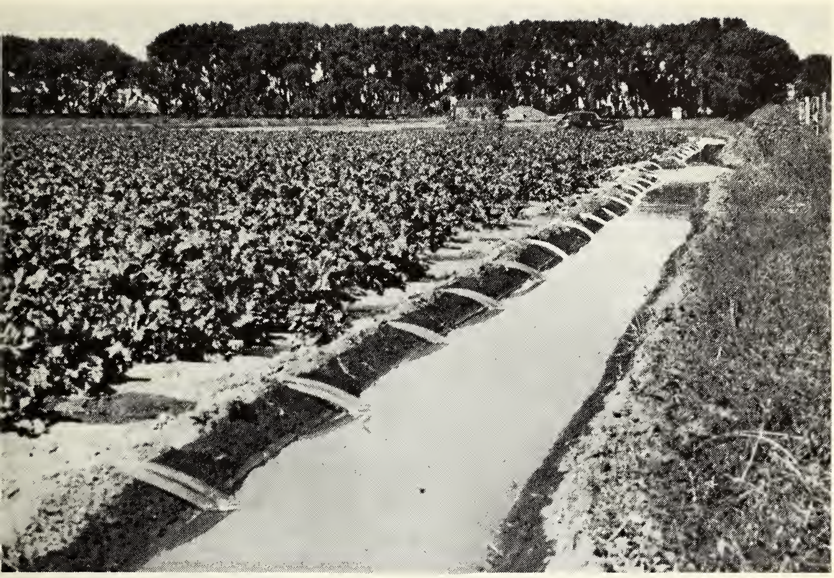

Fig. 10-7a. Irrigation with plastic siphons in Nebraska.
Courtesy U. S. Soil Conservation Service, 1950

Fig. 10-7b. Irrigation with grated pipe in Nebraska.
Courtesy U. S. Soil Conservation Service, 1950

Table 10-3. Percentages of Daytime Hours for Each Month of the Year

Latitude:	26°	32°	38°	44°	50°
January	7.49	7.20	6.87	6.49	5.98
February	7.12	6.97	6.79	6.58	6.32
March	8.40	8.37	8.34	8.30	8.25
April	8.64	8.75	8.90	9.05	9.25
May	9.38	9.63	9.92	10.26	10.69
June	9.30	9.60	9.95	10.38	10.93
July	9.49	9.77	10.10	10.49	10.99
August	9.10	9.28	9.47	9.70	10.00
September	8.31	8.34	8.38	8.41	8.44
October	8.06	7.93	7.80	7.63	7.43
November	7.36	7.11	6.82	6.49	6.07
December	7.35	7.05	6.66	6.22	5.65

After Blaney, 1955

Table 10-4. Consumptive Use of Water by Crops in Pine River, Wisconsin

Month	T (°F)	p (%)	f	K		u		r (inches)
				Alfalfa	Corn	Alfalfa	Corn	
May	57	10.26	5.85	0.85	0.80	4.97	4.68	3.84
June	66	10.38	6.85	0.85	0.80	5.82	5.48	4.12
July	71	10.49	7.45	0.85	0.80	6.33	5.96	3.46
August	68	9.70	6.60	0.85	0.80	5.61	5.28	3.47
September	61	8.41	5.13	0.85	0.80	4.36	4.10	3.65
May to September			f = 31.87			u = 27.09; 25.50		r = 18.54

Table 10-5. Amount of Irrigation Water Required at Pine River, Wisconsin

Crop	Acreage	U - R	Efficiency	Water Required *	
				Per Acre	Total
Alfalfa	25	8.55"	60%	14.25"	29'9"
Corn	15	6.96"	55%	12.65"	17'9"

* Refers to the amount of water needed for irrigation, e.g., 14.25 inches per acre, or 29 feet 9 inches for 25 acres of alfalfa.

evapotranspiration. Although these two factors cannot describe exactly the water requirements of crops, they are able to give a first approximation, and have been employed extensively for the scheduling of irrigation in many areas. Blaney & Criddle (1950) estimated the potential evapotranspiration by

$$U = KF = K\Sigma f, \qquad (10\text{-}3)$$

where U is the consumption of water by crops, in inches (or simply the potential evapotranspiration), for any period, K is the empirical coefficient, depending upon the irrigation season,[9] and F is the sum of the monthly consumptive use, f, for the period. The value of f is obtained from the product of mean monthly temperature, T, and the monthly percentage of daytime hours of the year, P. Thus, $F = K\Sigma f = K\Sigma(PT)$. This equation is known as the Blaney-Criddle formula.

For the computation of the coefficient K, Blaney used the normal supplies of irrigated water in arid and semiarid areas during the growing season, the standard coefficient values for various crops being as follows:

Alfalfa	0.85	Grass hay	0.75
Corn	0.80	Citrus trees	0.60
Cotton	0.65	Rice	1.20
Pasture	0.75	Vegetables	0.60
Potatoes	0.75	Deciduous trees	0.60

He claimed that these coefficient values should be reduced by about 10 percent for humid areas. For obtaining values of P, he divided the mean monthly possible sunshine hours by the total annual possible sunshine hours and expressed them in percentages. Examples of his computations are shown in Table 10-3.

The following is an illustration of the determination of the consumptive use of water by means of Equation (10-3). In Pine River, Wisconsin (Lat. 44°11' N), a certain farm consists of 35 acres of alfalfa and 40 acres of corn. The mean growing season of Pine River is May 5 to September 29. The normal rates of consumptive use of water by these two crops during the growing season for a period of 55 years are shown in Table 10-4. Theoretically, the difference between the consumptive use, U, and the total rainfall, R, or U - R, is the amount of water to be supplied by irrigation. In the case of Pine River, Wisconsin, it is 8.55" (or 27.09 - 18.54) for alfalfa, and 6.96" (25.50 - 18.54) for corn. But the actual amount of irrigation water to be supplied depends upon the amount of water loss. As mentioned previously, the water loss is determined by evaporation, transpiration, runoff, percolation, and the like. With the consideration of water loss, Blaney defined the "irrigation efficiency" as the "percentage of irrigated water

[9]This refers to the growing season which is designated as the time lapse between the last killing frost in the spring and the first in the autumn (see Section 4.2.2 for detail).

that is available for consumptive use by crops." When the water delivered is measured at the farm headgate, it is designated as "farm irrigation efficiency." The efficiency values used by Blaney at Montrose Area, Colorado, for alfalfa, corn, grass hay, and orchard, were 60, 55, 50, and 60 percent, respectively. For most crops, these values varied from 40 to 70 percent, depending upon soil conditions and irrigation systems. Applying these efficiency values to alfalfa and corn in Pine River, the actual values of irrigation water needed for the normal growing season are estimated as those shown in Table 10-5.

Thornthwaite & Mather (1955) have employed Equation (7-25) (Thornthwaite's formula, see Section 7.4.2) for the estimation of potential evaporation in their study of water budget at a given soil profile. Their bookkeeping scheme is based on the soil moisture gain by precipitation and loss by evapotranspiration. Surplus water exists when precipitation exceeds evapotranspiration, and the reverse results in water deficit, which is taken as an indication of the need for irrigation. Their computation of water balance for Seabrook, New Jersey, is given in Fig. 10-5, in which annual amounts of precipitation, evapotranspiration, water surplus, water deficit, soil water utilization, and soil water recharge are clearly shown. Table 10-6 gives the potential evapotranspiration estimate for Madison (43°08'N) for the growing season of May to September, 1952—1957, based on Thornthwaite's method.

Table 10-6. Computation of Potential Evapotranspiration by Thornthwaite's Method, Madison, Wisconsin, 1952-1957

Month	T(°F)	t(°C)	I	a	e* (mm/day)	C.F.**	E*** mm/mo.	E*** in/mo.
May	57.1	13.9	44.79	1.20	2.07	37.8	78.2	3.08
June	69.6	20.9	44.79	1.20	3.40	38.4	130.6	5.14
July	73.8	23.2	44.79	1.20	3.83	38.7	148.2	5.83
August	71.1	21.7	44.79	1.20	3.53	36.0	127.1	5.00
September	61.8	16.6	44.79	1.20	3.04	31.2	94.8	3.73
May to September							578.9	22.78

* Unadjusted potential evapotranspiration in millimeters per day.

** Correction factor (C.F.) — the mean possible monthly duration of sunlight for Madison, Wisconsin, latitude 43°N, expressed in units of 12 hours (see Thornthwaite & Mather, 1957, p. 228).

*** Total evaporation for a given month is equal to the product of e and C.F. of the same month.

Since evapotranspiration is not usually a directly measurable factor, it is essential that the estimation of potential evapotranspiration be as accurate as possible. Penman (1948) used the daily mean sunshine hours (n/N), temperature (T), humidity (r), and wind velocity at two-meter height (mph), for the evaluation of potential evapotranspiration (see Equations 4-49 and 4-50). Among various methods of estimation,[10] Penman's formula has generally been recognized as the most satisfactory. When Equations (4-49) and (4-50) are applied to the Madison data, the results are as given in Table 10-7.

As seen in Table 10-8, a comparison of the Blaney-Criddle, Thornthwaite, and Penman methods reveals that Penman's method gives higher estimates than the other two methods. Although in the present case similar results are obtained from the Blaney-Criddle and Thornthwaite methods, the results may not be quite so similar in other cases, depending upon the choice of K value in the Blaney-Criddle equation and the season of the year.

Table 10-7. Computation of Potential Evapotranspiration by Penman's Method, Madison, Wisconsin, 1952-1957

Month	n/N (%)	T (°F)	r (%)	U_2 (mph)	E mm/day	E inches/week
May	58	57.1	66	5.6	3.78	4.61
June	70	69.6	68	5.0	5.33	6.30
July	72	73.8	69	4.4	5.44	6.63
August	73	71.1	69	3.9	4.49	5.47
September	74	61.8	66	4.5	2.79	3.30
May to September						26.31"

Table 10-8. A Comparison of the Blaney-Criddle, Thornthwaite, and Penman Methods in the Computation of Evapotranspiration, Madison, Wisconsin, 1952-1957

Month	Blaney-Criddle	Thornthwaite	Penman
May	3.78	3.08	4.61
June	4.66	5.14	6.30
July	5.00	5.83	6.63
August	4.46	5.00	5.47
September	3.37	3.73	3.30
	21.27	22.78	26.31

In the above macroclimatic considerations, the water balance is obtained from the available climatic data of the weather shelter level

[10]E.g., Thornthwaite, 1948; Blaney & Criddle, 1950; Albrecht, 1950; Ivanov, 1954; Turc, 1955; Hamon, 1960; and many others (see Van der Bijl, 1956-1959).

Table 10-9. Daily Water Budget for a 14-day Period in Lethbridge, Canada

	A.E./P.E. Ratio: 1.00				0.50		0.20		0.10		0.05	
	Field Capacity: 0.25				0.25		0.25		0.25		0.25	
	PE	Rain	AE	SM	AE	SM	AE	SM	AE	SM	AE	SM
April												
1	0.15		0.15	0.10								
2	0.10		0.10	0.00								
3	0.05	0.06	0.05	0.01								
4	0.08	0.05	0.06	0.00	0.01	0.24						
5	0.22				0.11	0.13						
6	0.26				0.13	0.00						
7	0.20						0.04	0.21				
8	0.24						0.05	0.16				
9	0.28						0.06	0.10				
10	0.16						0.03	0.07				
11	0.16						0.03	0.04				
12	0.10						0.02	0.02				
13	0.05	0.35	0.05	0.25		0.05						
14	0.03	0.33	0.03	0.25		0.25		0.12				
Total	2.08	0.79	0.44	0.25	0.25	0.25	0.23	0.12	0.00	0.25	0.00	0.25

PE = potential evapotranspiration; AE = actual evapotranspiration; and SM = soil moisture, After Holmes (1959) with minor modification.

Remarks: The water budget for the 14-day period can be computed by $Mo + R - A = M_f$, where Mo is the total initial soil moisture content at all layers; R, the total rainfall during the period; A, the total actual evapotranspiration; and M_f, the final soil moisture after the 14-day period. Hence Mo = 1.25''; R = 79''; A = 92''; and M_f = 112''. Substituting in the above equation, we have: 1.25 + 79 - 92 = 112.

and is based on the estimation of potential evapotranspiration (P.E.), not the actual evapotranspiration (A. E.). When soil is wet or at its field capacity, the above methods give a fairly good approximation. But when soil is dry or near the permanent wilting point, and when irrigation is urgently needed, these methods are not very satisfactory. Stated in a different way, the P. E. values are over-estimated when the soil is dry, and a reduction of P. E. is required. Taking account of the degree of soil dryness and the expansion of the plant root system, Holmes (1959, 1960, and 1961) modified the classical method of P.E. estimation by multiplying a factor of A. E./P. E. ratio to P. E. for obtaining A. E. He assigned a value 1.00 to the ratio when soil is at field capacity; thus, P.E. = A.E. When the soil is below field capacity, the ratio becomes 0.50, 0.20, 0.10, and 0.05, respectively, at different depths, according to the amount of soil moisture present in each layer. In other words,. when the surface soil moisture is depleted, the rate of actual evapotranspiration is reduced, and a 50 percent of P.E. is accounted for A. E. Further reduction of soil moisture by 20, 10, and 5 percent of the P.E. is made for each successive layer. In actual practice, the percentage rate at which each successive layer of soil moisture is withdrawn is first determined experimentally. Table 10-9 illustrates Holmes' scheme of computation (Holmes, 1959). By using Coleman moisture blocks for the measurement of soil moisture, Holmes was able to confirm that the actual bookkeeping scheme is far more accurate than the classical scheme. His findings are shown in Fig. 10-8, where the available moisture contents in inches below the zero line are hypothetical.

In the microclimatic consideration, the energy balance approach, such as the radiation budget and/or heat budget (see Section 4.1.1), as well as the aerodynamic method, can be employed for the estimation of water balance. Applications of such methods have been demonstrated in the past with varying degrees of success. For a small

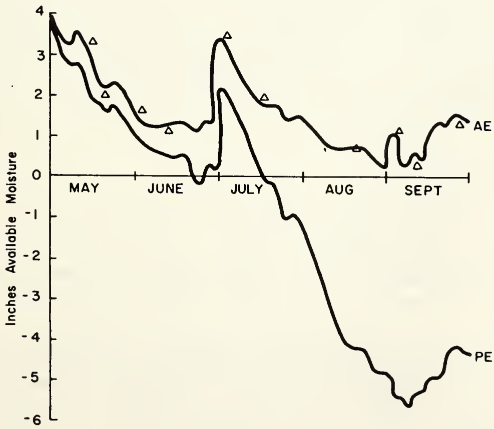

Fig. 10-8. A comparison of actual and potential evapotranspiration.
After Holmes, 1959

area, a greater accuracy can be achieved with an elaborate measurement. For example, the equation representing the thermal balance at an evaporating surface may be written as

$$Rn = LE + H + G, \qquad (10\text{-}4)$$

where Rn is the net radiative flux at the evaporating surface, L, the latent heat of evaporation of water, E, the rate of evaporation per unit area, H, the rate of transfer of sensitive heat per unit area from the evaporating surface, and G is the rate of heat storage per unit area below the evaporating surface. The Rn and G are usually measurable and thus the relative magnitudes of E and H can be determined.

Another aspect in the microclimatic consideration is the hydrological approach, in which factors other than precipitation and evapotranspiration are taken into account. This approach may be presented simply as

$$P = R + p + M \pm e, \qquad (10\text{-}5)$$

where P is the precipitation, R, the surface and subsurface runoff, p, the percolation or infiltration below the root zone, M, the soil moisture present in the layer concerned, and e is the error due to a number of factors other than those stated above. The choice of factors depends on physical and chemical properties of soil, topography, seasonal weather conditions, size of irrigated areas, and species and varieties of crops. A decision-maker, therefore, should carefully evaluate the effect of over-all factors for his own locality.

In the scheduling of irrigation, various instruments are available for the direct or indirect determination of soil moisture conditions, including the tensiometer, lysimeter, neutron scattering device, and Bellani atmometer.[11] For a small farmland, such instruments may be useful, but for a large area, the sampling techniques should be carefully examined and established.

10.3 WATER DRAINAGE

The scheme of water management includes conservation of soil moisture, irrigation, and land drainage. Conservation is to hold the existing water on, irrigation is to supply water to, and drainage is to remove excess water from, a given area. Sources of excess water on

[11]The characteristics of these instruments are discussed in Section 5.4.

Deacon et al. (1958) have summarized instrumentation for the determination of evaporation and water balance as: (a) the lysimetric method; (b) the soil moisture profile method; (c) the aerodynamic method; (d) the eddy correlation method; and (e) the energy balance method. For detail, see Deacon et al., 1958, Evaporation and water balance, in ***Climatology***, UNESCO, pp. 25-28.

Slatyer & McIlroy (1961) discussed methods of soil water measurement under the classification of (a) neutron scattering; (b) conductivity block; (c) tensiometer; (d) dielectric method; (e) thermal conductivity; and (f) gravimetric auger or tube sampling. For detail, see Chapter 3, pp. 30-32, in Slatyer & McIlroy's ***Practical Microclimatology***, UNESCO.

farmland are excessive rainfall, over-irrigation, seepage inflow, and even flooding. The purposes of drainage are to make possible spring planting, land preparation, tillage, and the harvest operations. Above all, it is used for the establishment of a better environment for the growth and development of crops, particularly for the survival of crops. When soil is constantly wet, its temperature is low and the growing season is noticeably shorter. In such an area, aeration is also poor and crop yield is greatly lowered. Wooten & Jones (1955) reported that 22 counties in northern Ohio and northeastern Indiana which were originally too wet for farming are now the most productive areas in the country, through successful drainage programs. According to the 1950 Census of Agriculture, directed by the U.S. Bureau of the Census, the agricultural products in those counties amounted to more than 225 million dollars. In fact, in the U. S. A., over 100 million acres of agricultural land were under drainage systems of one kind or another in the year 1950. For illustration, Fig. 10-9a shows the open drainage ditch, six miles long, being constructed in 1952 at Grafton, North Dakota. In 1953, a golf course and farms in the vicinity enjoyed their dry beautiful land. Fig. 10-9b shows the digging of a drainage ditch with a back hoe. Such work is rapidly executed by this method.

Physical processes which facilitate drainage are infiltration, percolation, and runoff. Through infiltration, excess water enters into the soil and moves downward. When the water reaches the deep soil and stays away from the root zone, the purpose of drainage is achieved. Factors governing the infiltration process are soil structure, soil moisture conditions, and soil temperature. Musgrave (1955) classified soil types into four groups according to their drainage potential:

Groups	Minimum Infiltration Rate	Examples[12]
A. Highest	0.30 to 0.45 inches per hour	Knox and Southeast Sandhills
B. Above-average	0.15 to 0.30 inches per hour	Durham and cecil fine sandy loam
C. Below-average	0.05 to 0.15 inches per hour	Crown heavy clay & cecil clay loam
D. Lowest	0.00 to 0.05 inches per hour	Houston and Trinity

After Musgrave, 1955

His classification is based upon the physical and chemical properties of soil, such as soil structure, degree of swelling, and degree of saturation, as well as composition of organic matter and colloids. When soil temperature is high, the infiltration rate increases; when low, it decreases. In some soil the infiltration rate is determined by the viscosity of soil water and thus infiltration is directly proportional to soil temperature. A common example of the effect of temperature and viscosity is the flow of molasses, which is much slower when cold than when warm.

[12]For details, the reader may refer to Musgrave, How much of the rain enters the soil?, in ***Water, Yearbook of Agriculture, 1955***, U. S. Dept. Agr., pp. 151-160.

Fig. 10-9a. Drainage with open ditch in Walsh County, North Dakota. Courtesy U. S. Soil Conservation Service, 1953

Percolation, on the other hand, is directly and indirectly associated with the water table. Thus, a knowledge of the position and the frequency of the fluctuation of the water table, particularly its diurnal and seasonal variation, is required in drainage design. Fig. 10-10 is an example of ponding and drowning of a crop after irrigation, due to high water table and lack of percolation. It has been reported that a change of wind direction and speed tends to alter the height of the water table. The seasonal and diurnal variation of local wind velocity, as well as the abrupt change of barometric pressure, as to the fluctuation in water table should be considered in relation to the rate of discharge of the water, the rate of capillary action, and the height of capillary fringe. The most important controlling factors, however, are the intensity, duration, and seasonal variation of rainfall. Drainage problems exist in a farmland whenever the rate of water inflow exceeds the rate of water outflow. Thus, the accumulation of water in the drainage area should be studied in conjunction with the rate of evapotranspiration, rainfall, runoff, infiltration, and percolation.

The layer of soil above the water table, its initial moisture content, pore size, and surface coverage conditions generally determine the feasibility of drainage. Soils below the capillary fringe and above the water table are always saturated, while soils above the capillary fringe are usually unsaturated. As far as drainage is concerned, the physical condition of this unsaturated layer is far more important than the water table itself. There have been many studies, both theoretical

Fig. 10-9b. Back hoe digging an open drainage ditch in North Dakota.
Courtesy U. S. Soil Conservation Service, 1953

and experimental, on the water flow in unsaturated soil in relation to drainage. Gardner & Widtsoe (1921) found that the higher the initial moisture content of the soil, the greater is the tension gradient and the more rapid is the percolation. With a moisture content of 15.9, 20.2, and 29.9 percent, the penetration reaches to about $1\frac{1}{4}$, 4, and $7\frac{1}{2}$ inches in depth, respectively. Lyon et al. (1952) concluded that the vertical movement of soil water is determined by the capillary adjustment, percolation, and vapor equalization. The redistribution of soil moisture after infiltration and the soil moisture condition at the initial stage has been studied by Philip (1957), Childs (1958), Young (1958), and Wesseling (1961). Young studied the moisture profiles during the redistribution of moisture after infiltration in the vertical

Fig. 10-10. Ponding of crops by high water table, Imperial Valley, California. Courtesy U. S. Soil Conservation Service, 1953

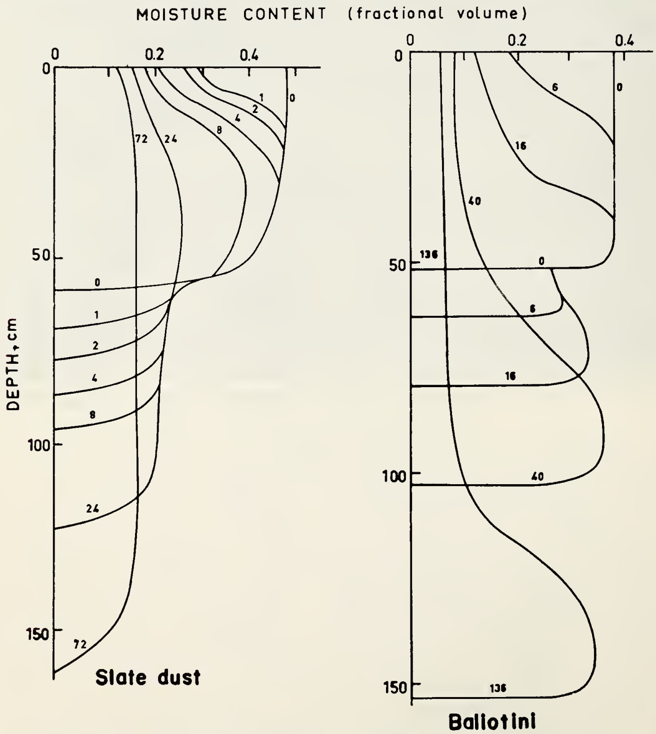

Fig. 10-11. Moisture profiles during the redistribution of moisture after the cessation of infiltration. After Young & Wessling, 1961

direction, of slate dust and "Ballotini" soil. Fig. 10-11 shows Young's findings on the redistribution of soil moisture with time, both in amount and depth. Figures on the curves indicate the time in hours after the cessation of infiltration; the left-hand curve indicates the redistribution of moisture in slate dust, and the right-hand curve, that in the "Ballotini" soil.

As to pore size, a soil with a high percentage of drainable pore space will give a smaller rise of the water table than a soil with a low drainable pore space. The pore space in sandy soils generally ranges from 35 to 50 percent; that in heavy soils varies from 40 to 60 percent or perhaps even more, in cases of high organic matter and marked granulation. Pore space also varies with depth; it may drop to as low as 25 to 30 percent in compact subsoil. An intense surface soil compaction tends to decrease the drainable pore space, and creates a serious drainage problem. Various formulations have been prepared by soil scientists for the computation of drainable pore space, or the soil moisture storage capacity. Recently, Visser (1962) demonstrated by his formulation for non-steady and quasi-steady water flow that the drain spacing varies inversely with the square root of the drainable pore space.

For determination of the drainage coefficient, various formulations, nomograms, and charts have been developed by hydrologists, agricultural engineers, and especially by soil conservationists. The drainage coefficient is defined as the rate of runoff to provide a specified degree of drainage with regard to climate, topography, land use, and soils. The estimate is based on the total runoff for drainage time, including the storm runoff and peak flow. In this connection, the intensity, duration, and total amount of rainfall associated with the cyclonic activities in an area are very important factors to be taken into consideration.

In agricultural practice, tillage, mulching, cropping system, and soil management improve the drainage of farmland to a certain extent. Discussion of this topic will be given shortly, in Section 11.1.4.

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CHAPTER 11

Environmental Controls

Environmental control in agricultural meteorology can best be described here as the artificial manipulation of a given environment for optimal production, protection against weather hazards, and production of crops and animals in unfavorable seasons. Another, and larger, area of the field of control in applied meteorology is concerned with human comfort, as dealt with in urban, medical, and human bioclimatology. In the past, control of the physical environment of crops has been accomplished more by means of artificial conditions (e.g., greenhouses); in the natural field, modification, rather than control, has been the objective. Moreover, although a given environment consists of several interacting factors, efforts are directed primarily to the control of one or two factors at a time, and only rarely — due mainly to economic considerations—to all environmental factors simultaneously. Furthermore, environmental modifications thus far accomplished are largely for preventive purposes (e.g., the avoidance of weather hazards) and/or for the improvement of environmental conditions. Strictly speaking, neither the application of soil and climatic criteria in appraisals of farming areas nor the formulation of genetic considerations in the selection of new species and varieties comes under the heading of environmental control. The former has to do with the selection of suitable areas for a specific crop or animal, while the latter deals with the selection of crops and animals to fit a given environment. The present chapter concerns the control and modification of physical factors in crop and animal environments, both natural and artificial, with emphasis on improving crop production. The discussion of crop environment is presented largely under the topic of natural field modification, with some separate consideration given to greenhouse and phytotron controls. The topic of farm animal environment control is treated in terms of the animal house, poultry house, and biotron. Some of the materials discussed in Chapters 3, 4, and 5 are cited or further elaborated in this chapter, and the reader may find it profitable to refer to them from time to time.

11.1 MODIFICATION OF THE NATURAL ENVIRONMENT

Since the great majority of agricultural crops are grown in the natural field, it is only reasonable to consider first the control or modification of the environment of crops in their natural surroundings. It should be emphasized that it is the microenvironment which is of concern here. And since all environmental factors are interrelated, any attempt to modify one may influence the others as well.

11.1.1 *Radiation*

As has been pointed out elsewhere in this text, intensity, duration, and quality are the three factors to be considered in the investigation of radiation-environment relations. Notwithstanding the interrelationships that exist among them, radiation modification in the natural field is usually undertaken by the variation of individual aspects of radiation, according to their significance to the growth and development of crops. The chrysanthemum, a short-day plant, may have to be shaded with tents of white or black cloth, when reduction in the duration of light is essential for flowering. Needless to say, such practices will also affect the quality of the light as well as such factors as wind, evaporation, and temperature. However, these are less significant than light duration to the floral initiation of the plant. In Pasadena, California, it has been found that tomato plants could set fruit as early as May or June if they were covered by black cloths during the late afternoon. Such plants start to form tomatoes at least a month ahead of uncovered plants. Reduction of day-length can also be accomplished by planting along the east side of a shelter hedge, to obtain the effects of shading.

Modification of radiation in the field can be approached in two ways: (a) the manipulation of incoming radiation during the day, or (b) the manipulation of outgoing radiation at night. In short, modification aims at increasing or decreasing the duration and intensity of various types of radiation for desired effects.

(a) Incoming radiation during the day. Radiation on a given field can be intensified by increasing the absorptive power of the soil or plant surface, by increasing the reflective power of surrounding objects, by improving exposure through site selection, and by other means.

The absorptive power of a surface can be increased by darkening (or reducing the albedo of) the surface. The albedo is influenced by the color, moisture condition, texture (smoothness or roughness), and shape of the surface, the cloudiness of the day, and the angle and wavelength of the incident ray. Table 11-1 illustrates the albedo of various soil surfaces. For the albedo of various other materials, including living plants, the reader may refer to Tables 4-1 and 4-2, which indicate a range from 93 percent (white plaster) to about 0 percent (lampblack), with corresponding absorptive powers of 7 percent and 100 percent, respectively.

In Table 11-1, low albedo values are noted for the longwave spectrum, indicating an extensive absorption of infrared radiation by most surfaces, particularly by snow. Since albedo values are determined by many factors, those values listed in Table 11-1 should be taken as comparative, rather than absolute, figures.

The incoming radiation energy, upon reaching the ground, is mostly converted into latent heat when the soil is wet, and into sensible heat when it is dry. During the growing season, the latent heat takes the form of vaporization heat, while in freezing weather, it becomes the heat of fusion; the former is consumed in the evaporation of plant and soil water, and the latter in the melting of snow and ice. The sensible heat is stored in the soil, the air, and the plant; thus it is usually expressed in terms of soil, air, and plant temperature. With respect to soil temperature and its relation to radiation, it has often been used as representing the absorptivity of the ground rather than the albedo, as indicated by the following illustrations.

As early as 1878, Wollny observed differences in soil temperature with the application of black and white coloring to three types of soil. Bouyoucos (1913) studied the sunlight absorption power of a shallow layer of dry, exposed sand. His findings are shown in Table 11-2. The observed temperature difference between white and black sand in the first trial was 6.3°C, and it was 5.9°C for the second, resulting in a mean difference of 6.1° C. With the use of dry sand, a rather close correlation between the temperature and color of the sand is obtained. As is shown in Table 11-1, moist soil has a lower albedo, as a portion of the radiation is totally reflected within the water films. Moist soils appear darker than dry soils, and thus the presence of water in soil overshadows the color effect to some extent.

Everson & Weaver (1949) investigated the effect of carbon black on soil temperature, using applications up to 4000 pounds to the acre. On average, the daily maximum temperature of the carbon-treated soil was 2.0°F higher than that of untreated soil at the surface, and 3.4°F higher at a depth of two inches. For the daily minimum temperature, it was 0.8°F and 0.5°F higher at these respective levels. For both maximum and minimum temperatures, the deviations between the treated and untreated soil were much larger during May and June than during the period from July through September. At the surface, the treated soil had an average daily temperature 1.2°F higher than untreated soil.

Table 11-1. The Albedo of Various Soil Surfaces

Soil Types	Albedo (%)	Spectral Ranges	Source of Information
Longwave spectrum:			
Desert surface	24-28	Infrared[1]	Ashburn & Weldon, 1956
Light color sand	11	Infrared	Falckenberg, 1928
Coarse gravel	8- 9	Infrared	Falckenberg, 1928
Light gray limestone	8- 9	Infrared	Falckenberg, 1928
Soil clods	2	Infrared	Falckenberg, 1928
Snow	0.5	Infrared	Falckenberg, 1928
Visible spectrum:			
Dry dune sand	37	Visible[2]	Büttner & Sutter, 1935
Moist dune sand	24	Visible	Büttner & Sutter, 1935
Heath & sand	10-25	Visible	Geiger, 1959
Chernozem	10-15	Visible	Ventŝkevich, 1958
Fresh snow cover	80-85	Visible	Geiger, 1959
Old snow cover	42-70	Visible	Geiger, 1959
Shortwave spectrum:			
Stones (gravel, granite & chalk)	22-25	Ultraviolet[3]	Hausmann & Kuen, 1934
Gray sand	18	Ultraviolet	Ångström, 1925
Dry dune sand	17	Ultraviolet	Büttner & Sutter, 1935
Moist dune sand	9	Ultraviolet	Büttner & Sutter, 1935
Dune heath	2	Ultraviolet	Büttner & Sutter, 1935
Garden soil	6	Ultraviolet	Hausmann & Kuen, 1934

1, 2, & 3 refer to wavelengths of 0.76 to about 100μ, 0.36 to 0.76μ, and below 0.36μ, respectively.

Table 11-2. Radiation Effects on the Maximum Temperatures of Various Colored Sands

Color	Maximum Soil Temperatures, Degrees Centigrade		
	Trial No. 1	Trial No. 2	Mean
Black	40.9	37.6	39.2
Blue	40.0	36.7	38.3
Red	38.6	35.9	37.2
Green	37.1	34.7	35.9
Yellow	35.8	32.7	34.2
White	34.6	31.7	33.1

After Bouyoucos, 1913

Various dark colored materials, such as carbon black and coal dust, have been applied to the soil surface for the purpose of prolonging the growing season and of preventing winter damage. In Hungary, Hank & Vásárhelyi (1954), in their study of the effect of soil color on the development of cotton, found that coal dust hastened the warming in the spring and postponed the first killing frost in the fall. An advance of a month or more in cotton ripening was reported in Kazakstan, USSR, with the application of 100 pounds of coal dust per acre. Coal dust is also known to accelerate the melting of snow and ice. Aderikhin (1952), also in the USSR, reported on the increase of soil temperature from darkening the soil.

Table 11-3. Radiation Effects on Temperatures of Wooden Blocks

Paint Color	Temperature Difference, Degrees C
White lead paint	10.8
Rosepaint (Zinc white with dammer lacquer)	11.0
Yellow ochre paint	14.8
Red oil paint	15.7
Lamp-black	16.9

After Dorno, 1931

The reduction in radiation energy can also be obtained by simply applying highly reflective material. For example, dusting tobacco leaves with white powder in summer is a common practice among tobacco growers. It increases albedo and decreases transpiration of the leaves. It is also reported that the percentage of wilting at noon is greatly reduced by this method. In India, Ramdas & Dravid (1934) experimented with the application of white lime powder on black cotton soils, and found the temperature of lime-treated soil to be 15°C lower than that of untreated soil at 10 cm depth. They also found that this effect continued for about one to two weeks after the removal of the lime. Dorno (1931) measured the temperature of variously painted small cylindrical wooden blocks exposed to the south. It was found that the temperature of a white-lead coated block was 6.1°C lower than a lampblack-coated one. His findings are shown in Table 11-3, in which the temperature values represent increases above the ambient air temperature.

Numerous observations have been made on the microclimatic conditions in the vicinity of a wall. The south and west facing wall, particularly a whitewashed wall, can serve as a reflector of the sunlight. It contributes a large amount of energy to the vicinity by reflection and affects various microclimatic factors, such as soil and air temperature, evaporation, soil moisture, and the like. In Germany,

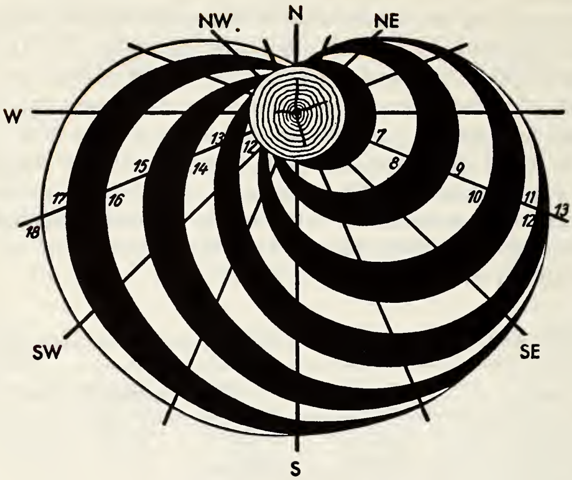

Fig. 11-1. Hourly amount of heat received on the surface of a tree trunk in April. After Krenn, 1933

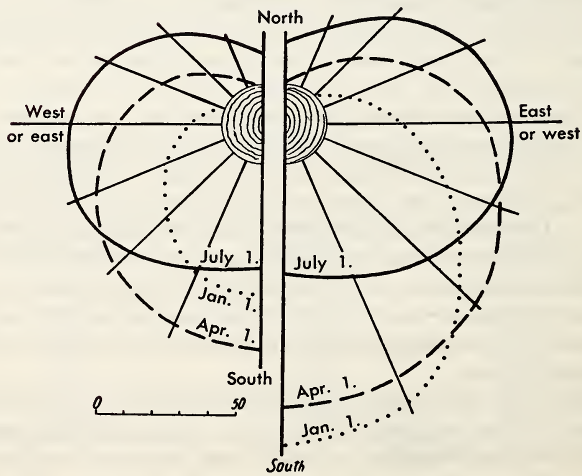

Fig. 11-2. Daily amount of heat received on the surface of a tree trunk in various seasons. After Krenn, 1933

Weger (1951) reported on the effect of a combination of variously colored walls and different soil covers (e.g., coal dust, sand, glass fibers, koalin, and aluminum foils) on soil temperature. In Cyprus, Boyko (1955) observed ***Stipa tortilis***, a grass, that under west and south walls can grow in places 500 meters above the normal upper growth limit. In Alaska, Bensin (1955) measured the effect of a vertical aluminum reflector on the temperature of coal dust-covered soil at a depth of six inches. Although many observations and experiments have been conducted on reflectors, application has rarely been done on a large scale. It is interesting to note that the solar intensity can occasionally be doubled by the reflection of clouds when the sun beam is passing through the gaps between clouds. On the other hand, with light cloud obscuring the sun, the direct beam will be reduced to zero (Slatyer & McIlroy, 1961).

Dissipation of fog and clouds by means of seeding techniques, as by the application of dry ice of freezing agent, is another approach to obtaining a greater intensity of incoming radiation. For example, Dessens & Soulage (1954) precipitated supercooled fog by the emission of iodide smoke from the ground. Olivier (1956) also succeeded in precipitating supercooled fog by releasing propane gas under pressure from a cylinder on the ground. In 1956, Aufm Kampe et al. and Weickman demonstrated that stratus cloud with temperature below -5°C can be dispersed at least temporarily by seeding from aircraft. The cloud seeding technique is not feasible for fog or cloud with temperature at or above 0°C. The technique is also restricted to calm and light wind conditions, and to small-scale operations. Other applicable methods of fog dissipation include blowing warm dry air from the ground, and the application of high voltage electric sparks or high frequency sound waves to promote coalescence.

A further means of modifying the intensity of incoming radiation is by control of the exposure. Although the duration and quality of light would also be affected by modification of exposure, the effect on the intensity is generally of primary concern. The greater the exposure, the higher is the intensity. Common agricultural considerations for obtaining variation in exposure are slope of sites, orientation and width of the crop rows, and companion cropping systems. In Section 4.1.2, the topic of sunniness has been fully discussed in relation to such factors as slope inclination, latitude, altitude, and the declination of the sun.

A combination of the effects of shading and altitude on solar intensity received by a tree trunk in the course of the day was observed by Krenn (1933) in Austria. He measured solar intensity on the trunk in 16 directions, on the Kanzel summit in Karnten (1474 meters msl), and on the plain in Vienna (202 meters msl), and summarized the results with diagrammatic sketches, as illustrated in Figs. 11-1 and

11-2. Fig. 11-1 indicates the hourly progress of the warming of the surface of the trunk on a cloudless day on April first on the Kanzel summit. In this figure, the center of the sketch is the cross-section of the tree; the edges of the black and white curves indicate the total hourly amount of heat received at each specific hour, with local time being labelled by Arabic numerals. The outermost border line represents the daily total heat received. Fig. 11-2 shows the bilateral systematic diagram, representing the daily total heat received by the surface of the trunk on a cloudless day in January, April, and July, for both Vienna and Karnten, the left half of the sketch being the Vienna basin, and the right half, the Kanzel summit. For the July cloudless day, not much difference is observed in the intensity between the lowland (Vienna) and the mountain (Karnten). But in January the east and west sides of the Kanzel tree received almost twice as much energy as the Vienna tree. In both locations, the south side of the trunk received more radiation in winter (January) than in summer (July). Geiger (1959) made a comprehensive summary of microclimatic effects of different sunshine exposures as well as the sunniness of different slopes, a reference recommended to the reader.

The shade created by companion crops or shelterbelts and other obstructions would also reduce the intensity of incoming radiation, and would modify quality and duration to some extent. The amount of the maximum solar beam falling perpendicular to plant leaves is 1.00 langley per minute for direct radiation, and 0.30 for diffuse radiation. The beam that falls parallel to the leaves is about 0.40 langley per minute at its maximum. Dinger (1941) and Sidorin (1950) estimated that about 50 percent of the incident radiation is absorbed by leaves. It follows, then, that 0.65 ly min^{-1} would be absorbed by the leaves when the light is falling perpendicularly, and 0.20 ly min^{-1} when parallel. The amount of radiation which passes through the leaves is even smaller. It varies with the color, thickness, and orientation of the leaves, and such weather conditions as wind velocity, solar declination, etc. In a large plant community, a portion of the radiation breaks through the canopy between the leaves, another portion may be reflected by the leaves, and still another portion may be transmitted through the leaves. The transmissivity or penetrability of leaves varies from 5 to 60 percent of the incident radiation, depending upon the wavelength. When all types of wavelength are considered, the transmissivity of plants in general is the percentage of indicent radiation which the leaves transmit. The light which is transmitted through the leaves appears greenish and is termed "green shade" (Seybold, 1936); it is 0.8 microns of the infrared spectrum at its maximum. Forest shade and infrared shade are green shades. Another type of shade, such as that of a wall, is known as "blue shade." Strictly speaking, the radiation under green shade is both transmitted and diffuse, whereas under blue shade it is all diffuse. Thus, under the companion crop system, or under the canopy of a shelterbelt, radiation is modified. Studies on reflection and absorption, or simply interception, of light by various species of plants would be useful in the modification of radiation.

Ångström (1925) observed light interception in a field with a mixture of meadow and ***Dactylis glomerata*** grass of about one meter height. The light intensity was measured at four different heights: at the top of the crown (100 cm above the ground), at 50 cm above the ground, at 10 cm above the ground, and at the surface. Corresponding results were 1.08, 1.04, 0.28, and 0.19 langley per minute. When the percentage of radiation received at the crown top is taken as 100, it is 96 and 26 percent at 50 cm and 10 cm above the ground, respectively, and 18 percent at the ground surface.

In 1933, Trapp, with a photocell, measured the luminance under the canopy of some 150-year-old beech at Lunz, Austria. He found that some 80 percent of the incident light is intercepted by the canopy, 10 to 15 percent by various obstructions at the trunk space, and the remaining 5 to 10 percent reaches the forest floor. According to Trapp, there was no significant difference in the amount of light received by the forest floor between clear and cloudy days. More absorption of light by the canopy was observed on sunny days than on cloudy days. Moreover, since the sky-light which characterizes cloudy days diffuses in all directions, the interception by the canopy is insignificant. On the basis of numerous measurements of illumination on the forest floor, Trapp (1938) presented several "cloudy weather illumination maps," in which the close association between the distribution of illumination and the foliage distribution is seen. In sunny conditions the illumination is very irregular, due to stray sunbeams breaking through the crowns; spotted light on the forest floor moves along with the course of the sun. The irregularity varies with the time of the day and season of the year.

In the USSR, Petrov (1954) studied the effects of illumination and soil moisture conditions on the growth (weight gain) of grasses under the following three groups of experimental conditions: (a) with soil moisture conditions at 15, 58, and 90 percent of the field capacity; (b) with cover of elm trees plus soil moisture conditions specified as above; and (c) with tree cover of lower density and soil moisture conditions at 15, 30, 45, 60, 75, and 95 percent of the field capacity. The results of his study are as follows: under full illumination, as in condition (a), the weight gain was much greater than under the shade, as in conditions (b) and (c), irrespective of soil moisture conditions. However, with the canopy of elm trees, as in condition (b), the growth varied with different soil moisture conditions. For those under sparser cover, as in condition (c), both the intensity of illumination and the soil moisture condition had bearing on the growth.

The effect of shading and plant density on growth and efficiency of solar energy utilization in barley, and that of plant density on efficiency of solar energy utilization in marigold were investigated by Kamel (1959) in Wageningen. With barley, 100 percent (full daylight), 80, 50, and 25 percent light intensities were applied for light treatment; for plant density, 500, 250 (normal), and 125 plants per square meter were employed. Two densities, 25 plants/m^2 and 8.3 plants/m^2 (normal), were applied with the marigold. It was found that the efficiency of solar energy utilization, in terms of production of dry matter, is low at the early stage and reaches minimum at the late stage of growth. However, the efficiency comes to its maximum at the time when the shoot, leaf number, growth rate, fresh weight, and total leaf area reach their maximum. Although the efficiency values increased with shading during the early and the late stage, the average efficiency was found to decrease with reduction of light intensity. The average values ranged from 2.9 percent for full daylight to 1.4 percent for 25 percent light intensity. In barley, increasing the plant density to 500 plants/m^2 favored the production of dry matter and led to higher efficiency values only during the early stage of growth. An increase in plant density from 125 to 250 plants/m^2 induced higher final yield and average efficiency. On the other hand, for marigold, an increase in plant density up to 25/m^2 induced maximum yield throughout the entire growing season with the exception of the late stage. Kamel concluded that the efficiency of solar energy conversion closely follows the age trend of growth and is not constant.

Additional examples of studies on shading-plant growth relations include that of Auchter & Schrader (1926, 1929) on the growth of fruit bud formation and chemical composition of apple trees; Paddock & Charles' (1928) on fruit bud differentiation; Gourley & Nightingale's (1921) and Kraybill's (1922) on flowering buds of peaches; Chamarro's (1952) and Smith's (1953) on the growth of cacao; Rolfs' (1903-1904) on pineapples and citrus fruits; and Kitchin's (1917) on the growth of some coniferous seedlings. On the measurement of shading, we have Friend's study (1959) on a chemical radiation meter, and Wright's determination (1943) of the degree of shading under forest canopy. With respect to microclimatic effects of shading, Shreve (1931) observed the microclimate in sunshine and shade, and the Lake States Forest Experiment Station (1935) investigated the reduction of surface soil temperature by shade.

(b) Outgoing radiation during the night. As mentioned earlier, the long-wave radiation at night consists of two vertical components: the downward flux resulting from the emission of water vapor, carbon dioxide, and ozone in the atmosphere, and the upward flux of radiation from the bare ground and the canopy of vegetation. The balance of the two components is termed the net long-wave radiation, or the effective outgoing radiation. The empirical formulations for the computation of the effective outgoing radiation have been given in equations (4-2) to (4-4), and the use of the energy balance method for this computation has been illustrated in equations (4-16) and (4-17). The spectrum range, as computed in terms of Wien's displacement law, is between 2 and 50 microns, with its maximum around 10 microns (see equation 4-5). Although the nocturnal radiation is much weaker than the shortwave radiation (daylight), it plays an important part in the microclimatic regime.

Under the companion cropping system, the outgoing nocturnal radiation flux is intercepted by the crowns of the companion plants, and thus a comparatively higher nocturnal temperature is maintained in the surface air layer and in the soil. Hence small plants are well protected from cold injury in the late fall. Smoke-screens, produced by the incomplete combustion of oil fuels or by chemical means, may serve the same purpose to an even greater extent. With dense aerosol from the smoke, the radiation is either absorbed or reflected back. This technique is commonly employed for frost protection in orchards. Calder & Mumford (1947) experimented with the reduction of nocturnal radiation by zinc chloride smoke. In general, the application of such techniques should be limited to calm nights, so as to avoid the drifting of smoke away from the target area, and to keep the spreading of unpleasant odors to a minimum. There have been many studies on the reduction of outgoing radiation in relation to frost prevention. Further discussion on this topic will be presented in Section 12.1.2.

In agriculture, the main interest in the modification of nocturnal radiation is to minimize the radiation loss, and to maximize the gain in incoming radiation. The combination of the two may be particularly effective, depending upon the choice and use of material, the local climate, and the species of crop to be benefited by such practice.

In Coachella Valley, California, Kraft paper shields are used commercially to promote off-season vegetable crops, including tomatoes, peppers, and squash. In the desert regions of California, Arizona, and other parts of the Southwest, where many days are characterized by bright sunshine and high temperature, frequent frost damage of crops due to nocturnal radiation cooling, and perhaps cold air drainage, is reported. With paper shields, plants are kept from exposure to the low sky temperature, which may range from 0° to -20°F, and are kept submerged in the warm air near the ground. The paper shields for seed beds are usually erected at about a 30° angle to the normal over the beds, running east and west on a south-facing slope. Both the slope of the seed bed and the inclination of the shield are so arranged as to receive the best incident angle of sunlight. This arrangement, of course, depends upon the latitude and season of the year. During the day, the shields reflect sunlight to the seed beds, and at night they minimize the back radiation. The shields also act as a windbreak against the cold northerly air. Hart & Zink (1957) tested the effectiveness of various shielding materials, and found no substantial difference, except that aluminum foil was found to be the least effective of the materials tested, in the conservation of heat at night.

Table 11-4. Diurnal Range of Radiation (ly per min.) as Affected by Various Mulches

	Bare Soil	Black Film	Translucent Film	Aluminum Film
Sept. 12, 1958 (clear day):				
R_i	0.36 to 1.82	0.36 to 1.76	0.36 to 1.81	0.36 to 1.77
R_o	-0.48 to -0.90	-0.48 to -0.88	-0.49 to -1.04	-0.38 to -1.46
Oct. 12, 1958 (clear day):				
R_i	0.31 to 1.49	0.31 to 1.51	0.31 to 1.42	0.31 to 1.50
R_o	-0.45 to -0.85	-0.45 to -0.79	-0.46 to -0.78	-0.33 to -1.10
	Bare Soil	**Black Film**	**Paper**	**Hay**
June 11, 1959 (clear day):				
R_i	0.42 to 2.06	0.42 to 2.04	0.42 to 2.05	0.42 to 2.06
R_o	-0.52 to -1.14	-0.52 to -1.05	-0.50 to -1.43	-0.50 to -1.19
June 12, 1959 (overcast day):				
R_i	0.49 to 0.76	0.55 to 0.76	0.55 to 0.76	0.55 to 0.76
R_o	-0.51 to -0.62	-0.55 to -0.63	-0.56 to -0.66	-0.56 to -0.64

After Waggoner et al., 1960

Table 11-5. Soil Temperature at Various Depths, Under Different Mulches, on June 24, 1958 (Temperatures in Degrees Centigrade)

Depth	Bare Soil	Black Film	Translucent Film	Aluminum Film
2.5 cm	24.7	25.0	28.3	22.8
15 cm	21.1	20.0	23.3	20.0
30 cm	19.4	18.3	20.0	18.3
61 cm	17.2	16.7	18.3	16.1

After Waggoner et al., 1960

In the Connecticut Valley alone, some eight thousand acres of tobacco fields are covered with shade tents of cotton cloth, erected eight feet above the ground on wooden poles. This method was tried first in Florida and then in Connecticut around 1900. It is reported that the shade tent improves the color, yield, and burning index[1] of the leaves. The earlier workers of the Connecticut Agricultural Experiment Station, Jenkins (1900), Stewart (1907), and Street (1934 and 1935), conducted investigations of the tent climate. Their findings indicate a reduction of 30 to 60 percent in illumination, an increase of 1° C in daily maximum air temperature, and a 10 percent increase in relative humidity, with the use of the tent. Reduction of wind speed and evaporation, and an increase of soil moisture, were also reported. More recently, Waggoner et al. (1959) conducted intensive studies on the tent climate. On clear or cloudy days, some 8 to 22 percent depletions of direct and diffuse sky radiation were observed, whereas the depletion of diffuse radiation alone as observed on overcast days was never more than 11 percent. On clear nights, some 12 to 25 percent more long-wave radiation was received by sheltered soil than by exposed soil. However, on cloudy nights, the sheltered soil received only 94 to 105 percent as much radiation as the exposed soil, depending upon the degree of cloudiness. In other words, the daytime soil temperature is slightly lower inside the tent than outside and vice versa at night, with the exception of overcast nights. Other conditions of tent-climate, such as wind, evaporation, air humidity, and soil moisture, as have been observed by Waggoner et al., will be discussed in Sections 11.1.3 and 11.1.4.

Emmert, in 1955, found that polyethylene row coverings could contribute a 7° F increase in temperature to the enclosed air. In 1959, Gliniecke pointed out that a clear polyethylene film used as a mulch resulted in a higher build-up of soil temperature, and better storage of heat, than is possible with black film. Waggoner et al. (1960) studied the microclimate under various mulches — black, translucent, and aluminum plastic films,[2] as well as paper and hay. Some of their measurements of radiation, both incoming (R_i) and outgoing (R_o), are summarized in Table 11-4 in terms of diurnal ranges. Also, the results of soil temperature measurements at various depths are listed in Table 11-5.

[1]An index of the quality of tobacco leaf in terms of the duration of glow in number of seconds after ignition.

[2]The black plastic film used here is a 38-micron film of opaque black polyethylene; the translucent film is a natural polyethylene of 152 microns; and the aluminum plastic film is a 152-micron aluminum film bonded to a 152-micron polyethylene film.

The findings indicated in Tables 11-4 and 11-5 reveal that the black film moderates the diurnal swing of temperature, the translucent film magnifies it, and the aluminum film minimizes it. The paper mulch was found to bear some resemblance to the aluminum film during the day, by reflection of insolation and emission of long-wave radiation, thus discouraging heat gain and encouraging heat loss. With hay, outgoing radiation above it was essentially the same as above the bare soil, during the day; at night, the loss of soil heat conduction to or from the soil was less — an indication of a good insulator. They also observed the growth of strawberry and tobacco under plastic mulching. Because of the warmer soil beneath the film, earlier blooming and fruiting and higher production of roots, runners, and fruits of strawberries were noted. Among all treatments, translucent film achieved the highest records. For the same reason, substantial increases in the root, stem, and leaf area, as well as improvement in quality and amount of yield were observed for tobacco. More shallow roots seen beneath the film were in addition to, not at the expense of, deeper roots.

Paper caps can also be used to modify radiation, and will be discussed in Section 12.1.2, in relation to frost prevention.

11.1.2 *Temperature*

Owing to the close relationship between heat and radiation, modifications of air and soil temperature must necessarily be considered in association with the radiation. It follows, then, that the various means of radiation modification mentioned in the previous section — particularly that of radiation intensity — are also applicable to temperature modification. Also, the use of the nocturnal temperature inversion layer, and of water and soil, for heat gain control, as well as various techniques of heat loss prevention are treated in Chapter 12, in relation to frost prevention (see Sections 12.1.1 and 12.1.2). Again, the effects on the thermal field, of various methods of soil water management, have been presented in Sections 10.1.1, 10.1.2, and 10.1.4. It remains only to add a few illustrations of thermal modification studies in the present section.

Smith, in 1936, investigated the effectiveness of five treatments on the reduction of soil temperature: alfalfa, dry clover, cowpea, and wild hemp coverings, and weekly irrigation of the citrus orchard soil in Yuma Mesa, Arizona. He found that the trees, when irrigated sufficiently to provide adequate moisture but not enough to lower the soil temperature, assumed a condition of summer dormancy. Of the five treatments tested, the dry clover covering exceeded the others in lowering soil temperature, resulting in optimal growth of the trees. Frequent applications of light irrigation were considered second best in reducing soil temperature.

Coloring the soil surface with white material is another method of soil temperature reduction. As mentioned in Section 11.1.1, the use of such methods was demonstrated by Wollny (1881), Bouyoucos (1913), and Ramdas & Dravid (1934). Biel (1956), in his study of the New Jersey climate and its influence upon life, also called attention to the cooling effect of white powder through its reflection of incoming radiation.

The use of dark cover produces the opposite effect, as has been pointed out in Section 11.1.1 (Bouyoucos, 1913; Everson & Weaver, 1949; and Hank & Vásárhelyi, 1954). Stanberry, in 1956, also reported the use of carbon black as a means of heating soil in Yuma, Arizona. He applied a water solution of carbon black (one pound per gallon of water) to seed beds sloped 30 degrees to the south. It was found that the soil temperature was increased 7°F during the day, and reduced 9°F at night.

11.1.3 *Wind*

Windbreaks, as discussed in Section 10.1.2 in relation to moisture conservation, are a good example of wind modification in the natural field. Other wind modification techniques utilize mulches, companion crops, and terracing. Further discussion on some recent studies of the effects of windbreaks on crops will be given in this section.

In Israel, Lorch (1959) observed wind patterns in banana plantations of the Jordan Valley which were protected by windbreaks of four to six meters in height, spaced 25 meters apart. In the plantations, variation in wind speed ranging from 35 to 60 percent of free wind speed was observed, with corresponding variation in the yield of bananas. He reported that the number of intact leaves and the tear-count per leaf, as well as the instrumental (Piché evaporimeter) measurement of evaporation, gave a good indication of wind conditions. He also noted the plants' self-protecting effect in lowering the wind speed to 60-65 percent of free wind.

Farmers in Japan have long adopted the use of straw fences around the vegetable field as windbreaks. Daigo & Maruyama (1954) studied the effects of this traditional practice, and found that it was more effective at night than during the day. In addition, the reduction of dust drift was conspicuous.

In the U.S.A., Schultz & Carlton (1958) tested the effectiveness of two windbreak systems in bare-ridged asparagus fields in Stockton, California: snow fences at intervals around the field, and fast-growing barley planted between the ridges. The comparison was made in terms of surface roughness and wind drag, determined from the vertical wind profile, and the results indicated that snow fence exceeded the interplanting of barley in windbreaking efficiency. Ferber (1958) also made a comparative study of various trees and shrubs as windbreaks applied to farming and soil conservation. From the analyses of characteristics of these trees and shrubs in relation to local topography, climatic conditions, and soil types, he concluded that all windbreaks are essential to soil conservation during both summer and winter. In England, Bagnold (1954) pointed out that wind erosion of sandy soil would be greatly reduced with any type of windbreak. He stated that once a certain threshold speed is exceeded, the rate of erosion in sandy soil is equal to the cube of the wind speed.

As shown in Table 10-2, most investigators estimate the average yield of crops protected by windbreaks to be 20 percent over those in open fields, though much higher yields have been reported for various types of shelterbelts and windbreaks. Andersen (1943), in Denmark, states that when allowance is made for the land space occupied by the windbreak itself, a net gain of at least 15 percent could be expected.

In the application of shelterbelts as wind barriers, the penetrability or density, width-height ratio, and spacing of the belts are the factors to be investigated for maximum efficiency. As shown in Fig. 10-1 (Section 10.1.2), a very dense belt is less effective than a moderately dense one. Sometimes a vigorous turbulence accompanied by descending air currents at some distance behind a belt causes considerable wind damage to plants. When a barrier is 50 percent open, it greatly reduces the wind turbulence which frequently occurs in the lee of the belt. Gloyne (1953), in England, compared the extent of protection in shelterbelts of varying density. He reported that with a 30 percent dense belt, the reduction of free wind to less than 80 percent extended 12h leeward, while with a 50 percent dense belt the effect extended 27h leeward. With 100 percent dense belt, the same effect was found to extend only 15h leeward. Similar findings have been reported by other investigators, including Panfilov (1936 and 1940), Nägeli (1946), and Lawrence (1955). The moderately penetrable shelterbelt is most suitable for optimal growth of low plants near the ground, while a virtually impenetrable belt is most effective in minimizing wind damage for plants of all heights. The use of the former is recommended for arable farming, while that of the latter is useful in fruit orchards.

It has been proved in wind-tunnel experiments that the width-height ratio has a significant bearing in determining the velocity of wind in the sheltered area. Wide belts tend to lead the air flow parallel to their upper surface and promote a rapid downward flow at the leeward edge, thus offering rather poor protection. Optimal width varies with the structure and height of the belt. When tree belts are employed, the width-height ratio, of course changes constantly with growth until the final height is attained. As to the interval between belts, it is usually maintained at 20h to 30h intervals. Although certain cumulative effects of parallel belts have been found in wind-tunnel experiments, they are restricted to closely spaced belts.

Aside from the shelterbelt, such techniques as mulching, companion cropping, terracing, and shields could also be employed to reduce air movement in the natural environment, although they are employed primarily for other purposes. Waggoner et al. (1959), in their experiment on shading effects of tobacco tents (see Section 11.1.1 for the construction of the tent), found an interesting relationship between the wind inside and outside the tent. With an empty tent, the reduction in wind velocity was 100 percent if the velocity outside the tent was less than 25 meters per minute. In other words, the air was nearly calm inside the tent. The reduction was 20 percent when the free wind speed was up to 50 m min^{-1}. When the outside velocity (u_p) exceeded 50 m min^{-1}, the velocity inside the tent (u_t) was approximately

$$u_t = 0.67(u_p - 50), \qquad (11\text{-}1)$$

and when u_p exceeded 135 m min^{-1}, the following relationship was found:

$$u_t = 0.20(u_p - 135). \qquad (11\text{-}2)$$

For higher wind speeds, there was greater reduction with tobacco under the tent than without. Chepil (1955) observed that a wheat-straw mulch increases soil particle aggregation and, in turn, reduces erosion during the first stage of decomposition, but after three or four years the reverse is true, resulting in an increase in erodibility.

Topographic features also influence wind movement. Yamamoto (1958), in Japan, studied various topographic effects on wind speed and direction. He concluded that air-flow around an isolated hill is similar to water flow around an obstacle. He pointed out that in a valley, the wind usually blows along the ridges of the valley, regardless of the prevailing wind direction and speed, with some reduction in the wind speed, when the prevailing wind direction is at an angle to the axis of the valley, and acceleration when the wind is parallel to the axis (if the ridge of the valley does not interfere). He also stated that the characteristic pattern of air flow over a cultivated field is determined by the undulation of the ground. Different orientation and magnitude of terracing would also modify the wind in the microlayer to some extent. As the wind direction changes, the topographic effect varies accordingly.

The wind profile of forest stands and companion crops, as well as the effects of topography on wind distribution, including eddy flow and turbulence, are subjects of microclimatology and mesoclimatology. For details, the reader may refer to the pertinent references cited in Chapter 4.

11.1.4 *Moisture*

Moisture modification has generally been restricted to soil moisture;

few applications have been made in the modification or control of moisture in the air. As pointed out in the preceding chapter, an increase in soil moisture is customarily attained through (a) prevention of water loss from a given area, or (b) bringing additional water to the area. The first approach, generally termed moisture conservation, utilizes mulching, shelterbelt, snow fence, and plastic film, and, occasionally, some means of reducing drainage. The second approach employs various types of irrigation and artificial rainmaking, although the latter is not a common practice.

Reduction of soil moisture is accomplished by various techniques of drainage. Since soil moisture modification was discussed in some detail in the previous chapter, the present section will present only brief summaries on the use of cloth tents, plastic mulching, and artificial rainmaking.

With respect to the use of cloth tent, Waggoner et al. (1959), in their study of tent climate in tobacco fields, observed that at noon the relative humidity was nearly the same inside and outside the tent, but the dew point inside was about 1°C higher during May and about 2.5°C higher in July, due to higher daily maximum temperature. In the early morning and late evening, the air inside the tent becomes saturated or approaches saturation, particularly in the presence of tobacco plants, and higher relative humidity is to be expected. Also, with low wind and high vapor pressure, evaporation as well as transpiration is low, about four-fifths of the evaporation rate outside. Because of better conservation of water and lesser evaporation, the soil moisture inside the tent is generally higher than outside.

In recent decades, much research has been done on the conservation of soil water by plastic film mulch. The reduction of wind, solar intensity and saturation deficit contribute to the increase in soil moisture. Russell & Danielson (1956) studied the time and depth patterns of water as used by corn plants under plastic films. De Roo (1957). found that tobacco plants obtained most of their water from 15 to 25 cm of the plow zone. Below this level, the plowsole hardpans act as a physical barrier to root penetration. Thus plastic films reserve much moisture for the development of roots. Allerton (1957) made a summary of the modern use of plastics by commercial growers. Waggoner et al. reported in 1960 that loss of moisture from soil covered with white and black plastic films was about 15 percent less than that from bare soil when the ground was wet, and 9 percent less when it was irrigated. But when the soil was dry, the moisture loss was 11 percent greater. Waggoner & Reifsnyder (1961) noted greater transpiration of tobacco plants grown in soil covered by plastic film. This indicates that the film suppresses the evaporation of soil moisture but promotes transpiration if the reflection of sunlight is strong. They indicated the amount of nitrate removal (pounds per acre) through leaching to be less in covered soils than in bare soil, with a value of 30 for both black and aluminum covered soils, 40 for translucent film covered soil, and 50 for the bare soil. Accordingly, estimated values of the amount of nitrate present (pounds per acre) in corresponding soils were 66, 38, 36, and 8, respectively.

The large-scale control of moisture in the air falls into two categories: the *production* and the *dissipation* of precipitation. Much effort has been expended on the first category, particularly on the production of rain, while little has been done on the dissipation of rainfall. The stimulating agents or nucleating substances commonly used since 1945 for artificial rainmaking are dry ice (or solid carbon dioxide) and silver iodide (AgI). More recently, common salt (NaCl) has been introduced. It is assumed that the seeding of such agents into the clouds will stimulate rainfall. With dry ice, its low vaporizing point (as low as -110°F) will bring down the ambient air temperature in the supercooled cloud to -40°F or lower. It is claimed that one gram of dry ice would produce approximately 10^{16} ice crystals, an amount that will cover a volume of some 10^{7} cubic meters of cloud air (Schaefer, 1950). Since vapor pressure over ice is much lower than that of the free water surface, these ice crystals will draw cloud droplets to be condensed on them. Thus rapid expansion in the crystal size is expected. The greater the cloud droplet size, the smaller the curvature and the faster the growth. This process is observed in the formation of natural rainfall, and is described by the Bergeron-Findeisen theory. This theory does not hold true for the formation of tropical rain coming from warm clouds; therefore the applicability of dry ice is limited to clouds with 23°F or lower temperature.

When silver iodide is employed, fine particles of about 10^{-6} cm. in diameter are sprayed into the clouds in the form of smoke. Since the structure of the silver iodide crystals is similar to that of ice crystals (i.e., hexagonal), they also act as nuclei for condensation for supercooled cloud droplets. Through a constant collision and coalescence, the rapid growth of particles is expected to occur. However, because silver iodide particles are subject to a photo-effect, the resident time of the particles should be taken into consideration. Smith, Heffernan, & Seely (1955), in their experiment with ground generators, found that the decay rate under daylight is at a factor of 10 per hour if the particles are generated by a kerosene burner, and a factor of 60 per hour if generated by a hydrogen burner.

For the production of rain from warm clouds, such workers as Bowen (1952) and Byers (1956) have experimented with water spray from aircraft, with varying degrees of success. More recently, the application of common salt, about 50 to 100 microns in diameter, has been introduced, as by Davies (1954) in East Africa and Fournier d'Albe et al. (1955) in the central Punjab. Although there are many reports of success with such cloud seeding techniques, scientific verification has not yet been established, due to difficulties in meeting the following criteria: (i) a measurable amount of rainfall to be received by the ground; (ii) predictability in amount, duration, and commencing time of rainfall; (iii) production of rain without restrictions as to the amount and type of cloud and geographical location; and (iv) sufficient proof of rainfall occurring only in the target area. Scientific evidence so far available indicates that only under certain weather conditions is there a possibility of obtaining an economically significant amount of rain. For supercooled clouds, the base should be above freezing level, with the top at or below -5°C, without measurable amounts of ice crystals present. Also, the clouds to be seeded should be at least 5000 ft. thick and the height of the cloud base should not exceed the thickness of the cloud.

11.2 CONTROL OF ARTIFICIAL ENVIRONMENT

An environment that is maintained under any form of construction is here designated as an "artificial" environment. The construction may be a simple cold frame or loosely structured animal barn, or it may be a carefully designed phytotron or insect cabinet. The main value of the artificially created environment is that it provides variable conditions, facilitating various experimental studies on environment-response relationships in plants, animals, and insects. In other words, it is not only an application in itself, but also a sort of laboratory where certain relationships between behavior and environment can be quantitatively determined and techniques of environmental control can be tested. Since response studies of various types have already been mentioned, the present section will concentrate on designing and operating the artificial microenvironment itself. In this connection two aspects are noted: the technique of construction and that of measuring the microclimate within the construction. The former is concerned with the climatic aspects of site, orientation, shape, and material of the structure, and the latter is concerned with the distribution of microclimatic elements within the structure. These topics will be discussed in Sections 11.2.2 and 11.2.4, respectively. Simple designs for plant environments, such as cold frames, hotbeds, and greenhouses, will be presented under the heading "greenhouse climate;" those for animal environments are given in the sections on animal and poultry houses. More complete control designs, such as control chambers and cabinets, will be described in the sections on the phytotron and biotron.

11.2.1 *Greenhouse climate*

The origin of the modern greenhouse goes back to the skylighted conservatory or orangery of the seventeenth century. The greenhouse is generally recognized as a glass house which promotes the optimal growth of plants by providing favorable environmental conditions. The ideal greenhouse is defined by Lawrence (1950, 1955) as providing spatial and temporal control of the factors to which plants are sensitive, so adjusted as to give the maximum rate of balanced growth and reproductive development.

The microclimate of the conventional greenhouse may be discussed in terms of (a) ventilation, (b) heating and cooling, (c) illumination, and (d) soil moisture and evapotranspiration. Sometimes air composition is also important. The greenhouse climate depends largely on the design of the greenhouse as well as the methods for measuring the climate. To be sure, the climatic factors concerned in each situation are all interrelated.

(a) Ventilation. Ordinarily, a greenhouse is ventilated at sides and top. The side ventilator brings in outside air, and the top one lets out warm humid air from inside. This is essentially a convective ventilation system by which cool air is mixed with warm air, moves upward close to the glass roof, and escapes. At best, less than half of the total enclosed air in the greenhouse, somewhat restricted to the top half, is removed, and the lower half, where most plants are located, remains stagnant. The supply of carbon dioxide, particularly on a bright sunny day, can be a problem.

Moreover, in areas with bright sunny summers, greenhouse plants are apt to receive full exposure without adequate ventilation. This would cause bleaching of leaf pigments and burning between the veins of the leaves. Most greenhouse plants would not survive such intensive radiative heating. To prevent this, white curtains are often spread under the glass roof (or the panes are sprayed with lime), in addition to the use of awnings and electric fans. Also, spraying the leaves with a 10% sucrose solution one day prior to exposure to full sunlight has been found effective (Went, 1944, 1957). Obviously, this practice must rely on the forecasting of a clear day. These techniques do not always produce a satisfactory result, and the glass roof may have to be removed entirely and side windows opened for better ventilation. Forced ventilation — rather than convective — as employed in the phytotron, would be the best solution, but this is rarely used in the ordinary greenhouse. If the greenhouse is well insulated, the problem of ventilation becomes even worse in winter. The supply and distribution of carbon dioxide as well as the presence of toxic gases such as ethylene, carbon monoxide, and ammonia in the stagnant air may present a serious problem. Furthermore, uneven distribution of temperature, moisture, and air composition would lower the validity of greenhouse research.

(b) Heating and cooling. In most modern greenhouses, a thermostat heating system,[3] including steam, electric, and hot-air heating, is employed for night temperature regulation. Since it automatically raises and maintains the room temperature at a specified level, the night temperature can be kept fairly constant. During the day, however, the greenhouse temperature is subject to diurnal as well as seasonal variations, under the influence of cloudiness, solar elevation and declination, and shading conditions of the greenhouse itself. Thus, it is extremely difficult to maintain a constant daytime temperature without resort to an air-conditioner.[4] Plants sensitive to day temperature, such as peas, strawberries, and stocks, are therefore not generally favored by a greenhouse environment. On the other hand, plants like potato, tomato, and chili pepper would do well, because their growth is controlled by night temperature.

The amount of short-wave radiation transmitted through glass panes into the greenhouse far exceeds that of long-wave or thermal radiation escaping to the outside. Ordinary glass transmits some 90 percent of the total incoming solar radiation, depending upon the angle of incidence and the thickness, texture, and shape of the glass. Some 50 percent, when it enters the greenhouse, is stored as latent heat; about 49 percent is stored as sensible heat, and the rest is transformed into chemical energy through the process of photosynthesis. Neither the latent heat nor the chemical energy can be re-transmitted through the glass. Only the sensible heat escapes, mostly through ventilators — particularly in summer — and a very small amount passes through the glass panes by conduction and radiation. Thus, the greenhouse temperature is kept high naturally; this phenomenon is known as the "greenhouse effect."

With respect to soil temperature in the greenhouse, it is by and large cooler than the overlaying air temperature and, of course, much lower than the bare soil outside. The heavy shading and evaporative cooling are the two factors responsible for this, and soil moisture content, type of plant, exposure, ventilation, and other environmental factors have some bearing on this. The soil temperature and/or root temperature under controlled conditions will be discussed shortly.

For the determination of air and soil temperatures, a record of vertical and horizontal distributions — preferably a continuous record — is recommended. This applies also to radiation, moisture, air composition, and wind. Thermocouples and thermistors are better instruments

[3]Other conventional heating systems, not automatically controlled, include manure heating and flue-heating. Such systems are usually adopted for sash houses and hotbeds.

[4]The use of an air-conditioner is recognized as the most effective means of cooling, but it is not a general practice in greenhouses. Went (1943) and Marshall et al. (1948) described the air-conditioning system used in the Clark greenhouse. More discussion is given in Section 11.2.4. Traditional cooling devices, such as fans and shades, as have been mentioned previously under "Ventilation," are far from adequate.

for temperature gradient measurement than mercury thermometers and thermographs. The characteristics of these sensing devices have been described in Section 5.3. In most commercial greenhouses, however, either mercury thermometers or thermographs are used, and the information thus obtained is not very reliable for research purposes.

(c) Illumination. There are two sources of illumination in a greenhouse: natural and artificial. Natural illumination can be increased through selection of a site with better exposure, improvements in construction (e.g., additional side windows and panes of good transmissibility), and the use of reflectors inside and outside the greenhouse. When the intensity of natural illumination is low and/or the day is short, supplementary lights, such as fluorescent lights, are required. Placing the lights in between plants would provide uniform distribution of radiation in all directions and obviate reflectors at the side and overhead. In a region like the southern states of the U. S. A., where sunshine is abundant throughout the year, natural illumination through the glass roof alone is sufficient even in winter. However, in an area where winter light intensity is extremely low, additional side windows plus artificial illumination would be necessary. Thus, through a combination of proper siting and design, greenhouses located north of latitude 48° can receive a maximum admission of light and reduction of light gradients. When supplementary lights are employed, the air temperature should be lowered at night in order to minimize the loss of plant carbohydrates through respiration. For some plants with good absorptivity, such as cucumbers, tomatoes, and lettuce, spray application of a 10% sugar solution on the leaves will offset this loss (Van Koot & Van Antwerpen, 1952). The nature of greenhouse construction makes it almost impossible to secure uniformity in the distribution of light intensity both vertically and horizontally. Further discussion on this problem will be given in Section 11.2.4.

(d) Soil moisture and evapotranspiration. Moisture supply in a greenhouse is usually provided by spraying or sprinkling, and the humidity is generally kept near saturation. Due to high temperature, abundant light, and generous water supply, soil moisture in the greenhouse is generally high. Reduced air circulation, high humidity, and/or low saturation vapor deficit suppress evaporation. Transpiration is also low because of high temperature and humidity. The net effect is an evaporation rate amounting to some 70 to 80 percent of the potential evapotranspiration outside.

The nature of the greenhouse climate poses some problems in research. First of all, a heavy reliance on solar radiation for illumination makes it difficult to maintain constant intensity or control the variation during the day. Secondly, daytime temperature regulation is often restricted by an inadequate cooling system. Thirdly, poor ventilation in the lower half of the greenhouse does not allow an even distribution of temperature, moisture, and air composition — particularly of carbon dioxide. Finally, the lack of filtration and sterilization of the air in the greenhouse tends to encourage the growth of pests and diseases and the accumulation of aerosols.

Despite such limitations, the greenhouse design has the following advantages for small-scale crop production: It allows normal growth of plants irrespective of season by (1) extending the day-length by supplementation of light and regulation of air temperature and humidity, especially the night temperature, and (2) modifying air circulation and composition. Because the greenhouse can extend the growing season, higher yield and better quality are obtainable, particularly for long-season crops in places where summers are short. Finally, the greenhouse provides protection against some weather hazards such as frost, drought, and severe winds.

The discussion thus far refers to greenhouses in temperate and subfreezing climates. In the tropics, they are generally provided with natural or artificial shading to reduce solar intensity, and are equipped with sufficient ventilation to avoid high temperatures and excessive humidity. The greenhouse of the Research Institute of Malaya in Kuala Lampur is partially open-sided, with a jack roof, and is supported by an angle framework. With low daily maximum temperature, high minimum temperature, and low relative humidity, this type of greenhouse is favorable for rubber seedlings (Bolle-Jones, 1956).

Simple and cheap sash houses, cold frames, and hotbeds can provide some of the advantages of a greenhouse; the degree of control depends on the covering material, site, and local climate.

A cold frame, usually used for a seed bed in early spring, is a wooden frame about 3' × 6' with the front extending 6" to 12" above ground, and the back extending 12" to 18". The top is usually covered with glass, polyethylene, heavy burlap, or straw mat. Since solar energy is the heat source, the degree of heating depends upon the covering material and the size and orientation of the frame. For best results, shading should be avoided, and the front should face south or southwest. The size of the frame is small enough to keep convective heat loss to a minimum, and the interior is usually painted black for greater absorption of short-wave radiation. The covering material is especially important, since the absorptivity of long-wave radiation is directly proportional to the degree of protection against cold injury. Waggoner in 1958 tested the protection afforded by plastic coverings for tomatoes in unheated shelters. He measured the absorptivity (expressed in percentage of long-wave radiation for wavelengths of 3 to 15 microns) of polyethylene, sisalglaze, polyvinyl chloride, and ordinary glass as 12.5, 66.7, 50.0, and 99.0 percent, respectively.[5]

[5]The polyethylene used here was a .002-inch thick film; the sisalglaze was an acrylonitrile-styrene copolymer film, .005 inch thick, marketed as "sisalglaze"; the polyvinyl

On the whole, 2° to 5° F higher temperatures were observed with the coverings than without. Excluding the glass pane, sisalglaze showed the best protection, polyvinyl chloride the second best, and polyethylene the least. However, when dew collected on the coverings, they became equally opaque to long-wave radiation. In general, tomato plants can stand temperatures as low as 31°F. The use of plastic coverings provided protection against temperatures as low as 25°F.[6]

With the coverings, an increase in the yield of tomatoes was noted for a cold spring, but the opposite occurs in a warm spring. This is explained when we recall that a warm spring is generally a result of local heating by intense sunshine, while a cold spring is associated with cloudy weather. The plastic material reflects more radiation during a clear day than on a cloudy day, simply because the amount of incident radiation is greater. Hence, in a warm spring, the incoming radiation for photosynthesis is reduced, and since in this case the outside temperature is sufficient for normal growth, the use of coverings is even harmful. Experimental results showed that in the climate of Connecticut, film coverings failed to give any protection 10 percent of the time, and appreciable protection 40 percent of the time; the remainder of the time, protection was not required.

Weger (1938) observed hourly temperatures inside pollenating bags of four different materials: gauze, parchment, transparent cellophane, and perforated cellophane, for five clear days and nights; these temperatures were compared with those of the open air. Among the bags the highest daily maximum temperature was recorded in the transparent cellophane bags, and the lowest, the gauze, with their difference ranging from 6° to 7°C. The perforated cellophane bags showed about 2°C lower temperature than the transparent ones, and the parchment bags followed. The open air temperature was about 14° lower than the temperature inside the transparent cellophane bags. During the night, however, about 2°C higher air temperature was observed in the open, with no significant differences among the different bags.

Waggoner also tested the conductivity of three types of coverings:[7] glass pane, sisalglaze, and polyethylene, for heated frames (hotbeds) erected on Cheshire sandy loam soil. The frame was made of .75" Celotex, elevated 8 and 12 inches above the ground at the south and north ends, respectively. In this experiment the minimum air temperature under the cover was kept between 44° and 52°F by an electric

chloride was a .002-inch plasticized film with dioctyl phtlialate; the glass pane was .125 inch thick.

[6]The temperature was taken at a weather shelter next to the cold frame.

[7]The thickness of the three sashes and their absorptivity were, respectively, glass, .125 inch and 99.0%, sisalglaze, .005 inch and 66.7%, and polyethylene, .005 inch and 25.0%.

heating cable placed on the soil. Table 11-6 gives the thermal conductivity and estimated heat loss for each material. The thermal conductivity is expressed in thousandths of Btu per square foot per second for each degree Fahrenheit difference in temperature for one inch thickness of the material, and the heat loss is expressed in terms of relative units, using glass as 100. It is obvious from this table that the heat loss through the soil and Celotex frame is negligible compared with the covering materials, and that the heat is best retained by glass pane.

Table 11-6. The Relative Possible Heat Losses Through Covering Materials

	Glass	Sisalglaze	Polyethylene	Celotex	Soil
Thermal Conductivity $Btu/ft^2/sec/\Delta F \times 10^{-3}$ for 1" thickness of material, where ΔF is the difference in temperature	1.3	.16	.64	.08	1.6
Relative heat loss (glass = 100)	100	230	880	6	6

After Waggoner, 1958

11.2.2 *Animal house climate*

Most domestic animals are kept in shelters or houses for protection mainly from summer heat and winter cold and other unfavorable weather conditions. The protective environment provides comfort and, hence, greater productivity. However, the degree of protection does not always indicate the degree of comfort. The climatic evaluation of comfort in animal environments is generally based on a combination of temperature, relative humidity, and ventilation. For example, Kibler & Brody (1954) studied comfort zones in cattle barns in terms of a combination of air temperature, relative humidity, and air speed (see Fig. 3-6 for detail). The factors determining comfort in the human environment are air temperature, radiation, air movement, and relative humidity, as determined by Olgyay (1962) and others. Air composition and contamination are other important factors in both human and animal environments. A comprehensive summary of microclimatic influences on human and domestic animal environments and the various techniques for modifying these environments was made by Lee (1958).

The animal house climate is governed directly by such internal factors as systems of modifying air composition, heating, cooling, humidification, ventilation, and illumination. Indirectly related factors are site orientation, and color, texture, and type of construction material. The effect of specific climatic conditions on the degree of comfort and, in turn, the productivity of animals, depends, of course, upon the species of animal. For example, the dairy cow is a rather cold-tolerant animal which shows greater resistance to low temperatures than to heat. Experiments with dairy cattle in the tropics have shown that milk production can be increased by cooling the shelter with an air-conditioner. In the middle and high latitudes, overheating of dairy barns in winter reduces milk production. Various examples of climatic effects on animal behavior are presented in Section 3.3. Phenological studies of farm animals and the measurement of animal organs have been discussed in Sections 6.2.2 and 5.7.2, respectively. Some illustrations of the climate conditioning of animal houses will be given in the present section, including experiments on climate conditioning of human living quarters which could be applied to animal houses without much modification.

An L-shaped house provides better illumination than a rectangular one, due to its wider range of orientation. When a house faces the sun, clerestory windows are sufficient for the admission of direct and diffuse light, and they are cheaper than skylights. On the shady side, clerestory windows admit reflected sunlight. With a white ceiling and walls, these windows would provide sufficient light for some animal quarters. Overhangs are useful for providing noon-day shade in summer without interfering with direct sunlight in the winter. In summer, when the angle of the sun is high at noon, overhangs shade both the windows and walls that face the sun. In winter, when the sun is low at noon, the windows and walls are exposed directly to sunlight. The specific size and orientation of the overhang can be designed according to the noon elevation of the sun in different seasons of the year for the particular latitude of the site. At high latitudes, wide overhangs are required to prevent the sunlight from entering the window at noon. However, in low latitudes, narrow overhangs are sufficient to shade the window. In this connection, a knowledge of the inclination and declination of the sun, as well as the amount of illumination, and the orientation of the slope, would be helpful (see Section 4.1.2). Other factors to be considered are construction and insulating materials, the shape, size, and color of the structure, and the ventilation of the house.

Neumann et al. (1955) in Israel tested several methods of natural cooling for reducing excessive summer heating: whitewashing the cement roof, use of insulating materials (e.g., sea-shells, vermiculite-concrete, burnt-clay blocks), laying a wooden board at 2.5 cm above the roof, and combinations of these. Their results indicated no substantial advantage of one method over another where the maximum ceiling temperature is concerned. It was found that each of these methods gives about 5°C reduction. Moreover, the thickness of insulation was not linearly related to the reduction; for example, a 6-cm sea-shell layer gave a reduction of 5°C, whereas a 12-cm layer provided a 6°C reduction. As for the minimum ceiling temperature, the insulating layer discourages cooling and maintains a high night temperature, whereas a whitewashed roof permits as much cooling as an untreated roof.

Shalon et al. (1957) compared the heating of pitched roofs with that of flat roofs.[8] During the day, the highest ceiling temperature of the former reached nearly 86°F at 3:00 p.m., while that of the latter was 80°F at 5:00 p.m., the maximum difference between the two being about 10.8°F, and the average difference, 7.2°F. The situation was reversed at night; the pitched roof was 0.5° to 1.0°F cooler than the flat roof. Thermocouple measurements of the temperature gradient at 10 cm below the ceiling and 1.2 meters above the floor showed that during the day the pitched-roof house was heated from above, while under the flat roof it was heated from the side through windows and doors. In general, the flat roof gave far better protection against excessive heat than the pitched roof.

Artificial cooling of animal housing with air-conditioner and other means has been studied by Van Straaten et al. (1957) in South Africa. He observed ceiling temperatures under attic-ventilated pitched roofs covered with thin corrugated galvanized steel sheets. The results indicated that attic ventilation, both natural and mechanical, reduces the ceiling temperature by as much as 5.4°F, and that the thinner the roof, the higher the cooling effect of attic ventilation. Further discussion of this subject is given in Section 11.2.4.

In studying the effect of the color of flat concrete roofs on heating, Givoni (1962) found that the ceiling temperature of the natural gray roof was higher than that of the whitewashed roof, during both day and night. The readings were 10.8°F, 4.5°F, and 1.4°F higher at 3 p.m., 9 p.m., and in the morning, respectively. This was also true for a comparison of red and whitewashed pitched roofs, though the difference was not as great as in the case of the flat concrete roof. With natural attic ventilation under a red pitched roof, 1.5° to 3.5°F reduction was observed, both day and night.

When studying the microclimate of two simple cattle summer shades, Ittner et al. (1954, 1955) found that a hay-covered shade in a wire pen provided much more heat protection than an aluminum shade in a wooden corral in Imperial Valley, California. They reported that a wire pen surrounded by a green alfalfa field has 3.8°F lower air temperature, 4.9°F lower water temperature, 1.32 mph greater wind velocity, and 9.5 Btu per hour per square foot of animal surface less radiant heat load. The cattle (Hereford steers) in wire pens gained 1.94 pounds

[8]The pitched roof was covered with red cement tiles and plastered with expanded metal-mesh ceiling. The flat cement roof was of whitewashed reinforced concrete of 10 cm thickness.

per head per day, while those in the wood corrals gained 1.51 pounds. The difference, 0.43 pounds, is significant at the one percent level.

With respect to heating, minimizing the heat loss or maximizing the heat gain is the major consideration. Heat gain is achieved either through solar heating or by artificial heating (as employed in greenhouses); the heat loss takes place mostly through the frames of windows and doors, roofs, and walls, and partly through glass window panes. The animal house heating load can be greatly reduced by proper choice of the site and use of suitable materials for construction; the species of animal to be housed, of course, determines the specific requirements. A house located at the leeward of a slope, facing south, southwest, or southeast would obtain much more heat from the sun and avoid much of the cold winter winds. Woodruff (1954), in his study of the effects of shelterbelts and surface barriers on house heating, defined the heating load of a house, Q, as a function of the difference in temperature inside and outside the house (ΔT), the distance from the shelterbelt (H), and the horizontal component of wind velocity (u). He gave the heating load of an unprotected house as

$$Q = 1.3\,\Delta T\,(10^{0.025\,u}), \tag{11-3}$$

and that with protection as

$$Q = 1.3\,\Delta T\,(10^{0.018\,u\,H^{0.07}}), \tag{11-4}$$

where Q is expressed in Btu per hour, ΔT in °F, u in mph, and H in a multiple of the barrier height. The regression line at the top of Fig. 11-3 is a graphical solution of equation (11-3) (i.e., without shelterbelt protection), with the heating load-temperature ratio ($Q/\Delta T$) as ordinate and wind velocity, u, as abscissa. Similar regression lines have been made for shelterbelts at various distances: 2H, 6H, 10H, 14H, and 18H. All points on the graph are averages of two trials. The percentage of reduction in heating load, Q, versus the multiple distance of the shelter height, H, is shown in Fig. 11-4. It is obvious that the higher the wind velocity, and the greater the distance of the shelterbelt from the house, the less is the protection. According to Fig. 11-3, with a 20 mph wind and 30°F outside temperature, a house located at 2H from the shelterbelt would require 3(80 - 30) or 150 Btu per hour heating load for an 80°F temperature inside, whereas for an unprotected house it would be 4.2(80-30) or 210 Btu per hour. According to Fig. 11-4, some 27 percent reduction in the house heating load is expected for the former. Of course, more exact values can be obtained from equations (11-3) and (11-4). In addition, it was noted that when deciduous trees are used as shelterbelt, the degree of protection is greater in summer than in winter. Frederick (1961) attempted to develop a measure of the contrast of wind speeds through deciduous

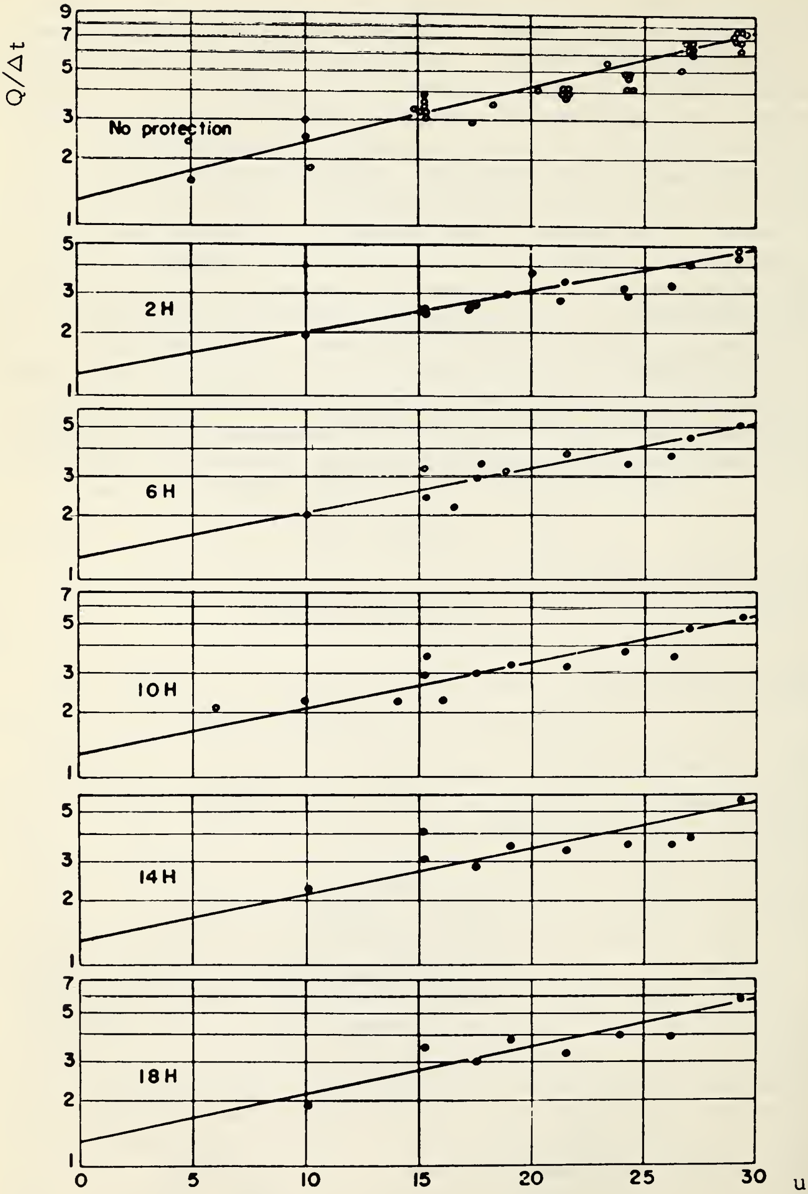

Fig. 11-3. Relationship between house heating load, temperature differences and wind velocity. After Woodruff, 1954

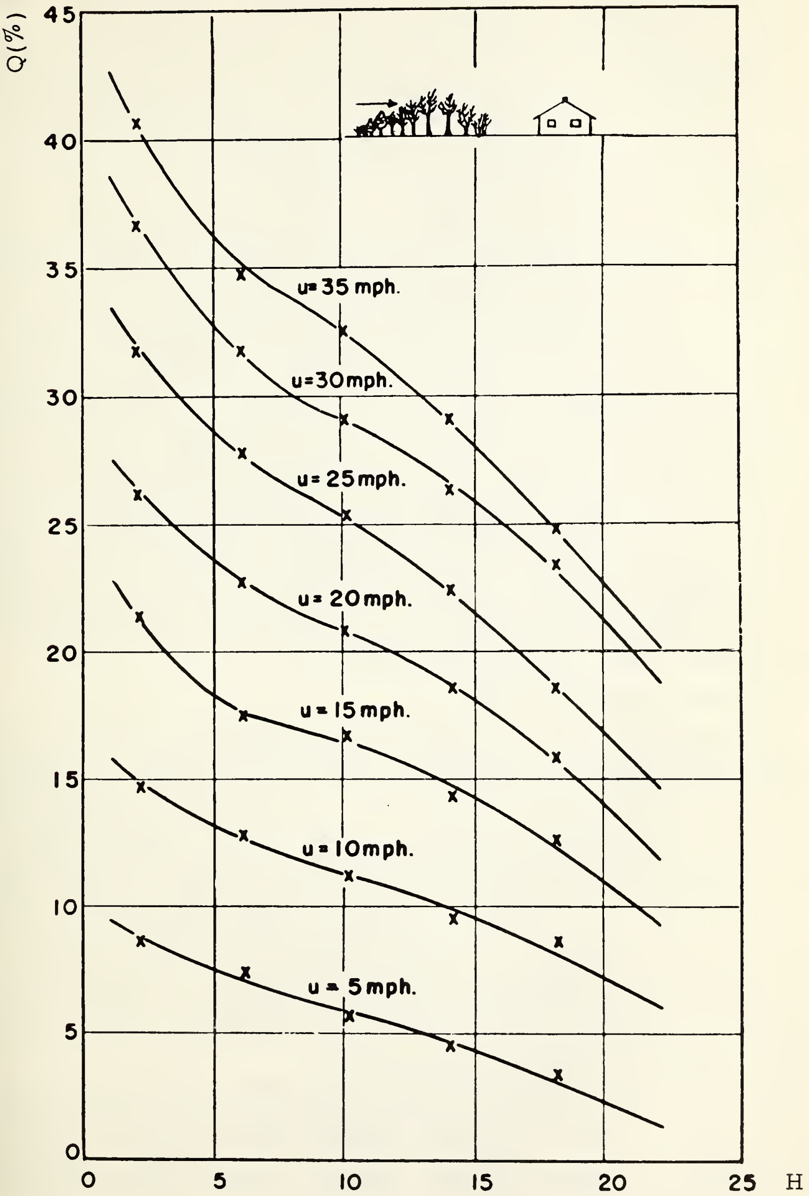

Fig. 11-4. Percentage reduction in heating load for houses at various distances from the shelterbelt. After Woodruff, 1954

trees during periods of foliation and defoliation. He found that wind is about 25-40 percent greater during the periods of defoliation.

A nearly perfect artificial environment on a small scale is that of an animal cabinet where the temperature, light, humidity, and sometimes even aerosol and air composition, could be kept under good control. Since the functioning of an animal cabinet is similar to that of the plant cabinet, they will be described together in Section 11.2.4.

A few of the more recent studies on animals under controlled environments are cited below to illustrate the variety of approach. Atmospheric electric field effects on cattle were studied by Büchi (1958) in Switzerland. Tests were made in cattle sheds with artificial electrodes to verify the effects of the fair weather electricity on stimulating blood circulation and on increasing natural resistance to disease. Climatic effects of high altitude on domestic animals have been investigated by Lörtscher et al. (1957) in France. A combination of strong radiation, low temperatures, and low atmospheric pressure that characterizes high altitude regions results in an increase in the longevity and fecundity of animals. Czajkowski (1951, 1952) and Czajkowski & Ugorski (1954, 1955) studied the composition of air in animal houses by examining the carbon dioxide, ammonia, hydrogen sulfide, and micro-organism content. These illustrations are given as examples of less common topics of interest. As shown in Section 3.3, most of the animal environment studies are restricted to the investigation of temperature, wind, humidity, and light.

11.2.3 *Poultry house climate*

Improvement in the knowledge of environmental influences on the physiology of humans, animals, and plants is necessary. In studying the poultry house climate, it has been found that such physiological functions as metabolism, fertility and hatchability, egg production, brooding, feathering, and various others are closely related to thermal and radiative stress, photoperiodicity, quality of light, air and litter moisture content, air circulation, and air composition (see Section 3.3.1b). In recent decades, increasing emphasis has been placed upon defining and maintaining the optimum range of poultry house climate, particularly that of chickens, for maximum production. Following is a brief presentation on the control of poultry house climate of two major domestic fowl, chicken and turkey.

Some basic criteria in the microclimatic evaluation of poultry houses are that the litter should be kept dry to avoid egg soilage and disease, the air should be well circulated to prevent contamination through the accumulation of ammonia, carbon dioxide, and even carbon monoxide and hydrogen sulfide, and the room temperature should be moderate.[9]

[9]For example, the Agricultural Research Service of the U.S. Department of Agriculture in Beltsville, Maryland, conducted experiments on egg production and feed consumption of Rhode Island Red hens at different constant temperature levels and 75% relative humidity during

The duration and intensity of light should be properly controlled to maintain chicken (or turkey) health and high egg production. Furthermore, as with the greenhouse and animal house, it should render protection against severe climatic stresses such as rain storms, severe winds, and cold spells.

The two most widely used housings for laying hens in the United States are the loose housing on litter and the wire cage. Ota (1956) described four types of loose housing in the United States in terms of a January isothermal map. Type I is characterized as a wall-less or wire-walled coop adopted for subtropical climates. In this type, both front and rear — and sometimes the end walls — are either open or wire-netted to provide adequate ventilation during the summer. When more ventilation is needed, continuous ridge ventilators and large doors are provided. In closed and insulated houses, the capacity of fans should be adequate to supply at least 3 cubic feet per minute of air per hen, at 0.125 inch static pressure. In summer, the fan is reversed to draw in cool northside air and force the hot air out on the south side. The sloping and overhanging roof admits little sunshine to the coop in summer, but allows a considerable amount to enter during the winter. To avoid wind in winter, removable panels of plastic screen are used to close openings, and sunshades facing the prevailing wind direction may be lowered. According to Ota, there is generally no wet-litter problem in Type I houses, except during foggy, humid weather.

The Type II, or uninsulated housing, is characteristic of continental temperate climate. Usually, this type has a large, south-facing front opening, with surrounding uninsulated walls, which can be closed by windows or curtains whenever necessary. Like Type I, this design keeps the litter dry, but it may permit freezing of eggs and drinking water during cold winters.

For continental cool climates of the middle latitudes, the Type III, or single-story straw-loft housing, with insulated walls on all sides and with attic ventilation, is preferred. Sometimes, uninsulated walls are used in areas of warmer climate.

Finally, the Type IV housing, typical of cold continental climate, is distinguished by wall and ceiling insulation and controlled ventilation. A newer design of this type has large windows of insulating glass to trap more winter sunlight, and overhangs to keep out most of the intense summer heat. This newer design, known as the solar house, has the advantage of full solar energy utilization. The Pennsylvania State University's one-story solar poultry house (30 by 100 ft), con-

1951-54 for three- to six-week periods after a 10- to 14-day period of acclimatization. The results indicated that with high temperature, feed consumption was less, accompanied by lower production. When the temperature was low, more feed was consumed, but again there was less production. Specifically, at temperatures of 45-65°F, the average daily feed consumption per hundred hens was 31 pounds, and egg production was 9.3 pounds. At 85° F, 25 pounds of feed was consumed, with egg production reduced to 6.5 pounds; at 23°F, it was 41 pounds and 3.3 pounds, respectively.

structed in 1951, is a good example. The functional features of this house are described (Bressler & Walton, 1956, 1957; Bressler & Jones, 1957) as follows: (a) Insulation — glass fiber insulation blankets are used in all walls and ceilings, resulting in 1/5 to 1/3 less heat loss than in the conventional house with uninsulated walls. In addition, vermiculite concrete block for the floor, and a double thickness of glass separated by trapped dry air (Farm Building Thermopane) for windows, are employed. (b) Insolation — like an ordinary house design, the front is oriented toward the south to receive more sunlight in winter, with a sunshade to control sunshine during spring, summer, and fall. Additional windows admit more sunlight without additional heat loss, due to better insulation. The area of glass in the south wall is approximately 17 percent of the floor area of the house, in contrast with 7 to 10 percent for most conventional houses.[10] (c) Ventilation—with thermostatically controlled pressurizing fans in winter, it has been possible to make extensive use of solar energy on clear days, with no chilling effect at night or on days when available solar heat is limited. In summer, with doors open and eight fans operating continuously, it has been possible to keep the house temperature about the same as outside, aside from an increased air flow two to three times greater than that in winter. The relative humidity is thus also maintained very close to that of outside air.

The wire cage, another common poultry house, has systems of insulation, insolation, and ventilation somewhat similar to those employed in loose housing. It has such advantages over loose housing as precise culling, lower feed cost, better control over parasites and diseases, and less competition for feed and water. However, it requires more heating during cold weather, more brooding to replace culled hens, and higher installation costs.

Aside from the above two main types of housing, there is a poultry cabinet to facilitate more precise studies on the effects of various environmental factors upon physiological development. As pointed out previously, the functional features of cabinets are more or less similar for both plants and animals, and will be described together in the next section.

The Wisconsin Meteorolpathology Building in Madison is designed for environmental studies of turkeys, particularly their behavioral patterns and respiratory diseases. It is a commercial type of turkey house, with a floor space of 2.7 square feet per bird. Fig. 11-5 shows a close view of the interior. A summary of the functional features and the house climate will be discussed briefly.[11]

[10]It has been estimated that on sunny days, as much as 150 to 200 Btu of solar heat per hour can be received through each square foot of window area.

[11]Material was received via personal communications with Dr. M.L. Frey and members of the Veterinary Science Department, University of Wisconsin — Madison.

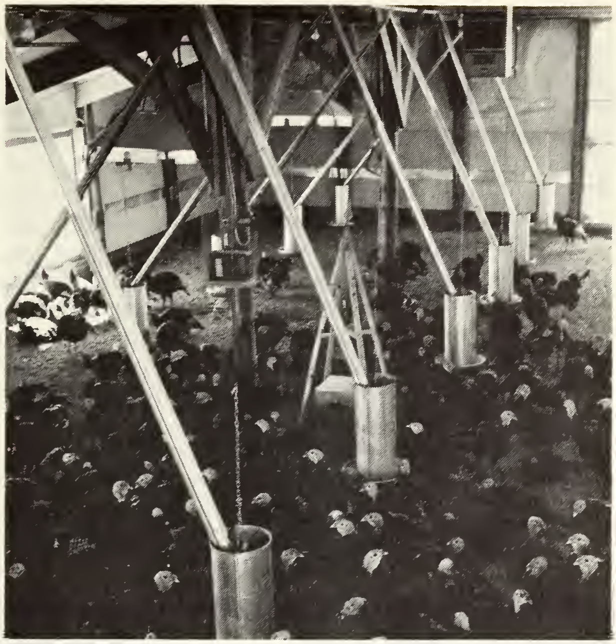

Fig. 11-5. The interior of the Wisconsin Meteorolpathology Building.

Air and litter temperature measurements are accomplished by a set of thermistors mounted on a portable aluminum mast and placed in the litter at bird height and at intervals between the floor and the ceiling. Since the mast is portable, vertical and horizontal temperature gradients can be obtained throughout the house. Two point observations of the outdoor temperature are made on the east and west sides of the building. When hovers are used, their temperature is also recorded. All temperature measurements are recorded on a 16-point Brown Electronic Recorder. In addition, hygrothermographs are placed in different parts of the building. With heaters and adequate ventilating fans, the air temperature can be held around 75°F at about 4-5 ft above the floor during the cold season. The temperature profile shows that the ceiling temperature is slightly higher than the bird-height temperature, but never by more than 4°F. Litter temperature is fairly constant, 64°F in June and 68°F in September. The moisture content of the litter of the winter flock averages about 30 or 35 percent, compared with a maximum of 25 percent during the summer. The west side of the building is often 2° to 4° warmer than the east side, during the afternoon.

The speed of air movement in feet per minute is measured directly by a velometer; the pattern of air currents is determined by smoke bombs in conjunction with time-lapse photographs. The ammonia and carbon dioxide concentrations are determined by a Kitagawa gas sampler. The ammonia concentration of the air in winter ranges from 2 to 12 ppm, while no measurable ammonia was detected at any time in the house during the summer. The carbon dioxide concentration builds up to 1500 ppm for several consecutive days during cold spells whenever there is a minimum of ventilation. Normally the concentration is about 300 ppm, and the highest concentration observed in the summer is 400 ppm. The number and size of air-borne particles in the house are determined by A. I. S. I. Model E air sampler with a continuous record. Particles as small as one micron can be detected on a membrane filter with an ocular micrometer and immersion oil. Most of the particles observed are much larger, many being visible with a hand lens or dissecting scope. Most of the particles appear in the air between 6 and 9 a.m. Large particles predominate during the day, but there is a much higher proportion of small particles at night.

Under such environmental conditions, the movements and drinking activities as well as sound responses of turkeys associated with various light intensities are studied. With the exception of movement activity, all behavioral data are recorded by a four-channel tape recorder provided with a synchronous clock motor which records a tone

Fig. 11-6. Insulated floor stand and water container.

derived from a variable-frequency oscillator every half hour. The frequency is controlled by a photocell which monitors the light intensity of the house. A camera which can be operated automatically at set intervals is being developed to help study the movements of the birds. Fig. 11-6 shows the insulated floor stand and the water container. Whenever a bird stands on one of the metal floors and drinks water, the metal floor — attached to a transistorized trigger circuit — is actuated as a small current passes through the body of the bird to the grounded water container. The trigger output is recorded on a slow-moving magnetic tape recorder which reproduces the impulses in digital or graphical form at high speed.

It has been observed that a summer flock begins its activity at dawn and reaches a maximum within an hour, then levels off during the day, and drops back to approximately zero when it is dark.

In addition to the above behavioral study, investigations under way deal with respiratory diseases and microbial flora of the house atmosphere and litter as related to such factors as temperature, moisture, light intensity, air composition and movement, and number and size of air-borne particles. Also, the behavioral pattern during different times of the day and seasons of the year is being studied in relation to temperature, moisture, and light gradient, with emphasis on the diurnal behavior relationship.

11.2.4 *Phytotron and biotron*

As has been pointed out, there are two aspects to the utilization of artificial environments for plants and animals: to facilitate production for consumption, and to provide for research in environmental studies. While both aspects are recognized, together or separately, in greenhouses, animal houses, poultry houses, and the like, it is the latter aspect which is the function of plant and animal cabinets, growth rooms, phytotrons, climatrons, and biotrons. Their designs permit a high degree of control over environmental factors and therefore make possible the precise determination of response patterns in plants, animals, and insects. The present section will discuss mainly the plant cabinet and phytotron, with some discussion of the biotron. Before proceeding, however, a brief description of existing types of highly controlled environment, as mentioned above, will be given.

A plant cabinet, also known as a growth cabinet, is a sealed box-like structure in which green plants are grown. Most are opaque and provided with artificial light, but some rely on daylight. An animal cabinet is somewhat similar to the plant cabinet in structure, with some provision for suitable living conditions for the animal, such as devices for the removal of waste and the supply of feed. A growth room is much larger than a cabinet, so as to permit the admission of an operator. It is not usually exposed to daylight; illumination must be provided to allow green plants to complete photosynthesis and respiration. The application of light may be either internal or external. In the literature, the term "growth chamber" is often used indiscriminately for a plant cabinet (growth cabinet) or a growth room. A phytotron may be considered a collection of growth rooms in which combinations of various environmental controls can be accomplished. A climatron, such as that in the St. Louis Botanical Gardens, is a huge growth room in which simultaneous control of various environmental factors is exercised. It is capable of reproducing the natural growth conditions of different climatic regions. A biotron is similar to the phytotron, except that it is designed to accommodate both plants and animals. It is the newest type of structure, and to our knowledge, the one at the University of Wisconsin – Madison is the only installation planned.

In the remainder of this section, the growth cabinet, phytotron, and biotron will be discussed separately, with emphasis on the first two.

(a) Growth cabinet. The purposes of the growth cabinet for plant research are summarized by Hudson (1957) as (i) to provide for environmental studies of plant material of known history in order to eliminate the hereditary variables between plants of the same species and varieties; (ii) to multiply and/or to reproduce various seasons in a year in order to facilitate and accelerate the research without relying upon natural seasonal changes; (iii) to create optimum conditions for growth and development in order to hasten growth and development; (iv) to study single and combined environmental factors as related to biological or physiological responses of plants; and (v) to retard natural development, as by keeping plants from maturation. Similar purposes can be cited for the growth room and phytotron. Of course, the greenhouse can also accomplish some of these objectives, but not very satisfactorily.

The growth cabinet entails less construction expense and provides a simpler system of environmental control than the growth room or phytotron. The nature of the cabinet climate is permanent in the sense that it is maintained at a specific fixed level and is not likely to be changed once the design of the cabinet is completed. Temperature, light, ventilation, and the like are regulated by thermostat, humidistat, ventilator, and other automatic devices to a near constant level. Instruments to measure and register cabinet climate, on the other hand, may be changed from time to time for improvement.

In plant response studies with growth cabinets, emphasis is placed upon phasic development associated with varietal differentiation. Since both the response studies and the measuring devices have been discussed elsewhere in this text, only the controlling system will be described in this section, under the headings (1) light control, (2) temperature and humidity control, and (3) air composition and movement control.

(1) Light control. With respect to intensity, duration, and quality of light in the growth cabinet and other controlled environments, the type of lamp and the methods of installation are the two primary factors. Methods of installation are more important to the growth room and phytotron than to the growth cabinet and will therefore be discussed in connection with the phytotron. As to the choice of lamp, two types are available: the incandescent and the gas discharge. When the light originates from an electrically-heated solid material (e.g., carbon, tungsten, porcelain, or metal tantalum), it is the incandescent type, whereas light coming from a gas-filled (e.g., helium, neon, sodium vapor, or mercury vapor) tube of low pressure and high voltage is categorized as being of the gas discharge type.

Incandescent lamps generally furnish a point-source light with a continuous spectrum. The carbon arc lamp, for example, has a very high luminosity and can be raised to almost any desired intensity level. However, it has such disadvantages as the following: (1) it furnishes only a point-source light, a high proportion of which is in the ultraviolet spectrum; (ii) it produces undesirable gases such as ozone and oxides of nitrogen through the ionization of the air; (iii) periodic replacement of the carbon element interrupts the continuity of illumination; (iv) its light intensity fluctuates through continuous shifting of the crater position; and (v) its intense heat causes burning of plant tissue. The tungsten lamp is superior to the carbon arc lamp in all respects. Its ease and relatively low cost of installation, safety and flexibility of operation, and fairly steady light intensity of continuous spectrum are considered the advantages of this lamp. The low-wattage tungsten filament lamps emit a high proportion of red light and are highly recommended for some species of plant. Its disadvantages are (i) that the emission consists of thermal radiation with a peak in the infrared region and a low proportion of short-wave radiation in the visible spectrum; (ii) that the utilization of electric energy by the emission is low; and (iii) that the control of the emission spectrum is difficult. Also, it too furnishes only a point-source light.

In the past decade, much improvement has been made in the use of incandescent lamps for plant research. In their study of biloxi soybean, Parker & Borthwick (1949) designed a special carbon element that would give a specific quality of light desired. They found that a combination of tungsten and carbon arc lights resulted in better growth. Van der Veen (1950) was able to eliminate the thermal effect of an incandescent lamp by running cold water between the lamp and the plants. Orchard & Heath (1957) also found that by immersing tungsten lamps in running water it is possible to reduce the infrared radiation and maintain a constant temperature in a growth room.

Two kinds of gas discharge lamps are noted: the direct discharge and the fluorescent. The former is characterized by line emission spectra, and includes such lamps as the neon, helium, and sodium lamps. Fluorescent lamps of various designs are characterized by continuous spectrum emission. Most growth cabinets employ fluorescent lamps for illumination. Since the phosphorescence, or simply "phosphor" of a fluorescent tube converts the short-wave line emission of mercury vapor into a continuous spectrum, it is possible to design a lamp with a peak emission at almost any point of the spectrum through proper selection of phosphors. Vince & Stoughton (1957) experimented with the elimination of undesirable wavelengths from the fluorescent emission through the use of highly selective filter or monochromator. They were able to control the quality of light with considerable success. Also, with the use of light panels, the distribution of light was rendered fairly uniform. Moreover, fluorescent lamps emit five times as much visible radiation per unit of electricity as incandescent lamps. The limitations of fluorescent lamps are higher initial cost of installation and low surface intensity at the plant level.

The choice of lamps depends upon the species and varieties of plants, as well as the specific phases to be investigated. It is obvious that the requirements of light intensity, quality, and duration for germination are quite different from those for fruitification. In this connection, information on the spectral band width and peak value for various types of lamps is necessary. Canham (1957) made a summary description of fluorescent and high-powered discharge lamps, with an emphasis on their spectral flux distribution and peak intensity. For the "color matching" fluorescent tubular lamps, for example, there is a wide range of spectral distribution (approximately 0.32 to 0.75 micron wavelength), but no significant peak. The "red pigmented" lamp has a comparatively narrow band of about 0.58 to 0.74 micron, with a significant peak at about 0.65 micron. For the 400W neon lamp, the high-powered discharge lamp, the spectral flux distribution is narrow, ranging from 0.60 to 0.70 micron, with the peak located at 0.65 micron; for the 400W mercury fluorescent lamp, the distribution ranges from 0.40 to 0.74 without significant peak. A combination of high-pressure mercury vapor (HPMV) lamp and mercury fluorescent lamp produces lower thermal emission and better spectral composition.

(2) Temperature and humidity control. Temperature regulation of a growth cabinet is usually done by thermostat. When different day and night temperatures are needed, a pair of "mid-off" thermostats may be employed; the time switch of the thermostat gives an automatic day and night temperature differentiation. The usual range of cabinet temperature is 40° to 120°F, the choice of a specific temperature level depending upon the type of experiment. Factors affecting the temperature control of a growth cabinet are radiative and convective heating from the lamp, conductive heating and/or cooling through walls and glass panels, if any, and, of course, the opening of the cabinet door by the operator.

Humidity regulation is not always attempted, and has often been unsuccessful. When humidity control is necessary, a humidistat is usually used. In general, it is much easier to increase the relative humidity than to decrease it. Since saturated vapor pressure of the air varies only with air temperature, lowering the relative humidity without bringing about a change in the air temperature involves a rather complicated system. A further discussion on this topic will be given shortly.

(3) Air composition and movement control. The rate of carbon dioxide production is usually controlled by a flowmeter, but there is no absolute control over its concentration. The appropriate air movement is important because sufficient turbulence is necessary for the even distribution of carbon dioxide. A constant supply of fresh air is particularly important for the removal of traces of such toxic gases as hydrogen sulfide and ethylene.

(b) Phytotron. At the time of its establishment in 1949 at Pasadena, California, the Earhart Plant Research Laboratory, known as the "phytotron," was the world's most extraordinary greenhouse (Went, 1950). It consists of 54 individual growth rooms, including artificially-illuminated rooms, dark rooms, constant-temperature rooms, rain room, and wind room, as well as rooms for various light-and-temperature combinations and a greenhouse. It covers an area of about 7,000 square feet and provides a total of 15,000 square feet of floor space. Since 1949, several phytotrons have been established elsewhere in the world, including those of the Institute of Plant Physiology, Moscow, USSR, the Centre National de la Recherche Scientifique, Gifsur-Yvette, near Paris, France, the Institute of Horticultural Plant Breeding and the Institute for Biological and Chemical Research on Field Crops and Herbage, Wageningen, Netherlands, the University of Liège, Belgium, the Division of Plant Industry, CSIRO, Canberra, Australia, and the Department of Scientific and Industrial Research in New Zealand. There are many other similar but small installations found in various countries. A brief description of the Earhart Plant Research Laboratory will illustrate the functional features of a phytotron. For a detailed description, the reader may refer to Went's book *The Experimental Control of Plant Growth* published by the Chronica Botanica Company in 1957.

In principle, the primary objectives in the phytotron design are to eliminate all variables other than the climatic factors and to integrate several climatic factors in a single room. The functional features of the phytotron may be described under the headings (i) air circulation control, (ii) temperature and humidity control, (iii) light control, and (iv) operational control.

(i) Air circulation control. Some 1000 tons of filtered and decontaminated fresh air are forced into the phytotron under high pressure at a speed of about 500 meters per minute. This makes it possible to maintain the air velocity in the growth rooms at 6 meters per minute, or 0.6 liter of air per minute per square centimeter of surface. With such an inflow of fresh air, sufficient air turbulence is created in all growth rooms to provide a uniform distribution of carbon dioxide. The air temperature and relative humidity, as well as the plant temperature, are also evenly distributed with respect to time and space. This type of forced ventilation is of importance not only inside the growth rooms, but even more in the ducts carrying the air to the growth rooms and in the plenums underneath the floor. In the wind room, wind tunnels are provided for the test of wind velocity effects and other related environmental factors.

(ii) Temperature and humidity control. The entire range of temperature is between 4° and 40°C (i.e., 39° to 104°F, approximately). In the constant temperature rooms, different temperature levels between 4° and 30°C are maintained in different rooms, with 3°C increments. The day-temperature range is usually 17° to 30°C, while the night-temperature range is 12° to 23°C. The entire range of relative humidity is from 17% to 95%, and for a higher temperature room (e.g., 40°C), it can be extended as low as 8% without changing the vapor content. Most experiments are conducted under 20%–80% night-humidity and 50%–70% day-humidity. At different times of the day, plants may be exposed to different temperatures by moving them from one constant temperature room to another on a wheel table. For the simultaneous control of temperature and relative humidity, a Drayer Hanson Package Unit is used. It contains two heat-exchange coils (hot- and cold-water coils), a 3/4 hp-motor centrifugal fan, and a humidifying spray nozzle operated by a humidistat. The fan forces the air in and out of the two coils. The relative amounts of hot and cold water in the coils are controlled by a pneumatic thermostat. The two controllers (i.e., humidistat and thermostat) regulate and maintain constant temperature and relative humidity for as long as desired. However, these facilities permit only the increase of humidity, and thus the humidity is kept at about 70% for room temperatures between 14° and 26°C, and at about 95% for room temperature of 4° to 10°C. The use of a Kathabar Air Conditioner makes it possible to regulate the relative humidity accurately.

(iii) Light control. Light intensity, quality, and duration are also kept under control in the phytotron. Of the three, the even distribution of light intensity, both horizontally and vertically, is the most difficult to achieve. Fluorescent light panels are employed for the illumination of the rooms. They consist of ten 8-ft Slimline fluorescent tubes hanging from the ceiling between a reflector and glass panes, at about 7 to 8 feet above the floor. Air circulates around and through the panels to avoid any heating effect. About half of the heat produced by the lamps is carried away by the circulating air, and the lamp temperature is kept between 40° and 50°C. These near-constant lamp temperatures, which are separately controlled, will not be affected by the cooler temperatures of the growth room. To assure a uniform light flux, a ceiling reflector and white side walls are employed. Also, the farther the plants are from the light panels, the lower is the light intensity. The adjustable height of the wheel-table is useful in eliminating this distance factor.

In the greenhouse, variations in the natural light intensity are minimized by spraying water on the roof. Since any wavelength above 0.12 micron could be removed by water, an estimation of some 20% of the total radiation is absorbed by the thin film of running water. The glass roof is the only source of natural light into the greenhouse, and side windows are eliminated to secure a better control.

(iv) Operational control. For all operations in the Earhart Laboratory, standard soils, standard plants, and sterilized air are employed. The standard soils include vermiculites, sands, and cultural solutions. The use of such planting materials eliminates soil-borne diseases and insects, as well as the variations in physical and chemical properties of ordinary soil. To avoid differentiations among the same variety and species, plants of identical genetic make-up are used. Such problems as air-borne diseases, insects, and aerosols, which can also cause variation in the growth and development of plants, are eliminated by the sterilization of all planting materials in an autoclave or fumigation chamber with ammonia-formaldehyde mixture, steam, or methyl bromide. Also, incoming air is filtered through the Farr Filter or electrostatic precipitator for the removal of solid particles and insects, and through carbon filters for the removal of smogs. Many other devices have been used in the phytotron for sterilization, including even the sterilization of visitors before admittance.

The facilities of some other phytotrons are briefly described below. The Russian phytotron, known as the "station of artificial climate," initiated in 1941 and operated by 1957, has some 6500 square feet of climatized room space beside the operation floor space. It serves not only for experiments on growth and reproductive development, but also for studies of the resistance of organisms to extreme environments, such as thawing, freezing, drought, and saline soil. Temperature control ranges from -94° to 104°F for different rooms. Sometimes, different parts of the same plant are treated with different temperatures. For the study of root development, 28 special thermostats, each having a capacity of 20 plant containers, are provided to facilitate variations in the temperature of soil or cultural solution within a range from 32° to 104°. As to light intensity, an illumination of 3716 foot-candles can be achieved through ceiling and wall lamps. In addition, the "light yard," which is a room with a movable glass roof, allows admission of sunlight on a fair day. The regulation of various combinations of light, temperature, and air humidity makes it possible to study vernalization in cereals, storage of vegetables and fruits, isotopes in plants, and many other topics. When necessary, plants are moved from one environment to another by a special elevator.

The Netherlands has two phytotrons. That of the Institute of Horticultural Plant Breeding, put into service in 1953, has five cold rooms with temperature ranging from 5° to 68°F, and three warm rooms ranging from 64° to 86° F. Sometimes, the temperature in the latter is maintained as high as 104°F. Six glasshouses are associated with the phytotron. The total experimental floor space is about 5200 square feet. The phytotron of the Institute for Biological and Chemical Research on Field Crops and Herbage has such features as seven glasshouses equipped with temperature and humidity control, six air-conditioned growth rooms equipped with different sources of artificial light, cold storage rooms, and a phytotron consisting of three glasshouses and six growth rooms.

In Australia, the Division of Plant Industry, C.S.I.R.O., Canberra, established the cabinet-type phytotron consisting of some 300 small cabinets. Under separate control, each cabinet provides a wide range of climatic environment, including control of temperature, humidity, and duration and intensity of light. All cabinets and growth rooms are flexible in the level of control and uniformity of conditions. The temperature ranges from 40° to 100°F, and can be maintained within 1°F. This cabinet-type phytotron makes possible the testing of interactions among several climatic factors at a time. There are special growth rooms for the control of air composition, frost, and humidity.

In France, the phytotron of the Centre National de la Recherche Scientifique has 34 growth rooms. There are 13 artificially-lighted rooms with full control of temperature, humidity, and air composition, 8 sun-lighted rooms with partial control of the other climatic factors, and a number of dark rooms. There are provisions for artificial rain, chemical control of the atmosphere, and the use of radioisotopes in tracer experiments.

(c) Biotron. As mentioned previously, the Biotron at the University of Wisconsin — Madison is being designed for both plant and animal experiments. Valuable experience in phytotron operations in various parts of the world helped to determine the design of the biotron. The structure consists of 50 controlled rooms of various sizes, housed in a building with total floor area of 94000 square feet. Plants, animals, and insects of various sizes and species will be accommodated. Specifications for environmental control are different for different rooms, ranging from -31° to +131°F in temperature, 0 to 6000 f.c. in light intensity, 5% to 100% in relative humidity, and up to 80 mph maximum wind speed. In some rooms, such weather phenomena as fog and rain will be produced, and in all of them, diurnal, seasonal, and other changes in temperature, light, and other physical variables are provided. A provision is also available for the inclusion of small cabinets similar to those described previously. One room is proposed to produce cross-gradients of temperature and light for the study of adaptation of plants and animals. In this room, specially designed controls will create various combinations of temperature and light intensity gradiating from one side of the room to the other. Provisions for the regulation of other factors, such as air composition, aerosols, sound, electrostatic and magnetic fields, will also be available. The recording of changes in all environmental factors in both the controlled rooms and cabinets will be done electronically.

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CHAPTER 12

Crop Protection from Weather Hazards

Any weather that is detrimental to cultivated plants, directly or indirectly, is referred to here as hazardous weather: thunderstorm, hailstorm, tornado, hurricane, drought, flood, freezing, chinook (or foehn), and many others. Crop damage caused by such weather may be total destruction, or it may consist of retardation of growth or development. Some crop damage results directly from the mechanical forces produced by hazardous weather, but more serious is the indirect damage resulting in physiological disorders, disease, and insect infestation. To minimize the effects of hazardous weather on crops, protection rather than control is emphasized, since such weather occurs sporadically and lasts for only short time intervals — a few minutes to a few days.

Extensive research has already been done on frost protection and prevention, a very popular subject among agriculturists. A considerable portion of the present chapter is devoted to a discussion of frost protection. In the remainder of the chapter, protection against forest fire, drought and flood, severe storm, disease, and insect infestation is presented. Since the size of the present volume necessarily limits the discussion to essentials, the reader is advised to consult the bibliography at the end of this chapter and to refer to Chapter 9 where the above topics are related to special weather warnings.

12.1 PROTECTION AGAINST FROST DAMAGE

There are two types of frost: white frost and black frost. White frost refers to feathery ice crystals deposited by sublimation, while no ice formation takes place in black frost, but its temperature is injurious to plant tissues. The specific critical temperature at which the injury takes place depends upon the susceptibility of plant tissue and upon the height of the most susceptible part of the plant above the ground. A general definition of frost, therefore, should include both black and white frost, that is, the critical temperature which causes freezing damage to plants.

Crops can be effectively protected against radiation frost. For the advection frost, which results mostly from the invasion of a cold wave and contains a large volume of cold air, an effective measure of protection has not been found. If the advection frost is caused by cold air drainage, the use of hedges or blowers may be attempted. If the frost is a radiation-advection type and the cold advection is not too intense, the prevention of crop damage, to some extent, is possible. Radiation frost is generally formed during a clear, calm, and fairly dry night. Usually, lowland fields, having soils with poor thermal conductivity and with little or no vegetative coverage, are most susceptible to frost formation caused by strong nocturnal cooling and cold air drainage.

The process of frost prevention consists essentially of raising the temperature to a few degrees higher than the critical temperature during the critical period, which may range from a few hours to several hours. Due to the expense involved, no attempts have been made to raise the temperature very high or to cover a very large area for a long period of time. Various methods of crop protection against frost damage may be summarized under three principal schemes: (a) application of heat to the ground and plants from various available heat sources; (b) reduction of heat loss from the ground or vegetation; and (c) a combination of both.

12.1.1 *Heat gain*

In the application of heat to the ground and plants, the sun is the direct source of heat, and the air, water, and soil act as heat storing agents. For instance, a layer of warm air overlying one of cold air at ground level, known as a temperature inversion layer, could be utilized as a protective agent by bringing it down to the ground. With the use of water, either by flooding or by sprinkling, the latent heat of fusion is utilized. Storing of solar radiative heat in the soil by various artificial means, such as a reflector or radiative shield (see Section 11.1), is another aspect of frost prevention by heat gain.

(a) Heat from the air. For the prevention of radiation frost, a wind blowing device is employed to stir warm air in the inversion layer and mix it with cold air near the ground, thus raising the temperature of both ground and plants. By such method, the temperature can be held steady for an hour or more, depending upon the intensity of inversion. As pointed out previously, radiation frost occurs during calm, clear nights; a wind of 4 mph would be adequate for the creation of turbulence and increased thermal conductivity of the air. In Florida, Georgia, and California, the use of wind machines in citrus orchards is a common practice. In the northern states, airplanes and helicopters are used

Fig. 12-1. Typical dual-engine wind machine in a citrus orchard.
After Brooks, 1959

Fig. 12-2. Ninety horsepower single-engine wind machine.
After Schultz, 1962

for the protection of wheat from freezing damage. One helicopter can operate over 50 to 70 acres, while a single wind machine is limited to 15 to 20 acres. However, the use of airplane or helicopter is an expensive practice and is usually reserved for emergencies.

In the United States, the use of large fans on the floor of citrus and walnut orchards was practiced as early as 1920. These fans produce a jet of air in a fixed direction, known as a stationary jet, which rapidly pushes the layer of cold air near the ground to lower spots, creating a downdraft for the warm air overhead. In Washington and Oregon, in deciduous orchards, multiple fans are still used to drive cold air over the forest floor to nearby river channels. With this technique, the temperature can be raised by a degree or two on the Fahrenheit scale. However, the fan-blowing technique is not fully satisfactory because of friction of the air stream against tree trunks, the orchard floor, and the heavy cold air layer, which decelerates the air stream. Also, the momentum of the stationary jet decreases with distance. At best, this method is capable of stirring the air for 100 feet in one direction. The efficiency could be greatly increased by replacing such fans with a rotating wind machine which would produce a rotating jet at a higher level above the ground. Propellors of a dual-engine wind machine are usually mounted at 30 to 35 feet above the ground, with an input of 60 to 80 horsepower. The top rotates slowly, producing a blast in a given direction every four to five minutes with an oscillating velocity of 50° to 90° of rotation per minute. The air blast thus created penetrates a distance of about 100 feet in all directions, producing strong low-level gusts over 150 to 300 feet. A single machine is capable of protecting some 15 to 20 acres of orchard, by either pushing or pulling down the warm air to the ground depending upon the height of the machine and that of the inversion layer. Fig. 12-1 shows a dual-engine wind machine installed in an orange orchard in California.

Schultz (1962) investigated the effectiveness of the single-engine wind machine at the Citrus Experiment Station in Riverside, California. As shown in Fig. 12-2, the 90-horsepower wind machine was installed at 32 feet above the ground and was operated at a 7-degree angle with the horizon. This machine brings a temperature rise of over 6°F for about an acre of land, whereas the conventional heaters can produce more. The isothermal analysis of the temperature rise, ranging from 2° to 6°F, shows an uneven pattern, indicating that the effectiveness of the protection is controlled by the air drifts. Moreover, effectiveness depends on the intensity of inversion at the wind machine level. Schultz has classified three types of inversion at a 40-ft level: the weak inversion (5-9°F), medium inversion (10-13°F), and strong inversion (14°F and over). As shown in Fig. 12-3, with a weak inversion of 6.2°F, the machine is able to bring a temperature rise of 3.5°F

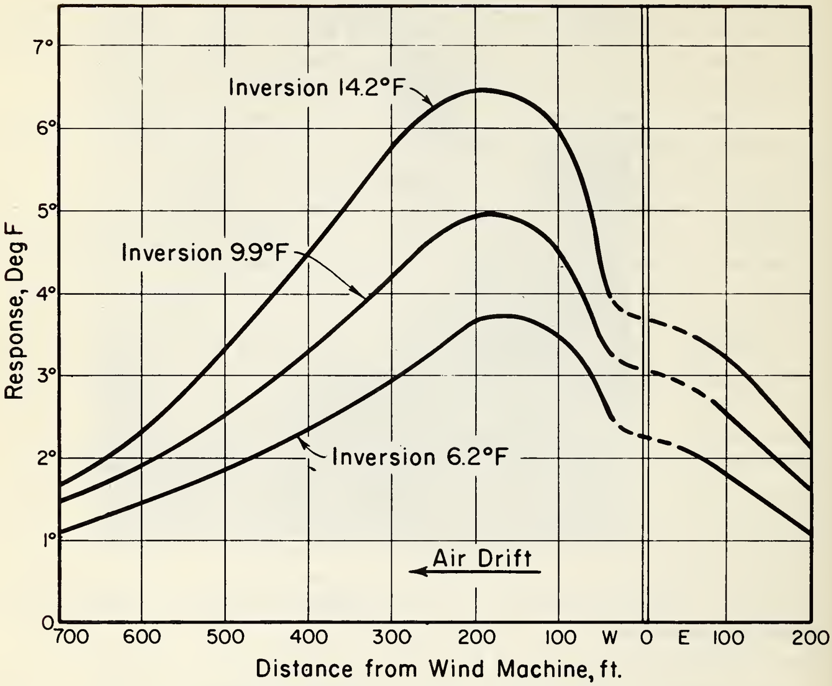

Fig. 12-3. Ninety horsepower single-engine wind machine; cross section of response area. **After Schultz, 1962**

at a distance of 200 feet, while with a strong inversion of 14.2°F, the rise is 6.5°F. At 400 ft, it is 2.2°F for the former, and 4.5°F for the latter. If a minimum temperature is higher than 28°F at 5 ft above the ground, winter protection of ripe or near-ripe citrus fruit is not necessary. When it is 25° to 27°F, sufficient protection is available from the machine for any type of inversion. At 24°F, protection can be achieved by a machine for a medium or strong inversion. At 23°F, a combination of wind machines with heaters, particularly a large number of small heaters, is recommended. Despite many limitations, Schultz found wind machines to be useful for the regional characteristics of California: frequent winter subsidence inversion, pronounced topographic influence, and the citrus trees themselves. The topographic feature tends to create drainage flow, resulting in the increased turbulence mixing through wind shear; thus a strong downward transport of heat occurs and brings a lowering of the subsidence inversion to the level of about 40 feet from the ground. The shape of a citrus tree, with its foliage reaching the surface, brings the "crown space" to ground, and thus the temperature is considerably lower under the crown than in the open field or at the top of the crown. However, the evergreen citrus interferes with cold-air drainage, hence a suppressed turbulence under the crown. A greater turbulence is above the crown due to the local wind system.

Inversion, so far discussed, refers to the low-level inversion known as the ground inversion.[1] For high level inversions, like subsidence inversion, which are several hundreds to thousands of feet above the ground, there is no effective frost protection unless they are lowered as has been described by Schultz.

Four common types of ground inversion are radiative inversion, air drainage inversion, advective inversion, and frontal inversion. The radiative inversion, often used as a source of heat by wind machines, is produced by strong nocturnal cooling during calm, clear nights. With wind speed of 5 to 7 mph and cloudiness of 3 to 4 tenths cover, the conditions which often exist over free water surfaces or swampy areas, this type of inversion is not likely to occur. On the other hand, over land, particularly bare land and/or sandy soil, and snow surface, radiative inversion is most likely to occur. Air drainage inversion is often found on valley slopes where the warm air is lifted from valley floors by cold air drainage. Thus, gentle slopes in valleys respond more profitably to frost protection measures. Advective inversion is produced by the advection of warm air over cold surfaces. Frontal inversion occurs either when cold air underruns warm air or when warm air advances over cold air, and the two airmasses meet. Subsidence inversion is produced through dynamic heating of subsidence free air aloft. Both frontal and subsidence inversions generally are upper air inversions and have not been subject, so far, to protective measures.

A comparison of the utilization of heat from the air with heat from other sources shows that the former is less expensive in the long run, despite the higher initial installation cost, particularly for light frost. Hence the wind machine is preferable where an ample supply of electricity is available. From the meteorological point of view, the feasibility of the use of wind machines depends upon the regional climatology, in particular the frequency, intensity, and height of temperature inversion during a frost period. With this consideration, more research on microclimatic characteristics of an area, in association with the large-scale synoptic pattern of the area, is to be encouraged.

The utilization of heat from the air for frost prevention has been investigated by many authors, particularly in the U.S.A., with respect to the use of wind machines. A brief summary of some of these studies is in order. Stationary jets produced by blowers have been studied by

[1]The frequency, duration, and height of temperature inversion below 500 ft. in various seasons in the United States has been studied by Hosler (1961).

Gunness (1941) and Lavanway (1947). The latter also investigated the effectiveness of stationary jets from multiple fans in the Oregon and Washington areas. Brooks, and Brooks et al. (1947-1959), in their experiment with the rotating jet, tested the efficiency of wind machines in citrus and deciduous orchards. During the 1953-59 period, Leonard made detailed analyses of the characteristics and efficiency of the rotating jet at the University of California at Davis. Rhoades et al. (1955) compared the protective efficiency of the wind machine in mature almond orchards and citrus orchards and found that it exhibited higher efficiency in the latter. A similar study was conducted by Goodall et al. (1957) with varying intensities of temperature inversion (i.e., 6°, 10°, and 14°F higher than the temperature next to the ground); their findings indicated that the intensity is directly proportional to the protection possible. The mean airflow pattern associated with the heat transport as a result of wind machine operation was analyzed by Baker (1955). Crawford & Leonard (1960) reported that for deciduous orchards, a combined use of the wind machine and heater is far more effective than separate operation. The use of helicopter rotor-blades installed on a tower and operated by farm tractor power was investigated by Mullett (1958), who found the cost of installation to be about one-third to one-half that of the commercial blower unit. In 1957, this type of installation proved to be satisfactorily effective in Michigan, except for the advection frost. Earlier work on this type of operation in Michigan was done by Hansen (1951).

(b) Heat from the water. The utilization of water, as by sprinkling and flooding, for frost prevention has been widely adopted in areas where water supply is not a problem. Cox, as early as 1902, adopted flooding techniques for cranberry bogs in Wisconsin for protection against summer frost, and Cline in 1914 employed the irrigation method in southern Texas.

The physical mechanism of frost protection by flooding is rather simple. A cubic foot of water, when cooled from 44°F to the freezing point, liberates some 750 Btu (or 1.89×10^5 calories) of heat, and when this amount of water solidifies, some 9,000 Btu (or 2.27×10^6 calories) additional heat is lost to the air, thus giving away a total of 9,750 Btu (or 2.46×10^6 calories) in the transformation of water to ice. This amount of latent heat present in the water is sufficient to prevent the formation of frost. In general, crops are totally submerged in water and are well protected from damage, even with the presence of advection frost. With intense nocturnal radiation, a large amount of water is required for a satisfactory result. Flooding can be performed successfully when (a) the plants are not affected by submersion; (b) the plants are short; (c) the soil can hold water without much loss through percolation and runoff; (d) the water supply is adequate and inexpensive; and (e) the frost warning is issued early enough to have adequate time for flooding. With such restrictions, flooding is rather a limited practice.

Sprinkling (i.e., spraying a thin film of water over buds, leaves, flowers, and fruit) is now being used more than flooding, since it has wider applicability. Sprinkling equipment is usually easily transported; less water is required; and the treatment is not limited by the plant size. Protection is provided in three ways: (a) latent heat is released when the water cools and freezes; (b) water vapor in the air above the ground reduces cooling of soil by intercepting the infrared radiation; and (c) the soil heat capacity is increased if the ground is sufficiently wet, so that more heat would be stored in the ground during the day than when it is dry.

A few of the most recent publications on frost protection by sprinkler are the following: In the Netherlands, de Zeeuw (1958) demonstrated that spraying was the most successful method in ground frost protection, while artificial mists do not obstruct back radiation sufficiently and the protective effect of both wind machines and heaters is small. Businger (1955) in Wageningen, the Netherlands, found the rate of sprinkling at 0.12 inches per hour to be sufficient for temperatures as low as 23°F. In France, Delbard (1957) designed an automatic water sprinkling system. When the mercury thermometer reaches 32°F, a relay starts an electric motor which operates the rotary pump which, in turn, feeds the sprinklers with water coming from an adjoining river or reservoir. In Switzerland, the sprinkling protection against frost was described by Gerber (1957) and Nicollier (1958). They investigated density, rate, and temperature of sprinkling water in relation to weather conditions (advection, radiation, and evaporation) and ground conditions (e.g., topography, plowed soil, and grass coverage, etc.). In Japan, Suzuki (1954) concluded that sprinkling a thin film of water on trees and garden vegetables gives sufficient heat to protect the plant tissue from freezing; a sudden rise of temperature during the freezing of the film was observed. In England, Rogers & Modlibowska (1954) conducted experiments on the sprinkling protection of apple trees in full blossoming with hourly application of 0.08, 0.16, and 0.24 inches of water at the minimum temperature of 26.0°, 23.5°, and 21.5° F, respectively. They concluded that the rate of application should be kept to a minimum. Their results agree well with the findings of Businger (1955). Franklin (1955) reported on the sprinkler application of 2000 gallons of water per acre per hour in England.[2] In the United States, Schultz & Parks (1957) tested sprinkling of blueberries grown in a closed small valley near Santa Cruz, California. They concluded that the application of 0.6 inch per hour was generally sufficient for frost protection. Davis (1955) reported that sprinkling

[2]This is approximately 0.07 inch of water per acre per hour (see Chapter 2, footnote 29, for the conversion).

was definitely effective in reducing frost injury and increasing yield of low crops. A field survey of frost protection with sprinklers in Michigan was made by Bilanski et al. in 1954. Brooks (1959) cited experimental studies of almond tree protection conducted by Ross & Meyer in Denair, California, during the spring of 1956, in which effective protection was observed with an application of 0.10 inch of water per hour.

(c) Heat from the soil. The utilization of heat from the soil is another means of frost protection, particularly for low crops, such as strawberries, cranberries, and tomatoes. This can be done by (a) increasing the absorptivity and conductivity of soil, e.g., by coal dusting; (b) increasing solar heating of soils by the use of reflectors; (c) increasing the thermal capacity of soils by irrigation; and (d) reducing the radiative heat loss from soil, as by mulch, shield, or shelterbelt. The first three have already been mentioned in the previous chapters; the last will be discussed briefly here. Further examples of research on the first three topics include Bensin's (1955) study of various solar reflectors as a means of increasing soil temperature, and de Vries & de Wit's (1954) study on the use of sand-cover on peat soil for frost prevention in the Netherlands.

12.1.2 *Reduction of heat loss*

There are a number of ways to reduce heat loss caused by nocturnal radiation in the soil-air and/or vegetation-air interface, and they may be classified according to the type of materials used. Smoke or aerosol produced by various types of devices, silver iodide artificial fog spraying from a helicopter, and ground covering materials such as paper caps and polyethylene sheets, are some of the many kinds of materials.

(a) Heater. A device such as a smudge pot or smoke pile provides a protective blanket of smoke over the area and reduces heat loss in much the same way that a cloud cover does, encouraging a convective current which results in the mixing of the cold air below with the warm air from above. To a certain extent, the combustive heat from the burners will also raise the ambient air temperature, but this effect is negligible. The major contribution of such devices is a combination of the retardation of radiative heat loss and the encouragement of heat gain from the inversion layer. Modern devices, such as the duplex chimney burner, are capable of producing this effect with less smoke. Kepner (1950) recommended the use of return-stack heaters and/or automatic regulators for lessening the smokiness. Such devices would have a uniform burning rate, less air-leakage around covers and bowls, and low soot accumulation. In general, the disadvantages of heaters, whether fueled by litter or otherwise, are (i) that the blanket of smoke produced reduces the incoming radiation during the day; (ii) that the formation of the smoke cover does not take place until a few hours after ignition of the fire; (iii) that soots, smogs, and other particles settle down on the plants and may result in some retardation of physiological functions; and (iv) that compared with the protection it offers, the cost of operation and the other harmful effects are rather objectionable. Yarick (1950) estimated that the average cost per acre-hour of operating a gasoline-driven wind machine (a dual, Ford V-8 motor-powered machine for 15 acres) is slightly higher than that of an electric wind machine (100 hp motor for 15 acres), and only about 13 percent of that of an oil heater. When a wind machine and a heater are combined, the operating cost is about 20 percent of that of the heater alone. Wahlberg (1950) found that the use of 10 to 12 heaters per acre in addition to the wind machine would provide better protection. Despite all these limitations, the smoker or heater provides the most reliable frost protection other than the flooding method, particularly with severe frost. The use of many small heaters (or smokers), 25 to 30 per acre, is more effective and economical than a few large units. There has been a tendency in recent years toward the utilization of radiant energy instead of smoke from heaters; the higher the radiant energy the greater the vertical mixing of the air. A series of experiments on this subject for vegetable crops was conducted at the Michigan Agricultural Experiment Station (Farrall et al., 1946; Hassler et al., 1947; Farrall, 1948; Hassler et al., 1948; Hansen & Farrall, 1949; and Hansen et al., 1949). With varying degrees of success, some California growers have employed infrared-ray lamps for orchard protection, though it is a very expensive practice for the extent of protection it offers.

(b) Fog producer. The use of artificial fog has been studied among several European countries as well as in Australia and the United States. Most of the research has emphasized drop size, height of application, and the choice of material. Various researches on cloud seeding, fog dissipation, and the like as related to the processes of condensation and precipitation contribute a great deal toward the understanding and practice of artificial fog formation. However, these methods are still in the experimental stages, and in general have not produced satisfactory results in frost protection. Experimental tests on frost protection by means of artificial clouds have been reported by Godard & Levy (1951) in Bas Languedoc, France. Useful methods of producing atmospheric turbidity for frost prevention have been investigated by Weger (1952).

(c) Ground coverings. Various types of material, such as paper caps, glass bells, metal cans, plastics, twigs, mats, straw, sawdust, manure, green plants, and even soils are employed as ground covers. The choice of a specific material depends upon the effectiveness of protection, the availability and cost of material, the manpower, and the species of plant to be protected (see also Section 10.1.1). The major microclimatic problems associated with ground covering methods include blocking of the short-wave radiation during the day and the discouragement of photosynthesis in plants totally covered; the disturbance of evaporation and condensation as well as soil moisture; and the increase of heat and the reduction of air circulation. These problems are naturally related to the protective efficiency that a particular covering material offers. The blocking of solar radiation by the covering can be avoided by uncovering the ground during the day, or could be partially compensated by the use of supplementary artificial light under the covers, though such practices are rather expensive. The heating effect of covering has been studied by a number of investigators. For example, in Germany, Schmidt (1927) studied the effect of ventilated caps on the reduction of heating effect at different heights of application. At a four-inch height, a rise of 3°F above the surrounding air temperature was observed inside the cap, while at a height of one inch it was 8°F. Hibbard (1932), in his investigation of various effects of frost protectors on tomato plants in Michigan, found that both waxed paper caps and continuous paper row coverings gave an increase of temperature in the center of the enclosed air space of 4° to 5°F. Franklin (1955) observed a rise of 9°F under glass bells. Tender plant seedlings are often covered with paper. Some plants, like potatoes, can be covered by soil, although the covering and uncovering processes cause a certain amount of damage. Molga (1958) pointed out that potato sets are well protected by a one- to two-inch layer of soil; a layer of soil can quickly cover the sets in case of impending frost danger, and it can be removed with a rake after the frost danger is over.

The cropping system employs tall, hardy crops for the protection of lower, tender plants from frost. Cultural practices, such as weed-control, mulching, irrigation, and fertilization, sometimes give indirect frost protection. Weeds, although they tend to interfere with the accumulation of solar heat in the soil by shading the ground during the day, their roots and stems which are poor conductors retard the passage of heat from the soil into the air at night. Mulches reduce both the upward capillary movement of water and the air movement next to the ground, and thus decrease evaporative cooling. Irrigation, on the other hand, increases the heat-holding capacity of soil, even with the presence of evaporative cooling, to prevent frost, as has been explained previously. Fertilizers change the chemical properties of the surface soil, and in turn change the temperature and moisture of the soil; by producing chemical heat, fertilizers in general tend to increase the temperature, depending, of course, upon the type of chemicals used and the amount and methods of application. Davtjan (1946) for example, investigated the influence of chemical fertilizers upon soil temperature. Various plastic materials have also been used for frost protection; for details, see Section 11.1.1b.

For the maximum efficiency of a protective measure, advance warning of frost danger is imperative (see Section 9.2.1). Also, such microclimatological aspects of frost warning as topography, types of soil, vegetative cover, and bodies of water should be taken into consideration, for without these, regional forecasting of frost is of little value.

12.2 PROTECTION AGAINST FOREST FIRE DAMAGE

A major consideration in forest fire control is to keep the total cost to a minimum. According to the "minimum damage" or "least cost" theory, the total cost is a summation of all expenditures: prevention (P), presuppression (R), suppression (S), and damage (D). Thus,

$$C = P + R + S + D , \qquad (12\text{-}1)$$

where C is the total cost, or the lowest cost, per year per acre of forest area with and without forest fire (without forest fire, the total cost, C, equals $P + R$).

In this equation, the term P designates the cost of activities directed at reducing the number and severity of fires; it consists of maintaining forest fire warning services and establishment of fire protection zones. Present techniques of forest-fire-weather forecasting (Section 9.2.2) allow sufficient preparation for fire control or prevention with advance warning. Susceptibility of a given area to fire and the frequency of occurrence of fire-causing factors (e.g., lightning), as well as fire-intensifying factors (e.g., dryness of the forest floor, wind, and air humidity) can provide information useful to the establishment of fire protection zones where potential fuels may be removed or reduced, or a clearance may be constructed between forests.

The presuppression term, R, includes costs of recruiting and training personnel, planning the fire control program, maintaining equipment, and procuring equipment and supplies. It is, in general, the activities in advance of fire occurrence which insure effective suppression. In the evaluation of this term, climatological considerations should be taken into account. For example, heavy fog may prevent the use of vehicles and aircraft in fire control. Microclimatologists are able to predict the likelihood of such circumstances 24 to 36 hours in advance. The essential microclimatic conditions relevant to the present topic include vertical and horizontal wind profiles, moisture, temperature, and radiation above and below the crown, and the thermal and moisture conditions of the forest floor — the last being of paramount importance. Evaporation and rain distribution inside and outside the forest stands should also be considered.

The term S, the expense of extinguishing or confining the fire, is influenced by synoptic conditions because of their importance not only to fire-weather forecasting but also to fire control operations. For example, with a knowledge of current wind velocity, the fire edge[3] can be determined according to the fire head;[4] the wind direction above the forest crown affects the direction of fire spread; and the wind speed, the intensity of burning, especially when the fire is crowning.[5] Also, if the fuel moisture, soil moisture, potential combustive heat and spread, along with the current weather conditions, are known, prescribed burning can be evaluated and measures for suppressing the spread, such as the scratch lines,[6] can be prepared or reinforced in advance. Moreover, at the time of fire, information on wind velocity and the topography will guide control operations (see Section 9.2.5).

The term D refers to all losses caused by the fire, the direct losses being the destruction of live trees, cut timber, and wildlife, while the indirect losses include the destruction (or disturbance) of the balance in forest habitat biocoenosis and pathological phenomena brought by fire wounds, which in turn affect the value of future products. The direct and indirect damages can often be prevented or reduced if the local climatic conditions are known. The climatological considerations are obviously important in achieving the reduction and prevention of direct fire damage, but they also play an important role in minimizing damage of an indirect nature. For instance, the conditions in a fire-attacked forest favor seasonal outbreaks of insects and diseases. Application of insecticides and fungicides prior to the time of such occurrences necessarily requires investigation of the climatological conditions favorable to such outbreaks. Also, the problem of erosion usually becomes intensified after the fire attack, and necessary steps for control could be taken immediately, with such knowledge.

The major causes of forest fire as given by the U.S. Forest Service are campfire, lumber fire, railroad fire, smoke fire, debris burning fire, incendiary fire, and lightning fire. Among these, lightning and spontaneous combustion are natural causes, and the rest are so-called "man-made" fires — but even with the man-made fire, the speed and the extent of damage are the joint effect of weather and fuel.[7] Robinson (1953), in his study of fires caused by power saws, found that the majority of such fires occurred when the air humidity was below 40 percent and the fuel-moisture-stick value was below 10 percent. Under such conditions, the heated muffler (500-600°F) of the power

[3]The boundary of a fire at a given moment.

[4]A fire spreading or set to spread with the wind.

[5]The spread of fire advancing from crown to crown of trees or shrubs.

[6]A protective belt hastily established during a forest fire as an emergency measure to check the spread of the fire.

[7]This refers to fine fuels, not heavy fuels. The former, also known as flash fuel, consist of grass, leaves, draped pine needles, fern tree moss, and some kinds of slash, which ignite readily and are consumed rapidly when dry. The latter, also known as coarse fuel, consist of snags, logs, and large limbwood, which ignite and are consumed more slowly than the former.

saw will start a fire when it is in contact with forest fuel. He suggests, besides a number of improvements in construction, the maintenance of muffler surface temperature below 500°F under full load as a remedy for this problem. Again, the macro- and microclimatic approaches are essential, as has been explained previously.

For successful fire control programs, a list of instruments to be maintained at the fire weather station should include the fuel moisture indicator, haze meter, and spread meter, as well as meteorological instruments for the measurement of surface and upper air conditions (e.g., pilot balloon, rawin, radiosonde, and radar).

Studies on forest fire prevention and control have been done largely in relation to fire weather forecast. A close association of foresters and meteorologists on forest fire research is perhaps the only way of realizing the minimum damage cost.

12.3 PROTECTION AGAINST DROUGHT AND FLOOD

Drought and flood, the two extreme weather conditions, have brought serious damage to plants, animals, and men for centuries, and various methods of protection against them have been studied in hydrology, agricultural engineering, and other fields. In meteorology, the study aims at determining the causes as well as at predicting the magnitude, duration, and intensity of drought and flood. Drought is a greater problem to agriculture than is flood. In general, drought covers a larger geographical area, and is more frequent and of longer duration.

Since complete control of drought and flood is not yet possible, protective and preventive measures are confined to minimizing damage to agricultural production. We generally define drought as a lack of precipitation, and flood as excessive precipitation. More technically, drought and flood are hydrological imbalances involving a number of factors pertaining to regional characteristics: drainage, runoff, topography, soil structure, species of plants and animals of the area, as well as solar radiation, wind, temperature, humidity, and, in turn, evaporation. In an arid area where permanent drought prevails, it is not a drought for xerophytes and camels. Subhumid and semi-arid climates do not represent drought for sorghum crops, but do for wheat and corn. Also, humid areas do not constitude a flood situation for most aquatic plants, such as rice and water chestnuts, unless these plants are totally submerged in the water for more than a week. In two regions having the same amount and duration of rainfall and evaporation, it may be considered as flooding in one region and not in the other. It follows that the severity of drought and flood depends primarily upon their duration and intensity.

Various aspects of drought have already been discussed in previous chapters. Irrigation is a very common practice in drought control in farming areas. Determining the need for irrigation in terms of rate, period, and total amount of water was presented in Sections 10.2.1 and 10.2.2. Drought warning has been covered in Section 9.3. The various microclimatic factors concerned in the physiology of plants as related to drought were discussed in Sections 4.3 and 4.4, and the modification of drought by various methods of soil conservation was described in Section 10.1. It remains for the present section to discuss the feasible procedures in drought prevention; these are (a) the identification of the type of drought to be attacked; (b) the climatic evaluation of the probability of drought occurrence in a given area with the specification of drought types; (c) prediction of the probability of drought occurrence at least two weeks in advance; and (d) the design or selection of appropriate methods of drought prevention or control.

Drought types may be defined arbitrarily according to the concerns of the agriculturist — for instance, in the survival of a specific crop, the adequacy of water supply from a reservoir, or the comfort of his animals. The conventional classification distinguishes atmospheric drought, agricultural drought, physiological drought, absolute drought, and partial drought. Atmospheric drought may be designated as atmospheric stress during the period of high temperature, bright sunshine, low humidity, and intense transpiration; it may be associated with high wind velocity. The period can be as short as a few hours at midday or early afternoon, and it can be as long as a month or two, if weather conditions favor the drought. In short, the severity of drought is determined by the degree of dryness of the air (as measured by the water vapor deficit). Soil drought, also termed agricultural drought, is due to the deficit of moisture in the soil. In the case where the soil moisture content is too low, or the tensile stress is too high, blocking of the moisture uptake by plant roots occurs. This is detrimental to the survival of almost all agricultural crops. The evaluation of agricultural drought is based upon the soil moisture deficit that causes temporary or permanent wilt of crops. If the wilting is temporary, the growth of crops will continue after recovery, but the quality and yield may be reduced. In the case of permanent wilt, no recovery occurs, and the plants die. The severity of agricultural drought is assessed in terms of the amount of moisture present after the temporary wilting point is reached. Since the temporary wilting point varies for different crops, the species and variety of the crop should be specified. Further specification requires the threshold of soil temperature. When the soil temperature is too low, the intake of moisture by plant roots ceases, even with apparently adequate soil moisture. This is known as physiological drought.

Absolute and partial droughts, as defined in British climatology, are "a period of at least fifteen consecutive days, on none of which 0.04 inch or more rainfall was recorded," and "a period of at least twenty-nine consecutive days during which the average rainfall does not exceed 0.01 inch," respectively. The above definitions, of course, differ in different regions. In agrometeorology, the most suitable definition of such drought is that of agricultural drought.

Climatologically, the soil moisture at different times of the year could be computed in probability terms for a given area (see Section 10.2.2), and then an analysis of probability isolines could be made for larger geographical regions. The probability values of soil moisture thus obtained would serve as a climatological means of drought estimation.

When the occurrence of drought varies from year to year, the synoptic approach is indispensable. Extended weather forecasting for drought has been discussed in Sections 9.1.2 and 9.3.2.

Finally, the control and prevention of drought depend upon regional characteristics including regional climate, especially the microclimate. As pointed out previously, such factors as soil type, drainage condition, wind in the microlayer, and the like, should be carefully considered in planning preventive measures. Drought can be avoided by advancing or delaying the planting date, choosing a different site, and selecting appropriate species and varieties. For example, in the case of seasonal drought in a subhumid region, scheduling of the planting date can sometimes be adjusted to permit maturity and harvest before the arrival of the drought season. However, this is possible only if the growing season is long enough to allow shifting of the planting to an earlier date.

The exact opposite of drought is flood. The majority of floods are caused by the overflowing of rivers, known as discharge of stream. However, the common cause of farmland flooding of concern to agriculture is precipitation which exceeds runoff and percolation. The term "runoff," as used by agriculturalists and soil conservationists, refers to the surface and subsurface runoff of soil water, while in hydrologic considerations it designates river runoff. It is the former definition that is employed in the present discussion. In coastal regions, floods come mostly from the melting snow in spring; thus snow cover surveys in the winter and the subsequent runoff estimates provide information for flood warning services. Techniques for flood control include soil management, forestation, flood dams, and flood canals, which are beyond the province of agrometeorology. The agrometeorologist's primary concern in flood control programs is in providing flood warning. Since the amount of rainfall is measurable, and since the sources of rainfall and runoff are always at a considerable distance from the floodplain or farming area, the flood warning can be issued several hours to several days in advance, unless intense downpour occurs on the floodplain or farm area. Should the latter situation occur, prediction of precipitation becomes important — in terms of intensity of precipitation, rate of runoff, and soil moisture condition. Here accuracy depends, of course, upon the careful measurement of precipitation and runoff.

12.4 PROTECTION AGAINST OTHER SEVERE WEATHER CONDITIONS

Other than the hazards mentioned above, weather hazardous to agricultural production may be in the form of destructive winds (e.g., hurricanes, tornadoes, hailstorms, thunderstorms), or other local storms of a severe nature. These severe storms are usually accompanied by heavy precipitation in the form of rain, or sometimes hail. The destructive effects of such storms upon plant and animal life, buildings, and aircraft and other transportation facilities render them of prime significance in weather forecasting and weather modification studies. In agrometeorology, we are interested not only in forecasting and modification, but also in the geographical distribution of storms in order to provide appropriate protection for plants and animals.

12.4.1 *Hailstorms*

Damage caused by hailstorms is vast. For small animals, and in some instances for horses and cattle, the damage is great when the hailstones range from 3" to 5" in diameter. Stones of about 1" diameter are considered disastrous to crops in general.[8] Flora (1956), in his book, ***Hailstorms of the United States***, called hail the white plague. He considered hail to be more destructive than tornadoes in the United States, the greatest monetary loss being in crops with minor losses in houses, automobiles, and airplanes, in addition to the threat to livestock and people. In the United States, hailstorms are most severe in the Middle West, especially in Kansas, Nebraska, and Montana, and sometimes in Iowa, Minnesota, Texas, Oklahoma, and Colorado. The largest hailstones officially recorded in the U.S. were seen on July 6, 1928, in Potter, Nebraska; although sparsely distributed (10 to 15 feet apart), the maximum size of the stones was $5\frac{1}{2}$" in diameter, weighing $1\frac{1}{2}$ pounds each. Stones of this size achieve a very high falling velocity and produce a loud roaring sound, due probably to an aerodynamic noise immediately prior to the observed fall.

For the world as a whole, hailstorms are responsible for roughly the same annual monetary damage to crops as the combination of hurricanes and tornadoes. This is due to their higher frequency and wider distribution. Lemons (1942, 1943) reported that hailstorms occur most frequently in the continental interiors at middle latitudes, diminishing seaward and becoming less frequent as one approaches the equatorial and polar regions. Nevertheless, the severity of hailstorms in the tropics, particularly at high altitudes, is not less than that of the middle latitudes (Hann, 1915; Visher, 1922; Cornthwaite, 1919;

[8]However, Schleusener & Jennings found that the stone of less than $\frac{1}{2}$" diameter has the greatest impact. See Section 5.4.6.

Hariharan, 1950; and Flora, 1956). In high latitudes, no severe damage has been reported.

Theoretically, the degree of damage inflicted upon plants by hailstorms depends upon the stone size, shape, areal density, depth of coverage, duration of the storm, falling velocity, area coverage, and the age of the plants. Heavy rainfall and severe wind accompanying the hail cause considerable additional damage. Therefore, wind direction and speed, and types of fronts and their movement — including airmasses, paths of storms, frequency of seasonal and diurnal occurrence, as well as the synoptic conditions associated with them — should be carefully investigated. Information on such factors would serve as a guide to effective protection from hail damage. It is generally recognized that the size of hailstorm area, the density of hailstones at ground level, and strength of surface winds are three major factors in the extent of damage. When the stone density is less than 10 stones per square foot, usually there is no noticeable damage. With respect to stone types, crop damage occurs with either oblate or spherical stones; damage has not been reported in areas where the disc type of stones predominates. By and large, in most of the areas where crop damage occurs, the hail duration exceeds 15 minutes, while in areas of no crop damage, it is 10 minutes or less. In general, density, size, and type of hailstone and the duration of the storm are not as important as the effect of high wind.

Hailstones cause injury to plants because the leaves are torn into shreds and parts of the leaf tissue are destroyed. Reduction in yield due to the loss of leaf tissue is roughly proportional to the amount of tissue lost. In the case of corn plants, for example, the reduction in yield is comparatively insignificant at the knee-high stage, but is serious at the stage immediately preceding tasseling, and again the danger is less as the maturity of the plant approaches. In severe cases, the entire leaf blade is stripped from the midrib and the stalk and ears may be bruised, broken, or even beaten into the ground. Young plants that are not heavily foliaged can withstand considerable hail attack. Most plants are likely to be seriously damaged during the blooming period. Just as in heavy rainfall, the compaction of the soil makes the emergence of seedlings difficult. Small grains are often beaten down or buried by hailstones and the accompanying rainfall, making the harvest difficult. Fig. 12-4a shows destruction of tobacco during harvest time by a hailstorm at Greenville, Tennessee, in 1939; and Fig. 12-4b, damage to apples near Winchester, Virginia, in 1934.

Observations on hail in the United States have been conducted by the U. S. Weather Bureau, hail insurance companies, airline weather services, and state water surveys. The First Order stations of the U.S. Weather Bureau have made observations on the duration and the

Fig. 12-4a. Tobacco destroyed by hail at Greenville, Tennessee, in 1939. (Courtesy of The Rain and Hail Insurance Bureau, Chicago, Ill.)

Fig. 12-4b. Apples destroyed by hailstorm on August 9, 1934, Winchester, Virginia.
(Courtesy of The Rain and Hail Insurance Bureau, Chicago, Ill.)

beginning and ending hours of storms, as well as the maximum diameter of the stones. Hail insurance companies have also made hail surveys in terms of crop damage. For an area the size of the United States, however, none of the above organizations gives sufficient information for area distribution analysis.[9] Therefore, an accurate survey of the large-area distribution of hailstorms, for each hazardous type, is urgently needed. In addition, intensive observations on various aspects of the physics of hailstones as well as dynamic and synoptic investigations of small areas are desired.

Some states have made more studies of hailstorms than others; in the case of Illinois, a great deal of statewide survey work has been done. A summary of such study is in order here.

Huff (1960) made use of a 50-year record (1910-1959) for a total of 113 hailstorm days, to investigate the relation between summer hailstorms in Illinois and the synoptic weather. With respect to the frequency distribution of hailstorms associated with frontal systems, it was found that 64 percent of the total were associated with cold fronts, including pre-frontal (50%), frontal (44%), and indeterminate (6%). This indicates that summer hailstorms are most frequently associated with cold fronts. Other synoptic patterns of minor importance were stationary fronts (18%), warm fronts (4%), air mass storms (4%), and low center passages (6%). In the northern part of Illinois, the percentage frequency of all types of hail with cold fronts was somewhat greater than that in the central part of the state. Hailstorms associated with stationary fronts were somewhat more frequent in the central and southern portions of the state than in the northern part. Huff used a number of hail reports to indicate the areal extent of hailstorms, and found those of the stationary front and air mass types to be somewhat less extensive than those associated with cold and warm fronts. Fifty percent of the time, the storms occurred within 50 miles of the front, regardless of type, 22 percent between 51 and 100 miles, 14 percent between 101 and 150 miles, and 8 percent over 200 miles. With stationary fronts, hail occurs primarily to the north or cold side of the front. The median speed with which cold fronts associated with hailstorms traveled was 15 mph, a rather slow speed for cold fronts. It

[9] In the United States, many maps on nationwide hailstorm distribution have been published, but they are incomplete and inaccurate with respect to the specification of types and sizes. Moreover, the number of First Order U.S. Weather Bureau stations (127 stations) does not provide sufficient information for satisfactory mapping, and surveys conducted by hail insurance companies are far from being reliable, since only a small percentage of crops is covered. The compiled figures on hail losses other than to crops are, in most instances, deficient in that no attempt is made to ascertain how much of the total loss is attributable to hail and how much to the wind. Other agencies have only small areas of interest, and could not be of use for extended analyses. For example, Lamoureux (1952) pointed out that there is a distinction between hail as an economic phenomenon and hail as a meteorological phenomenon. Thus, he developed methods for the adjustment of hail damage statistics in the state of Iowa.

was found that over 92 percent of the time they moved at or under 24 mph; the speed rarely exceeds 29 mph, with the range of 10 to 20 mph being the most frequent speed. For stationary fronts, the speed is 5 mph or less. The most common orientation of cold fronts[10] ranged from 230° to 250°, while that of hail patterns in all storms combined ranged from 240° to 259° and from 300° to 319°. Thus, the differences between the orientation of the cold front and that of the hailstorm pattern are 0° to 10° and 71° to 80°; the former is known as the primary maximum, the latter as the secondary maximum. The primary maximum indicates a pattern nearly parallel to the front, usually as the result of numerous hailstorms occurring along a front or squall line, and at nearly the same time, having short durations. The secondary maximum reflects the effect of hailstorms with longer durations, which break out along a front or squall line and continue for several hours. Widespread hailstorms are accompanied by heavy rainstorms. Approximately 90 percent of the hail in these occurs within 25 miles of the associated rainstorm axis or core.

The western part of Illinois was most often a part of a widespread hail zone, but the storms were concentrated most frequently in the northwest and west-southwest portions of the state. Summer hailstorms occurred primarily in June (53%), and secondarily in July (26%) and August (21%); cold fronts alone were found to be responsible for widespread storms in August. Changnon (1960b), in his study of severe summer hailstorms in Illinois during 1915-1950, claimed that hailstorms occurred most frequently in the late afternoon and early evening. According to the U. S. Weather Bureau statistics (Flora, 1956), for the period 1944-1953, over 73 percent of the total hail reports indicated that the storms occurred between 2:00 and 9:00 p. m. local time, and over 84 percent between May and August. In Illinois, more than 80 percent of the crop damage by hail occurred in July and August (Stout et al., 1959). Changnon (1960c) also studied the 25 most severe hailstorms in Illinois during 1915-1959, and concluded that these severe storms occurred most frequently in northwestern Illinois, and were least frequent in southern Illinois. Almost 50 percent of these storms were associated with pre-cold front squall lines, and 33 percent were produced by warm fronts. He claimed that no single synoptic factor could be held responsible for severe hailstorms.

Detailed scientific investigation of hailstorms is necessary in order to interpret the physical behavior of the hail, including formation, development, movement, and other properties. It follows, then, that forecasting and demarcation of the hail zone is necessary for minimizing damage. The ultimate goal is to modify and even control such storms. A good example of such detailed investigation on a single

[10]The orientation of cold fronts for the period of 1910 to 1959 in Illinois, under investigation by Huff, varies from 180 to 250 azimuthal angles expressed in degrees; the median is 240 degrees.

storm is that of Changnon (1960a). This was the storm that occurred on June 22, 1960, in the vicinity of Decatur, Illinois. Various schemes have been employed for the collection of data: from radar observations, by aerial photography through flights over the area of the hail path, from the U.S. Weather Bureau's upper soundings and surface observations, through organized teams conducting special field surveys, and others.[11] Data included the time of hailing (beginning and end), stone size (maximum and average), stone type (spheres, oblates, discs, and their combinations), stone color, stone density on the ground, direction of storm movement, associated weather conditions such as rainfall, lightning, direction of destructive wind, and estimates of crop and property damages.

A 3-cm. CPS-9 radar set operated at the CMI radar station at the University of Illinois Airport in Savoy, Illinois, can depict thunderstorm cells in the storm by PPI photographs.[12] These photographs, as indicated in Fig. 12-5, help delineate the hail path, its movement, development, and orientation. They also delineate the hail boundary within a 100-mile radar range. The echo areas shown reveal that the thunderstorm under study developed as two separate storms, the first hail falling from the southern edge of an eastward-moving thunderstorm cell (see echo area B), the second hailstorm (echo area A) moving in an east-southeastward direction to join the first cell, with a rapid increase in the total area of hail incidence.

From analyses of the upper (850-, 700-, 500-, and 300-mb levels) and surface synoptic maps of June 22, 1960, it is evident that the thunderstorm and hailstorm developed along a cold front, pushing forward across north central Illinois, penetrating as far south as Vandalia and as far east as South Bend. Meanwhile, the maximum air temperature to the south of the front exceeded 90°F, and the dewpoint temperatures in central Illinois were quite high at 18:00 CST, varying from 74° to 77°F. At this time, the cold front became stationary and juxtaposed with an unstable, convergent, low level flow and high upper-air flow. The 500-mb level jet appeared to be about 50 to 55 knots, probably responsible for the development of the storm through its vertical shear effects on the vertical movements of the individual storm cells along the front.

An examination of the distribution, stone type and size, time of hail initiation (or isochrones of the beginning time of hail), areas of stone types, and diameters of the largest stones (or isodiametric lines) was made. The analyzed isodiametric lines are shown in Fig. 12-6.

[11]Through TV announcements, citizens in the storm area saved stones in their refrigerators and turned them in to the Illinois Water Survey for measurement of stone size and shape. Also, the adjusted data for crop loss insurance of the storm area were supplied by the Crop-Hail Insurance Actuarial Association.

[12]For explanations, see Glossary of Terms (Appendix A), under "Radar."

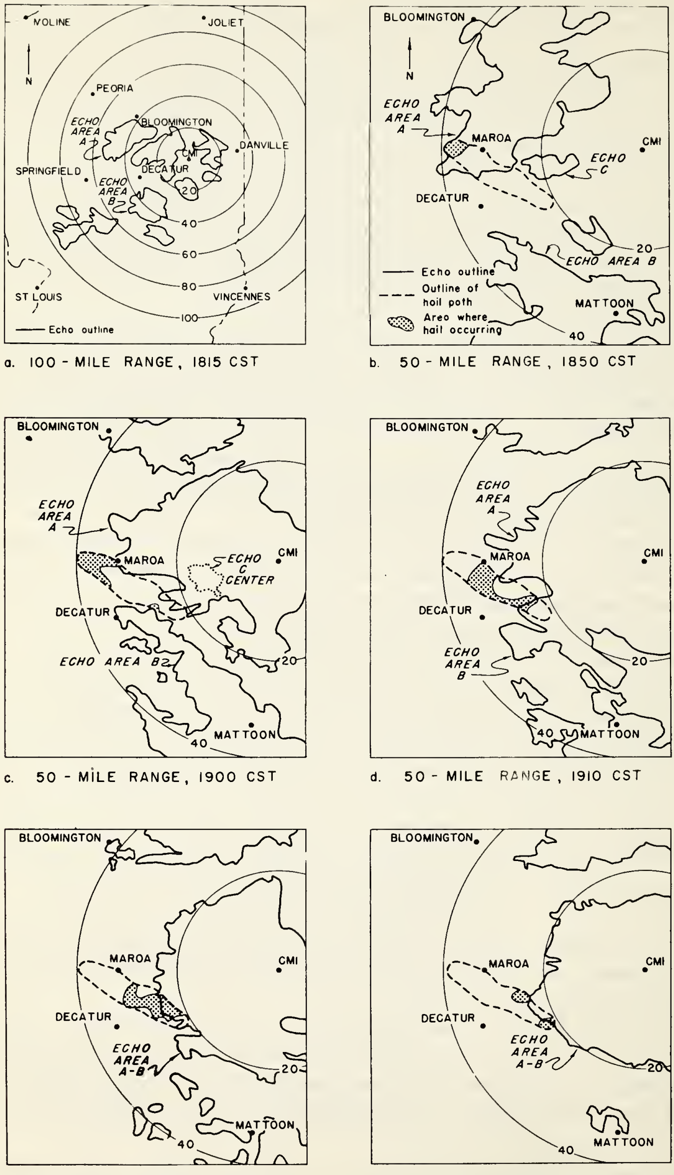

Fig. 12-5. Radar echo of hailstorm from CMI radar station during the night of June 22, 1960. After Chagnon, 1960

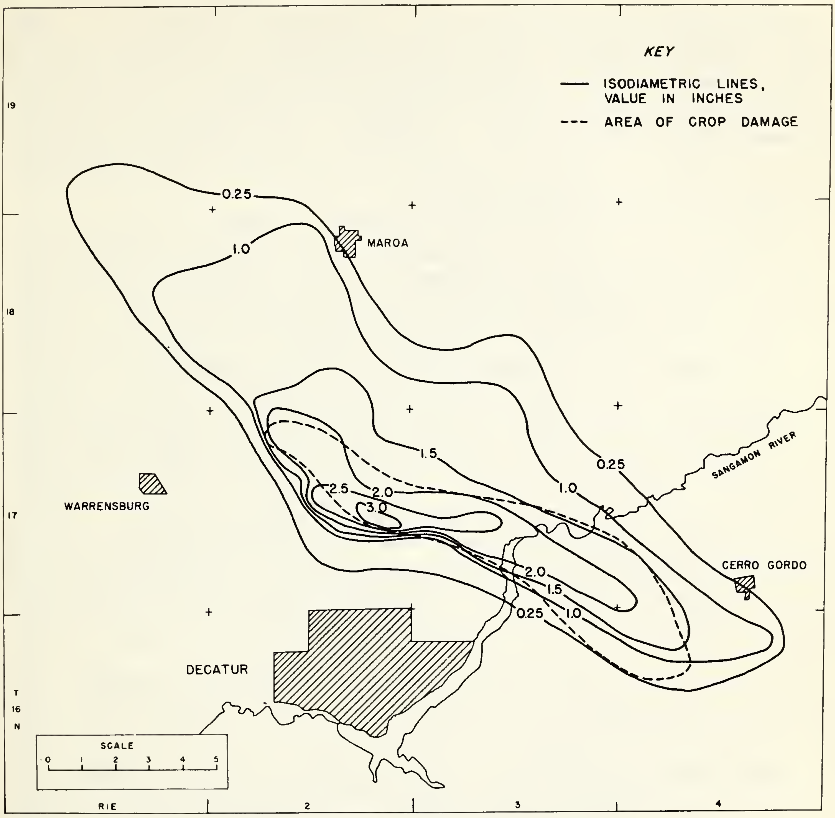

Fig. 12-6. Isodiametric lines and area of crop damage.

After Chagnon, 1960

It was found that the area of crop damage coincides rather closely with the isodiametric line of the largest stones (for the average stone size, the isodiametric line is approximately 1.0"). Observations on stone size and type indicate that the oblate type was the largest, the disc type the second largest, and the spherical type the smallest, with the occurrence of the latter being the most frequent and widespread, and the oblate and disc types the second and third in order. These three are the major types observed, although there were many other varieties of stone types and shapes. Stone density was found to be directly proportional to the damage; in general, the damaged crop area coincided with areas of stone density of 10 or more per square foot.[13] Factors other than stone density influencing crop damage were

[13]The stone density is usually hard to measure accurately.

maximum stone size of 2" diameter or more, point duration of 15 minutes or longer, oblate or spherical stone shape, and surface wind of 60 mph or more. Of all these factors, the wind speed is the most important, as was stated earlier. Finally, in the isohyetal analysis, it was revealed that the rain core is generally associated with the hailstorm and with 3" rainfall during the 12-hour period (18:00 CST, June 22, to 06:00 CST, June 23, 1960).

In the prevention of hailstorm damage, it is first necessary to delineate the boundaries of the areas of most frequent hailstorms, in relation to the choice of crop and the selection of farming areas. Secondly, the time of occurrence of hailstorms and their duration should be considered when scheduling planting dates. Extensive scientific data are needed for a detailed analysis of this problem. Most hailstorm areas are lacking complete hailstorm records, and it is essential to determine what weather phenomena are closely associated with hailstorm formation. Such factors as types and movements of fronts, cyclonic and anticyclonic tracks, distribution of intensive rainfall, trajectory, streamline, isogonal and isotack analyses for the surface and upper air, and the frequency and duration of thunderstorms should be seriously considered. The topographic effects on hail distribution is another factor of importance, because it determines the speed and direction of local winds and, in turn, affects the distribution of hailstorms.

For the prediction of hail, information on upper air conditions is necessary. The radar echo can give a short-term warning, but at best this is only a one- or two-hour warning and is of little practical use. For forecasting, the reader may refer to Section 9.3.3. Suppression control by cloud seeding on a large scale has recently been attempted. In Switzerland, attempts have been made to seed the storm clouds with smoke of particles containing some silver iodide produced by generators on the ground. Ludlam (1958) estimated a concentration of 10 grams per cubic centimeter nuclei in the supercooled region of the cloud to be sufficient for discouraging the growth of large stones. In southwestern France, both ground generators and rockets have been used. The rocket with explosive charges, sometimes impregnated with special chemicals, can be fired directly into the cloud base where and when it is required. In northern Italy, 270 and 10,000 rockets were fired in the hail seasons of 1949 and 1955, respectively. Similar experiments have been conducted in the United States, Australia, England, and Spain. Ludlam (1958) suggested the use of common salt of mass 10^{-9} as hygroscopic nuclei. These nuclei become droplets of 30 microns radius within a few minutes of their arrival in the cloud base, with a concentration of 10^{-13} to 10^{-12} grams per cubic centimeter. The total quantity of salt required for an hour operation is one kilogram. If such experiments become successful, hailstorm control would no longer be a problem. Foster (1961) has reviewed such experimental work. The basic assumption of suppression control is that an increase in the number of nuclei for the formation of ice crystals will result in a greater number of smaller hailstones. When the stones are kept to minimum size, they would presumably melt before reaching the ground.

A brief review of the literature on various aspects of hail concludes this section. In Kansas, Reitz (1942) found that there are differences in the degree of hail damage among winter wheat varieties. Estimation of monetary loss due to hail has been done by Whittier (1923), Reed (1943), Decker (1952), Lamoureux (1952), and Roth (1955). The latter has compiled hail statistics on hail-stricken areas in a number of states. De Reimer & Abbe (1898), Henry (1917), and Day (1928) are some of the earlier workers who investigated the average number of hailstorms in the United States. Pasek (1932) observed that the reduction in the yield of winter grains was due to anatomical changes in the vegetative organ tissue. For corn, Dungan (1928) studied the effect of hail injury on the development of the plants and on the eventual yield. In Iowa, Eldredge (1935) made a similar study, and concluded that corn plants can recover from severe hail damage during the early growth stages, whereas in late July or early August, just prior to tasseling, hail may completely ruin all crop prospects. In 1918, MacMillan was convinced that the epidemic of corn smut was initiated by hail. Kalton & Eldredge (1947) demonstrated that in the case of soybeans, the greatest damage is done when hail strikes during pod development. Sugar cane and a number of other cultivated plants such as tobacco, tomatoes, cabbage, lettuce, and bananas were studied as to hail damage by de Calvino in 1925. The sensitivity of fruit varieties to hail was observed by Schipper in Germany in 1925. The effect of hail on forest trees has been studied by Arnaud (1916) and Holmes (1921). For vineyards in the southeastern Alps, the invasion of a cold front causes considerable damage, as reported by Reya (1957). In Germany, Maier (1957) made microscopic examinations of hailstone structure on a collection of 3-cm diameter, apple-shaped stones which were formed in an axis position of thunderstorm eddies. He also studied the hailstone distribution. Fournier d'Albe (1955) found that the giant hygroscopic nuclei in the atmosphere are important to the formation of rain and hail. Nidetzky (1955) studied hailstone size distribution in Leoben, Austria. Molga (1951) analyzed the frequency of hailstorms in the districts of Ghansk, Olsztyn, and Batystok, for the period 1946-1950 in Poland. In Switzerland, List (1961) reviewed all the current methods and instrumentation in his study of the physical characteristics of hailstones. In addition to the simple measurement of diameter, shape, roughness, density, surface temperature, etc., he emphasized the aerodynamic forces acting on free-falling hailstones, illustrating the way in which these forces are determined. He explained in detail the technique of obtaining a thin section of the stone for the examination of growth structure and air bubbles. In addition, apparatus for determining the buoyancy and drag coefficient of, and presence of liquid water in, the hailstone were described. List's summary is highly recommended for the study of physical characteristics of hailstone formation and structure.

Ramdas et al. (1938) analyzed the frequency of occurrence of hailstorms in India. Decker (1952) defined the frequency distribution of hail damage to agricultural crops in statistical terms. His approach can be used as a means of evaluating the nature of hail hazards in various geographical areas. It is also possible to use the frequency distribution to estimate the probability of specific extent of hail damage. Schleusener & Jennings (1960) have designed a simple instrument for the measurement of the momentum impact produced by falling stones, and Foster & Bates (1956) developed a scheme for hailstone size forecasting. The former has been discussed in detail in Section 5.4.6, and the latter in Section 9.3.3.

In Texas, Hawthorn (1946) found that defoliation studies can be used as a basis for the estimation of hail losses in onions. On the subject of farm protection against hail damages, Maya (1950) studied various protection methods, and Albani (1954) reported on anti-hail measures in Europe. Numerous other reports of this sort can be found in the literature. This review is by no means complete, but is meant to pave the way for the reader on various possible approaches.

12.4.2 *Tornado*

Tornado damage is usually caused by exceedingly high winds sometimes accompanied by hail and thunderstorms. In general, it is not possible to provide material protection against crop damage by tornadoes. Shelterbelts, if very strong, may reduce damage by a weak tornado or the edge of a tornado to some extent, but are ineffective for any tornado with more than 200 mph speed. Since the problem of dissipating the tornado has not been solved, the only defense available for crops is to avoid farming in areas where tornadoes are frequently reported. In the United States, tornadoes occur most frequently in the valleys of the Mississippi, Ohio, and lower Missouri Rivers. Areas where intense differential heating prevails are prone to tornadoes. In countries other than the United States, tornadoes are rare, and have not been considered hazardous to agricultural production. In the United States, tornadoes are most likely to occur in spring and early summer; damage to crops could theoretically be avoided with midsummer plantings, but this approach is impractical for most horticultural and agronomic crops. As a whole, however, tornado damage to crops is insignificant in comparison with that of hurricanes and hailstorms, for the tornado destruction usually ranges from a few hundred yards to one or two miles in length. Of the three types of storm, tornado is the most severe but brings the least total crop damage; the hurricane is the least severe but the most destructive, because of its widespread coverage.

For the tornado forecast to be useful in a protection program, it should be issued at least 24 hours in advance and be precise as to time and area of occurrence. Also, the precision forecast should include information as to size, path, and strength of the tornado. As yet, reliable techniques of forecasting a specific tornado with respect to time and place of development have not been found. At best, it is possible to identify the conditions which are favorable for the development of a tornado and to determine its future course once it has formed. Tornado forecasting has been described in Section 9.3.3. Some additional references on various aspects of tornado research include: a comprehensive description of tornadoes in the United States by Flora (1953); a detailed study of tornadoes in Illinois by Huff et al. (1954); a method of determining areas of incipient tornadic conditions by Carr (1954); a study on the development and trajectories of tornadoes by Lloyd (1942); and the analysis of antecedent meteorological conditions for the formation of tornadoes in the U.S.A. by Showalter (1943). Further information on dynamic and synoptic treatments of the tornado can be found in numerous meteorological publications.

12.4.3 *Hurricane*

The hurricane is a severe tropical cyclone, accompanied by torrential rain, with wind speed of 65 knots or higher (some exceeding 175 knots have been reported). In general, cumulus or cumulonimbus clouds prevail, with a rain ceiling as low as 200 feet. Hurricanes originate along the equatorial convergence zone over the tropical ocean. After formation, they usually move to the west and generally slightly poleward; then they may or may not "recurve," moving toward the midlatitude westerlies and back toward the east. At maturity, they develop to sizes ranging from 60 to 1000 miles in diameter. As they move farther away from the low latitudes, the diameter increases and strength decreases.

The geographical distribution of tropical cyclones can be recognized by the various local names assigned to them. Those cyclones which originate in the North Atlantic, Caribbean Sea, Gulf of Mexico, or off the west coast of Mexico are commonly called hurricanes.[14]

[14]In parts of the Greater Antilles, including Haiti, they are known as "taino" instead of hurricanes. Although "hurricane" is the generally accepted spelling, they are sometimes referred to as "foracan" or "herocane." The term "hurricane" is used in this book for wind speeds exceeding 65 knots. Tropical cyclones with wind speeds up to 34 knots are termed "tropical depressions," and those of 35 to 64 knots are considered "tropical storms."

Those in the western north Pacific and most of the south Pacific, particularly China and Japan, are called typhoons.[15] In the Indian Ocean and along the eastern African coast and the northeast and northwest coasts of Australia, they are called cyclones, but off the northwest coast of Australia they are locally known as willywillies. Due to their worldwide distribution, tropical cyclones (or hurricanes) represent a source of serious damage to farm crops, livestock, and farmsteads.

Since hurricanes originate in the ocean, some distance from agricultural areas, they can usually be predicted a few days in advance (see Section 9.3.3). In fact, the advance prediction of hurricanes is far superior to that of tornadoes or hailstorms. There is time, then, to evacuate livestock, and if transportation is available, to remove harvestable crops. Wind damage can be controlled if special structures are available for livestock, and can be greatly reduced with appropriate shelterbelt systems.

Along coastal regions and on islands, the hurricane tide, known as the hurricane surge or wave, often brings disaster with its sudden flooding of land. In the lower latitudes, this tide occurs in the region of the hurricane center, while in the higher latitudes it is associated with the danger semi-circle[16] of the storm. The dams which might be used for protection are usually too expensive to be practical.

12.5 PROTECTION AGAINST INSECTS AND DISEASE

Various aspects of the influences of weather on insects and disease have been described elsewhere in this book, and the reader may find it helpful to refer back to these discussions.

It is generally recognized that for most vegetable and fruit crops, once the epidemic has started, the effectiveness of control or protective measures is greatly reduced or even completely lost. In Section 9.2.6, we stressed the dependence of the outbreak forecast on the seasonal weather changes. Protective measures may include quarantine of infested areas, development of pest-resistant varieties, and chemical spraying. Of the three, the last belongs more to the study of agrometeorology, and has been discussed in Section 9.2.5.

Roberts & Evenden (1949) have reported on Idaho's program for control of the Douglas fir tussock moth, ***Hemerocampa pseudotsugata*** McD., near Moscow, Idaho, where infestation covered some 450,000 acres of rough terrain in a mountainous region, and where an early quarantine of the area was necessary. The program required the examination of past climatological records on extreme winds, precipita-

[15] In the Philippines, however, they are known as "baruio" or "baguio," the latter being named after the city of Baguio, where the world's record of 46 inches of rainfall in 24 hours occurred during the passage of a tropical cyclone in July 1911. The word "typhone" or "typhoon" is derived from the Chinese word "t'ai fung," meaning a great wind.

[16] The right hand direction of a moving tropical cyclone (or hurricane) is associated with the area of violent hurricane tides.

tion, hailstorms, and other severe weather of the region in relation to their effects upon insect outbreak. In addition, synoptic weather conditions were analyzed for airplane spraying, and the following criteria were established: (a) planes should fly only in clear, calm weather, and cease operations if wind exceeding 8 mph or much turbulence appears; (b) spraying should be stopped one hour before rain and not resume until the foliage is dry; and (c) the spraying operations should be performed after midnight or in the early morning.

The tussock moths lay eggs in August and September, which hatch in late May. The hairy caterpillars of the young are active and can travel some distance in search of food. However, it is the air current (both direction and speed) which governs the spread of infestation. It has been noted that the thread and body hairs of the caterpillar offer considerable wind resistance, but can be destroyed with a wind of 10 mph or greater. The spraying program in Moscow, Idaho, was conducted between May 20 and June 30, the general hatching period of the moth. The airplane speed was limited to 90 mph or less, with the flights being made between 3:30 and 9:00 a.m., when the air was calm and cool. The swath width generally ranged from 100 to 300 feet; the maximum height of the plane above the treetops was held between 50 and 150 feet; insecticide was applied at the rate of about 35 gallons per minute.

A generally accepted minimum safe altitude above treetops for forest spraying is 50 feet, but in the case of crop spraying, it is 5 to 10 feet above the field. Over rough terrain, or with larger or less maneuverable planes, this height must be increased. In order to check the effectiveness of spraying under various weather conditions, plates were placed on the spraying route for the collection of deposits. A total of about four billion gallons of insecticide (a solution of 1 pound DDT per gallon of fuel oil) was consumed in this program.

Yuill & Eaton (1949), in their study of the use of airplanes in forest pest control, indicated that spraying should be confined to the early morning and evening when wind and convective currents are at their minimum. They stated that a wind over 10 mph could cause enough turbulence to make the air bumpy. They also suggested a light, high-wing monoplane flight at 150 mph, carrying 1000 gallons of spray. For a small area, helicopters were proved very satisfactory because of their ability to fly low and slowly, as well as their maneuverability in small areas. In the Idaho operation, the U.S. Weather Bureau established a 24-hour weather service at field headquarters in Moscow. Hourly information on both current and predicted weather was issued to assure safety of flight and successful spraying. Roberts & Evenden (1949) reported that no live tussock moth caterpillars were found a week after the spraying, and no serious effects of the spray on birds or mammals were discovered.

In summary, the application of insecticide during the most susceptible stage of the life cycle of the insect pest is essential to effective insect control. Prediction of the future populations of insects requires knowledge of weather effects on insect development. Forest entomologists, in particular, have turned to the field of meteorological entomology, as have workers in biological control. Much study has been done on control and prediction of insects, with varying success. For example: In 1928, Stear predicted the population of the leaf hopper, *Empoa pomaria*, McA. Williams (1949) attempted the forecast of insect population changes. Pratt (1955) analyzed meteorological problems in the forecasting of citrus insect infestations, as has been described in Section 9.2.6. Flitters (1962) designed insect cabinets in Brownsville, Texas, for the study of the potential distribution, development, and reproduction of four tropical fruit fly species — the oriental, melon, Mexican, and Mediterranean fruit flies. In the cabinets, natural fluctuation of temperature and humidity was reproduced and controlled to a considerable extent, with temperature ranging from -5° to 125°F, and relative humidity from 10 to 98 percent. The Agricultural Research Service, U.S. Department of Agriculture, sponsored this project. A cooperative study has been made in Honolulu, Hawaii. Similar studies were executed previously by Shelford (1927), on the codling moth, and by Christenson, Flitters & Messenger (1953) on the oriental fruit fly. Flitters & Messenger studied three species of Hawaiian fruit fly in addition to the Mexican fruit fly and the pink bollworm (1954-1958). Thermal regulation of the insect cabinet with various instrument designs was investigated by Potter (1920), Stone (1939), Wishart (1940), Munger (1944), and many others.

Crop damage by disease is just as serious as that by insects, if not more so. Two main types of disease are the parasitic and nonparasitic. The parasitic or infectious diseases include fungi, viruses, and bacteria, and are frequently highly contagious. Among the nonparasitic diseases are sunscald, winter injury, drought injury, root drowning or suffocation, malnutrition (excess as well as deficiency), and injuries from gas, smoke, and fumes. Many of the control and preventive measures discussed in Part III of this book are useful for the nonparasitic diseases. For example, irrigation, as well as the various techniques of moisture conservation, would be important to drought-caused diseases; improvement of drainage would reduce root rot diseases; and methods of combating frost hazards would be valuable in minimizing winter injury.

The control of parasitics — the spraying program, the avoidance of disease-favoring areas, testing for disease resistance — again requires accurate coordination with weather factors. The agrometeorological implications of the control of diseases are similar to those of insect control. In fact, the infestation of disease and insects are closely related to the availability of food, to the existence of favorable weather conditions, and to each other, for insects are often carriers of disease.

Research on crop diseases in relation to weather covers a wide range. Based upon microclimatical measurement, Van Arsdel (1961) suggested that blister rust of white pine can be reduced by maintaining the microenvironment dry and warm, with a closed canopy, pruning lower branches and avoiding small openings in the crown. Since over 99 percent of all blister rust cankers in the Lake States of the United States are within six feet of the ground and since these diseases are favored by cool and wet conditions, he claimed that these aids would keep 95 percent of the trees from rust. On disease prediction, we have Chester's determination (1942) of factors for the prediction of wheat leaf rust epiphytotics; prediction of plant diseases with the use of 5-day standard units by Felix (1957); and a description of plant disease prediction by Pietkiewicz (1949). The effect of sprinkler irrigation in an arid climate on the spread of bacterial diseases of beans was investigated by Menzies (1954). Such studies are useful in the preparation of a disease control program.

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APPENDIX A

Glossary of Terms

For the convenience of the user, the terms appearing in the text without definitions are defined in this appendix. Those defined in the text can be located readily in the Subject Index. Definitions given below were obtained from the following references:

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A

Abiotic factor

Factors other than biotic pertaining to any climatic and/or edaphic type of environmental factors.

Accelerated erosion

The excessive wearing away of rock or soil brought about by changes in the natural cover or ground conditions, including changes due to human activity.

Actinomyces bovis

A pathogenic fungus affecting the jawbones of cattle and swine.

Adiabatic process

Thermodynamic process or system in which there is no transfer of heat or mass into or out of the boundary of the system. For adiabatic compression, it is warming; for adiabatic expansion, it is cooling.

Advection
The transfer of heat by horizontal wind.

Aerobic bacteria
Bacteria which are able to live only in the presence of free oxygen; see also "Anaerobic bacteria."

Aerodynamically rough surface
A surface whose irregularities are sufficiently high that the turbulent boundary layer reaches right down to the surface.

Ageostrophic wind (or geostrophic departure)
The vector difference between the real (or observed) wind and the geostrophic wind.

Albedo
The ratio of the total amount of reflected radiation to that of incident radiation of the surface of a body is the albedo of that body. For the same body, it varies with the incident wavelength, surface roughness, moisture condition, etc. For a specific single wavelength (monochromatic radiation), we speak of reflectivity and not albedo; for a specific spectrum, such as visible, infrared, and ultraviolet, we use the term albedo. Sometimes the totality of wavelength in the solar spectrum is referred to as the albedo of the visible spectrum.

Alcoholic insoluble products (AIS)
That portion of a substance which will not dissolve in alcohol.

Altocumulus
A principal cloud type (cloud genus), white and/or gray in color, which occurs as a layer or patch with a waved aspect, the elements of which appear as laminar, rounded masses, rolls, etc.

Altostratus
A principal cloud type (cloud genus), in the form of a gray or bluish (never white) sheet or layer of striated, fibrous, or uniform appearance.

Aminization
Microbiological decomposition of protein into amino compounds.

Ammonification
A process that decomposes complex nitrogenous compounds into a number of simpler compounds. Most of the nitrogen is released in the form of ammonia by means of ammonifying bacteria.

Anabolism
The building up of nutritive substances into living tissues.

Anaerobic bacteria
Bacteria which are able to live without free oxygen; they get oxygen by decomposing compounds containing it.

Anticyclone
A clockwise rotation of air in any geographical region of the northern hemisphere; counterclockwise in the southern hemisphere; undefined at the equator; as indicated by a weather map.

Apiculture
Beekeeping or method of rearing bees.

Arachnids
Arthropods with four pairs of legs, lunglike sacs or breathing tubes, and bodies usually divided into two segments, e.g., spiders, mites, ticks, and scorpions.

Atmospherics
Pertaining to atmospheric electricity, with special reference to lightning discharges.

Autotrophic bacteria
Bacteria which produce their own food, i. e., in which photosynthesis can occur.

B

Barogram
The record of a barograph; see "Barometer."

Barometer
An absolute pressure gauge designed specifically to measure air pressure. The automatic barometer is a barograph, the record of which is a barogram.

Beaufort scale
A system of estimating and reporting wind speed through visual observation of land objects and sea surface. The modified and modernized scale for land use can be found in any standard meteorology textbook or the U. S. Weather Bureau Circular N, 7th ed., 1955, p. 100.

Bolometer
An instrument which measures the intensity of radiant energy by employing a thermally sensitive electrical resistor; a type of actinometer. In meteorological applications, two identical, blackened, thermally sensitive electrical resistors are used in a Wheat-

stone bridge circuit. Radiation is allowed to fall on one of the elements, causing a change in its resistance. The change is a measure of the intensity of the radiation.

Brood

To sit on and hatch eggs.

Buffer capacity

Resistance to change in acidity or alkalinity; the ratio of soil resistance to the distinct change in pH other than that offered by the soil solution. The higher the exchange ratio of the soil, the greater its buffer capacity. See also "pH value."

C

Calcification

A process in which the deposition of insoluble lime salts such as calcium carbonate or carbonate in a tissue, etc., occurs.

Capillary fringe

The height boundary that capillary water frequently reaches.

Carnot cycle

A hypothetical thermodynamic cycle in which a heat engine accepts energy from a high-temperature source, converts part of the received energy into mechanical or electrical work, and rejects the remaining energy to a low-temperature sink or cold body. It is impossible for an engine to convert all the heat supplied to it into mechanical energy.

Cation exchange capacity

Many small soil particles, both mineral and organic, possess net negative charges. These charges are balanced by cations which exist in more or less diffuse swarms near the surface of the particles. The balancing ions are called exchangeable cations, and are in kinetic equilibrium with the soil solution. Their quantity, usually expressed as milliequivalents (meq) per 100 g of dry soil, is the cation exchange capacity.

Ceilometer

An automatic recording cloud-height indicator.

Centipede

Any of a group of related worm-like animals with a pair of legs for each body segment; the two front legs are modified into poison fangs.

Chloroplast

The body in the cell cytoplasm which contains the green chlorophyll pigment.

Chlorosis

An abnormal condition of plants in which the green parts turn yellow as a result of the inhibition of chlorophyll synthesis.

Cirrocumulus

A principal cloud type (cloud genus) appearing as a thin white patch of cloud without shadows, composed of very small elements in the form of grains, ripples, etc.

Cirrostratus

A principal cloud type (cloud genus) appearing as a whitish veil, usually fibrous but sometimes smooth, which may totally cover the sky, and which often produces halo phenomena, either partial or complete.

Cirrus cloud

A principal cloud type (cloud genus) composed of detached cirriform elements in the form of delicate white filaments, of white (or mostly white) patches, or of narrow bands.

Cold front

The "leading edge" of a relatively cold air mass; the front at which the colder air replaces warmer air.

Colloid

A non-homogeneous mixture made up of very small, insoluble non-diffusible particles larger than molecules but small enough that they remain suspended without settling to the bottom.

Comfort zone (also "comfort index")

Used to refer to combination of variables describing air temperature, moisture, and wind speed of an environment, to express the degree of comfort for human beings and animals.

Coriolis force

An apparent force, which arises from the earth's rotation.

Cosine law of illumination

The relationship between the illuminance, I, of the surface and the angle of incidence can be expressed as $I = F \cos \theta$, where F is the flux density of the illuminating beam.

Cumulonimbus

A principal cloud type (cloud genus), exceptionally dense and vertically developed, occurring either as isolated clouds or as a line or wall of clouds with separated upper portions.

Cyclonic scale (synoptic scale)

The scale of the migratory high and low pressure systems (or cyclone waves) of the lower troposphere, with wavelengths of 1000 to 2500 km.

D

Deformation thermometer
A thermometer using transducing elements which deform with changing temperature. Examples of deformation thermometers are the bimetallic thermometer and the Bourdon type of thermometer.

Denitrification
A process that reduces nitrates to nitrites and ammonia by means of denitrifying bacteria.

Differentiation
Any change in shape, texture, or structure associated with growth of plants.

Diptera
A large group of insects, including the housefly, mosquito, gnat, etc., having one pair of membraneous wings.

E

Ecological coordinate system
A coordinate system with some response of a plant to a single or synthetic environmental factor as vertical axis and phenological calendar as horizontal axis.

Edaphon
The whole living community of the soil, i.e., soil flora and fauna.

Electromagnetic radiation
Energy propagated through space or through material media in the form of an advancing disturbance in electric and magnetic fields existing in space or in the media. This type of radiation is generally known as "radiation."

Emission
With respect to radiation, the generation and sending out of radiant energy.

Endocrine gland
A structure which produces and secretes a hormone directly into the circulatory system.

Estivation
The habit or state of spending the summer in a dormant state for an animal (same as "Aestivation").

Etiolation
The development of plants in the complete absence of light.

Eulerian correlation
The correlation between the properties of flow at various points of space at a single instant of time.

F

Facsimile equipment
Apparatus used for the electrical transmission of a graphic record (as, for example, a weather map) either over wires or by radio. The received image is built up from dots or lines which may be of constant or varying intensity, depending on the type of system employed.

Fecundity
Quality or power of producing offspring, or productivity.

Flocculation
The aggregation of suspended colloidal materials into aggregates, as contrasted to their dispersion.

Floral primordia
The earliest condition of flower.

Frost heaving
The lifting of soil surfaces by mechanical expansion through the formation of ice.

Function
Y is a function of x, for a certain range of values of x, if to each x of the range there is a corresponding value of y assigned; x is termed the independent variable, y, the dependent variable.

G

General circulation
The complete statistical description of atmospheric motions over the earth.

Geostrophic wind
The horizontal wind that moves along the isobaric surface; the wind which would flow along an isobaric surface.

Glei horizon
A soil horizon in which the material is ordinarily bluish-gray or olive gray, more or less sticky, compact, and often structureless. It is developed under saturation in the presence of organic matter. The iron compounds are ferrous.

Gleization
A process of soil formation, due to excess moisture, leading to the development of Glei-Horizon (Gley-Horizon). It is the major process for the formation of bog and/or half-bog soil. See Glei-Horizon.

Green manuring
A crop which is plowed under ground while green for its beneficial effect on the soil as fertilizer (or organic matter).

Gully erosion
Erosion in which the concentrated runoff is sufficiently large to cut deep trenches, or where continued cutting in the same groove deepens the incision.

Guttation
The process by which plants expel liquid water and other dissolved substances from uninjured leaves in excess of transpiration.

H

Height contour, or contour line
A line of constant elevation above a certain reference level (usually mean sea level) on a previously defined surface, which may be the earth's surface, a constant pressure surface, an isotropic surface, etc.

Heterotrophic bacteria
Those bacteria which obtain food from organic material, unable to use inorganic matter to form proteins and carbohydrates.

Hibernation
For an animal, the habit or state of spending the winter in a dormant state.

Hydroponics
Refers to the cultivation of plants in cultural solution.

Hygroscopic coefficient
The moisture, in percentage of dry weight, that a dry soil will absorb in saturated air at a given temperature.

I

Illuminometer
Same as photometer; see "Photometer."

Inflorescence
A cluster of flowers and the manner in which the individual flowers are arranged.

Isogon
An isopleth of wind direction; see also "Isotach."

Isopleth
A line of equal or constant value of a given quantity, with respect to space or time; same as isogram.

Isotach
A line in a given surface connecting points with equal wind speed.

L

Lactation
The secretion of milk by a mammary gland; the period during which milk is secreted.

Laminar flow
Streamline flow of a viscous fluid in which the fluid moves in layers without large irregular fluctuations.

Laterite soil
The zonal group of soils having very thin organic and inorganic mineral layers over leached soil that rests upon highly weathered material, rich in alumina or iron oxide, or both, and poor in silica; the soils are usually, but not necessarily, red in color.

Laterization
The formation of lateritic soils; essentially the process of silica removal with consequent increase in the alumina and iron oxide content, and decrease in cation exchange capacity of the soil. See also "Lateritic soil."

M

Mho
The unit of electrical conductance; 1 mho = 1 ohm^{-1}.

Moist adiabatic process
An adiabatic process in which the air is maintained at saturation by the evaporation or condensation of water substance, the latent heat being supplied by or to the air, respectively. The ascent of cloudy air, for example, is often assumed to be such a process.

Monochromatic light
Electromagnetic radiation of a single color or wavelength.

N

Nematodes
A class of worms with long, cylindrical, unsegmented bodies, e.g., hookworm, periworm, vinegar eel, trichinella.

Nimbostratus
A principal cloud type (cloud genus), gray colored and often dark, rendered diffuse by more or less continuously falling rain, snow, sleet, etc., of the ordinary varieties and not accompanied by lightning, thunder, or hail.

Nitrification
A process that decomposes nitrogen compounds into nitrites and further into nitrates through oxidation, especially by nitrifying bacteria.

O

Occluded front
A composite of two fronts, formed as a cold front overtakes a warm front.

Optical air mass
A measure of length of the path through the atmosphere to sea level traversed by light rays from a celestial body, expressed as a multiple of the path length for a light source at the zenith. It is approximately equal to the secant of the zenith distance of the given celestial body for zenith distances up to about 70°.

P

Pedology
The study of soil science.

Perennial
A plant having a life cycle of more than two years.

Perturbation
Any departure introduced into an assumed steady state of a weather system.

pF value
The logarithm of the height, in centimeters, of a water column necessary to produce a force equal to the energy with which moisture is held by a soil.

pH value
The negative logarithm of the hydrogen ion concentration of a solution; a pH of 7.0 indicates neutrality; higher values indicate alkalinity, lower values, acidity.

Phloem
Vascular tissue in which most food materials move from one part of the plant to another.

Photometer
An instrument for measuring the intensity of visible light or the relative intensity of a pair of lights. If the instrument is designed to measure the intensity of light as a function of wavelength, it is called a spectrophotometer.

Plan position indicator
See "Radar."

Podzol
Soil with acid-humus horizon overlying the B-horizon of iron oxide or iron oxide with humus accumulation.

Podzolization
The process by which a podzolic soil is developed, including the more rapid removal of iron and aluminum than silica from the surface horizons of the soil.

Pore space
The total space not occupied by solid soil particles. See also "Porosity."

Porosity
The fraction of the total soil volume not occupied by solid particles; percentage of total pore space, i.e., $100 - \frac{\text{bulk density}}{\text{particle density}} \times 100$.

Potentiometer
A device for the measurement of an electromotive force (emf) by comparison with a known potential difference. The known potential difference is established by the flow of a definite current through a known resistance, using a standard cell as a reference.

Prevailing wind direction
The wind direction most frequently observed during a given period.

Protoplasm
A semifluid viscous translucent colloid, the essential matter of all animal and plant cells; it consists largely of water, proteins, lipoids, carbohydrates, and inorganic salts.

R

Radar
An electronic instrument used for the detection and ranging of distant objects of such composition that they scatter or reflect radio energy. There are various indicators of a radar apparatus or radarscope on which echoes from targets detected by the radar are visually displayed. For example, RHI scope is a range-height indicator scope simulating a vertical cross-section of the atmosphere along some azimuth from the radar; PPI scope is a plan-position indicator on which the range and azimuth of a target being displayed in polar coordinates and the position of radar is at the center of the scope.

Rayleigh scattering
Scattering by particles whose diversions are considerably smaller than the wavelength of the incident radiation.

Reversible engine
A thermodynamic system in which all changes in the thermodynamic coordinates are infinitesimal; i.e., a succession of equilibrium states.

Reversible process
A succession of equilibrium states, or of states that depart only infinitesimally from equilibrium.

Reynolds number
The non-dimensional ratio of the inertia force (LU) to viscous force (ν) in fluid motion, thus

$$R_e = \frac{LU}{\nu},$$

where L is a characteristic length, U is a characteristic velocity, and ν is the kinemetic viscosity. For laminar flow, R_e is less than 2000, whereas for turbulent flow it is above 3000. $\nu = m\mu$.

Ridge
In meteorology, an elongated area of relatively high atmospheric pressure, almost always associated with and most clearly identified as an area of maximum anticyclonic curvature of wind flow. The locus of this maximum curvature is called the ridge line.

Rill erosion
Narrow trenches called rills are cut by small streamlets or rivulets in which runoff water is concentrated during heavy rains.

Rough surface
See "Aerodynamically rough surface."

S

Salinity
The degree of saltiness. Since salt ionizes in solution, the conductivity of a salt solution (mhos/cm) can be used to measure this property. See also "Mho."

Salinization
The process of accumulation of salts in the soil.

Secondary circulation
Atmospheric circulations of cyclonic scale.

Sensor
The component of an instrument which converts an input signal into a quantity which is measured by another part of the instrument. Thereby a good sensor used in agrometeorology should be sensitive either to the microenvironmental changes or to the changes of the living organism.

Sericulture
The production of raw silk by raising silkworms.

Sferics (also spelled "Spherics")
The study of atmospherics, especially from a meteorological point of view. This involves techniques of locating and tracking atmospherics sources and evaluating received signals (waveform, frequency, etc.) in terms of sources.

Sheet erosion
Removal of a thin layer of soil, more or less uniformly, from the entire surface of an area.

Signal
Any carrier of information; opposite of noise.

Siphon raingauge
A recording raingauge utilizing the principle of a siphon to remove continuously the rainfall received to a recording device.

Sodic soils
Soils that contain sufficient sodium to interfere with the growth of most crop plants; soils for which the exchangeable sodium percentage is 15 or more.

Soil tilth
The physical conditions of soil relative to its response to tillage machinery and its mechanical impedance to root penetration.

Squall line
Any non-frontal line or narrow band of active thunderstorms, as shown on a weather map.

Stationary front
A front which is moving at a speed less than about five knots.

Steering
Any influence upon the direction of movement of an atmospheric disturbance exerted by another aspect of the state of the atmosphere.

Stratosphere
The part of the earth's atmosphere extended from the tropopause to the height where temperature begins to increase. The temperature in the stratosphere ranges from about -45° to -75°C, and is approximately isothermal. See also "Troposphere" and "Tropopause."

Stratus
A principal cloud type (cloud genus) in the form of a gray layer with a rather uniform base. Stratus does not usually produce precipitation, but when it does occur it is in the form of minute particles such as drizzle, ice crystals, and snow grains.

Subterranean ears
The primordia of ear buds of corn that develop underground.

Sunspot
A dark area in the photosphere of the sun caused by a lowered surface temperature.

Suture
A line or a groove marking a natural division of union as in the plum, peach, and/or similar fruit; the plane cut through such a line of a fruit is the suture surface, and its maximum diameter is the suture diameter.

T

Temperature anomaly
The deviation of temperature in a given region over a specified period from the normal value for the same region.

Tertiary circulation
The generally small, localized atmospheric circulation, generally represented by such phenomena as local winds, thunderstorms, and tornadoes.

Thermocouple
A device that uses the voltage developed by the junction of two dissimilar metals to measure temperature differences.

Thermopile
A transducer for converting thermal energy directly into electrical energy. It is composed of pairs of thermocouples which are connected either in series or in parallel. See also "Thermocouple."

Thyroid secretion
The hormone, thyroxin, secreted by the thyroid gland, which regulates metabolism.

Transducer
Any device or element which converts input energy into output energy of another form, such as the transformation of electrical energy into heat energy.

Translocation
Transportation of products of metabolism, etc., from one part of a plant to another.

Trichotomy
Division into three parts and/or arrangement in three divisions, as applied in the treatment of one real number related to another.

Tropopause
The boundary layer between the troposphere and stratosphere, usually characterized by an abrupt change in lapse rate. See also "Troposphere" and "Stratosphere."

Troposphere
The lowest part of the earth's atmosphere, characterized by strong convective air current and by decrease of temperature with height.

Trough
In meteorology, an elongated area of relative low atmospheric pressure. The axis of a trough is a trough line.

Turbulent boundary layer
The layer in which the Reynolds stresses are much larger than the viscous stresses.

Turbulent flow
Motion of fluids in which local velocities and pressures fluctuate irregularly.

U

Upper air
That portion of the atmosphere which is above the lower troposphere.

V

Variable
See "Function."

Vascular bundles
Strand-like parts of the vascular system containing the conducting system of plants — the xylem and phloem.

Viscosity
The force per unit area which resists the flow of two parallel fluid layers past one another when their differential velocity is one centimeter per second separation.

Visibility
In the United States weather observing practice, the greatest distance in a given direction in which it is just possible to see and identify with the unaided eye (a) in the daytime, a prominent dark object against the sky at the horizon, and (b) at night, a known, preferably unfocused, moderately intense light source. After visibilities have been determined around the entire horizon circle, they are resolved into a single value of prevailing visibility for reporting purposes.

W

Warm front

Any non-occluded front, or portion thereof, that moves in such a way that warmer air replaces colder air.

Warm sector

That area, within the circulation of a wave cyclone, where the warm air is found. It lies between the cold front and the warm front of the storm.

Westerlies

Zonal winds dominated by a west-to-east motion of the atmosphere, generally centered over the middle latitudes of both hemispheres.

Wet bulb freezing level

The height of the 0°C constant wet bulb temperature.

Wheatstone bridge

A device used to measure the electrical resistance of an unknown resistor by comparing it with a known resistance.

Wind drag

The frictional impedance (or frictional force) offerred by air movement passing through the surface of a body.

X

Xylem

The woody portion of root and stem; a complex tissue of higher plants, variously consisting of tracheids, tracheae, wood fibers, and parenchyma.

Z

Zonal wind

The wind, or wind components, along the local parallel of latitude, as distinguished from the meridional wind component parallel to the local longitudinal meridian.

APPENDIX B

Some Fundamental Statistics

Statistics constitutes the science of decision-making in the face of uncertainty. It deals with those problems where, for individual observations, laws of cause and effect are not apparent to the observer and where an objective approach is needed. It provides the framework for looking at such uncertain situations in a logical and systematic way, often squeezing usable information from a limited amount of raw material (observational data). It can be said to include everything dealing with the collection, processing, analysis, interpretation, and presentation of numerical data.

Customarily, statistics is divided into major categories of descriptive and inductive statistics. Descriptive statistics refers to any treatment of numerical data that does not directly involve generalization or decision-making. Inductive statistics or statistical inference, on the other hand, involves generalization, prediction, and estimation. It is inductive statistics that we are primarily concerned with. In this appendix, attention is given to the application of sampling principles to some of the basic problems of statistical inference. This is done by the use of definitions, formulas, and examples.

1. *Frequency distribution*

This is the grouping and the classification of observational data, either numerically or categorically, according to certain characteristics. However, the use of grouped data is emphasized here. The distribution curve may be symmetric or skew. Symbols commonly used are:

- n — number of cases or of individual variables
- x_i — individual variables
- c_i — mid-point of any class interval, or class average
- f_i — frequency of x_i within each class interval
- k — number of classes in distribution, or number of samples

2. *Measure of central tendency*

Some measures of central tendency and their symbols are listed:

$\bar{x}$ — arithmetic mean of a sample (for a population mean, it is μ)
M_w— weighted mean.
M_r — moving mean (or running mean).
M_e— median.
M_o— mode.

(a) Arithmetic mean. This generally refers to the sum of the individual variables x_i divided by the number of cases, n. For ungrouped data, it is written

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{B-1}$$

The *mean of distribution* (grouped data) is represented as the sum of the products of the class averages, c_i, and their frequencies, f_i, divided by the number of cases, n. Symbolically, it is written

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} c_i f_i \tag{B-2}$$

For example, the mean ($\bar{x}$) of night temperature data below is

$$\bar{x} = \frac{1477.0}{22} = 67.1$$

Table B-1. Frequency Table for Night Temperature Measurements, °F

Class Interval	f_i	c_i	$c_i f_i$	Class Boundaries
54-57	1	55.5	55.5	53.5 - 57.5
58-61	3	59.5	178.5	57.5 - 61.5
62-65	6	63.5	381.0	61.5 - 65.5
66-69	4(f_{Me})	67.5	270.0	65.5 (L)-69.5
70-73	3	71.5	214.5	69.5 - 73.5
74-77	5	75.5	377.5	73.5 - 77.5

$$\sum_{i=1}^{k} f_i = 22; \quad \sum_{i=1}^{k} c_i f_i = 1477.0$$

Note: The explanation of f_{Me}, L, and class boundaries will be given in Equation (B-4).

(b) Weighted mean. This refers to the over-all mean of several sets of data on the basis of their individual means and the number of cases in each set. Thus it is obtained by weighting the individual means, $\bar{x}_i$, with the number of cases on which each is based. The formula for the weighted mean is expressed as

$$M_w = \frac{\sum_{i=1}^{k} n_i \bar{x}_i}{\sum_{i=1}^{k} n_i} \qquad \text{(B-3)}$$

For example, the average yield of sweet potato for a certain farmer in Alabama was 55 bushels per acre for 35 acres of land, 85 for 10 acres and 100 for 37 acres. Substituting $n_1=35$, $n_2=10$, $n_3=37$ and $\bar{x}_1 = 55$, $\bar{x}_2 = 85$, $\bar{x}_3 = 100$ into Equation (B-3), we have

$$M_w = \frac{35(55) + 10(85) + 37(100)}{35 + 10 + 37} = \frac{6475}{82} = 79.0$$

for the over-all mean yield of sweet potato for these 82 acres of land.

(c) Moving mean. This is a measure of seasonal fluctuation or trend. It is an artificially constructed time series in which each annual, monthly, or hourly figure is replaced by the mean of itself and values corresponding to a number of preceding and succeeding periods. For instance, in a three-year moving average, each annual figure is replaced by the mean of itself and those of the immediately preceding and succeeding years. The moving mean can also be called the "running mean." Sometimes the accumulated mean is the arithmetic mean of the nth period following the whole time series. For example, when annual temperatures in one locality for the successive n-year period are 80, 90, 91, . . . , the mean for the first year is 80/1 = 80; that for the second year is (80 + 90)/2 = 85; that for the third year is (80 + 90 + 91)/3 = 87; and so on. Thus, the accumulated mean is expressed by 80, 85, 87, ... Other types of means, such as the geometric and harmonic means, are not often used in agrometeorology.

(d) Median. This is defined as the central position where a distribution is divided into two equal areas under the distribution curve. The median of a distribution (Me) with equal class intervals can be expressed by the following equation.

When counting from the lower end of a distribution,

$$Me = L + C\frac{j}{f_{Me}}, \qquad \text{(B-4)}$$

where L is the lower boundary of the class into which the median must fall, C is the class interval, j is one-half of the total frequency minus the number of cases before reaching L; and f_{Me}, the frequency of the class at which L is established. For example, the median of the night temperature data as illustrated under Equation (B-2) can be obtained as Me = 65.5 + 4(1/4) = 66.5, where L = 65.5, C = 58 - 54 (with 4 between the class boundaries), j = (11 - 10), or 1, and $f_{Me} = 4$.

(e) Mode. This is the value, class, or category, of most frequent occurrence — that is, the value most typical of the set of data. A set of data may not possess a mode at all, or it may have more than one mode. Thus we can have non-modal, monomodal, bimodal, trimodal, and multimodal distributions.

3. *Measure of variation*

The symbols used are:

s — standard deviation of sample (for the population, the symbol σ is used).

δ — coefficient of variation.

(a) Standard deviation. This is also known as the root-mean-square deviation. It consists of dividing the sum of the squared deviations by n - 1. For ungrouped data, it is formulated

$$s = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n - 1}}\,, \tag{B-5}$$

where $\bar{x}$ is obtained from Equation (B-1). The standard deviation of a distribution is

$$s = \sqrt{\frac{\sum_{i=1}^{k} (c_i - \bar{x})^2 f_i}{n - 1}}\,. \tag{B-6}$$

where $\bar{x}$ is obtained from Equation (B-2).

(b) Coefficient of variation. This is the most widely used measure of the magnitude of the variation relative to the size of whatever objects one is measuring, or for the comparison of the dispersions of two or more sets of data that are given in different units. The formula for this is

$$\delta = \frac{s}{\bar{x}}(100)\,. \tag{B-7}$$

4. *Shape of distribution*

In a perfectly symmetrical distribution, the mean will coincide with the median and the mode. If not, there will generally be discrepancies between these measures of central tendency. The skewness is the degree of discrepancy.

Peakedness of a distribution describes the shape of a distribution in terms such as "broad," "narrow," "humped," or "bell."

5. *Probability*

Inductive statistics or statistical inference is presented in the form of estimation and of the testing of hypotheses. Whether a generalization is made in the form of estimates, or by testing hypotheses, it is expressed in terms of probability. The role played by probability in statistics is that of a substitute for certainty. The probability, or "the chance," is defined as the limit of the relative frequency of the occurrence of an event in the long run. Notations and some basic rules of probability are presented below.

p	The probability of success or of the occurrence of an event.
$p(A)$	The probability of the occurrence of an event A.
$p(A \text{ or } B)$	The probability of the occurrence of A or B.
$p(A \text{ and } B)$	The probability of the occurrence of both A and B.
$p(A/B)$	The conditional probability that the occurrence of A takes place provided that B has taken place.
q	The probability of failure, or of an event not occurring.
n	The number of events in a trial; the number of ways in which an event can occur.

Some basic rules of probability:

(1) The probability cannot be negative or exceed 1. Thus, the probability of the occurrence of A is $0 \leq p(A) \leq 1$. This applies to q as well.

(2) If n mutually exclusive events have equal probabilities, and if x represents the number of successes and x', the failures, then the probability of a success may be expressed as

$$p = \frac{x}{n} \tag{B-8}$$

and the probability of a failure (q) is

$$q = \frac{x'}{n} \tag{B-9}$$

(3) If the probability of the occurrence of an event A is p(A), and that of non-occurrence is q(A), then $q(A) = 1 - p(A)$, or

$$p + q = 1 \tag{B-10}$$

(4) If events A and B are mutually exclusive, then

$$p(A \text{ or } B) = p(A) + p(B) \tag{B-11}$$

and likewise,

$$p(A_1 \text{ or } A_2 \text{ or } \ldots \text{ or } A_n) = p(A_1) + p(A_2) + \ldots + p(A_n) \tag{B-12}$$

$$p(A \text{ and } B) = 0 \tag{B-13}$$

$$p(A/B) = 0, \text{ or } p(B/A) = 0 \tag{B-14}$$

(5) If A and B are independent events, then

$$p(A \text{ or } B) = p(A) + p(B) - p(A \text{ and } B) \tag{B-15}$$

$$p(A \text{ and } B) = p(A) \cdot p(B) \tag{B-16}$$

and likewise,

$$p(A_1 \text{ and } A_2 \text{ and } \ldots A_n) = p(A_1) \cdot p(A_2) \cdot \ldots \cdot p(A_n) \tag{B-17}$$

$$p(A/B) = p(A) \tag{B-18}$$

and likewise,

$$p(B/A) = p(B) \tag{B-19}$$

(6) If A and B are dependent, but not necessarily mutually exclusive, then formula (B-15) is valid, and

$$p(A \text{ and } B) = p(A/B) \cdot p(B), \text{ or } p(A \text{ and } B) = p(B/A) \cdot p(A) \quad \text{(B-20)}$$

$$p(A/B) = \frac{p(A \text{ and } B)}{p(B)} \quad \text{(B-21)}$$

and likewise,

$$p(B/A) = \frac{p(A \text{ and } B)}{p(A)} \quad \text{(B-22)}$$

6. *Probability distribution*

(a) Binomial distribution. This may be defined as the probability of a certain number of successes x taking place in a given number of trials, n, when probability p in any trial is constant and the trials are independent. The binomial distribution will become symmetrical when p and q are equal and when n is large. The formula for the binomial distribution, B, may be expressed as

$$B = \frac{n!}{x!(n-x)!}\, p^x q^{n-x} \quad \text{(B-23)}$$

where n! is read as factorial n, e.g., $3! = 3 \times 2 \times 1 = 6$.

The mean of the binomial distribution may be expressed as $\mu = np$, and the standard deviation of the binomial distribution as $\sigma = \sqrt{npq}$.

(b) Normal distribution. This is a continuous, symmetrical distribution. An important property of a normal distribution is that the area under the distribution curve between any two points on the horizontal scale can be determined if the mean, μ, and the standard deviation, σ, are given.

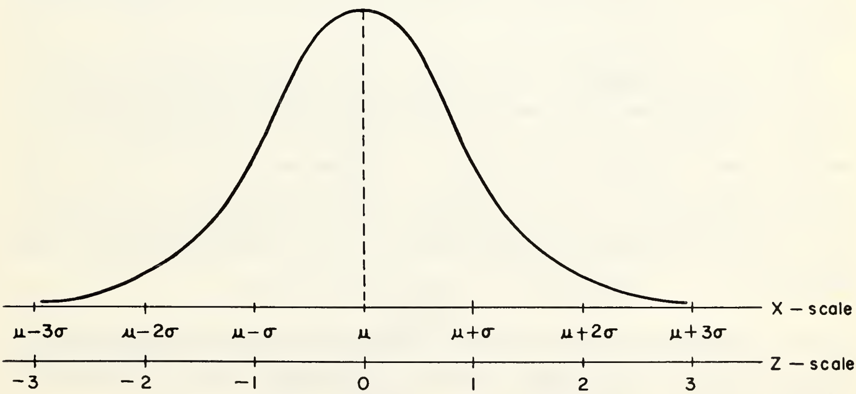


Fig. B-1. Standard normal distribution curve.

It is always possible to convert the normal distribution into a standard normal curve ($\mu = 0$, and $\sigma = 1$), by changing the scale of measurement x's into standard units, z's; this is illustrated in Fig. B-1.

Thus, for obtaining the area between two points x_1 and x_2 on the axis of a normal curve with mean μ and standard deviation σ, it is only necessary to obtain the area between the corresponding z_1 and z_2 on a standard curve where $\mu = 0$ and $\sigma = 1$, thus

$$z_1 = \frac{x_1 - \mu}{\sigma} \;; \quad z_2 = \frac{x_2 - \mu}{\sigma} \,. \qquad \text{(B-24)}$$

If a distribution can be approximated closely with a normal curve, 99.7 percent of the area under the curve falls between $+3\sigma$ and -3σ.

As indicated previously, a binomial distribution is approximated by a normal curve when n is sufficiently large and/or p is close to q. Thus, in a normal approximation of the binomial distribution, np approaches μ and $\sqrt{npq}$ approaches σ, and the probability may be obtained from Equation (B-24).

There are situations in which forms of continuous distribution other than the normal curve are expected. Among them, the t-distribution, the Chi-square distribution, and the F-distribution play very important roles in problems of estimation, prediction, and testing of hypotheses.

7. *Problems of estimation*

Estimation provides a generalization based on the known facts of a randomly drawn sample about the unknown values of the parameters that define the characteristics of a population from which the sample is drawn. There are two types of estimation, namely, the point and the interval estimates. The former is concerned with the estimation of parameters in terms of a single figure. The latter defines the specific limits within which the actual value of the parameter may be expected to lie, the reliability of which is expressed in terms of probability.

(a) Point estimates.

Estimation of means: The theoretical sampling distribution of a sample mean ($\bar{x}$) has the mean μ and the standard deviation $\sigma/\sqrt{n}$, if random samples of the size n are taken from the population with a mean μ and a standard deviation σ. Furthermore, if n is large, the theoretical sampling distribution of $\bar{x}$ can be approximated very closely with a normal curve having a mean μ and standard deviation $\sigma/\sqrt{n}$. Thus the distribution estimate of means from a large sample is expressed as

$$z = \frac{\bar{x} - \mu}{\sigma/\sqrt{n}} \qquad \text{(B-25)}$$

For the estimation of means from a small sample, the t-distribution is used instead of the normal curve, and the distribution estimate is expressed as

$$t = \frac{\bar{x} - \mu}{s/\sqrt{n}} \qquad \text{(B-26)}$$

where $\bar{x}$ and s are the mean and standard deviation of a random sample of size n.

Estimation of proportions: When a random sample is drawn from a large population, we can assume that the probabilities of getting x successes in n trials will approximate the binomial distribution. Therefore, the proportion estimate becomes

$$z = \frac{x - np}{\sqrt{npq}}. \qquad \text{(B-27)}$$

(b) Interval estimate. The main disadvantage of the point estimate is that it does not actually equal the quantity that it is supposed to estimate. Therefore, the point estimate must be supplemented with some statement of error. If s is some point estimate on the basis of a random sample, with 95 percent confidence interval, the population parameter which s is supposed to estimate is represented as

$$s - 1.96\sigma_s < \text{population parameter} < s + 1.96\sigma_s,$$

where -1.96 and +1.96 are values of the two points on the horizontal scale of the normal curve between which 95 percent of the area under the curve lies, σ_s is the standard error of s. Thus, depending on what s represents, the 95 percent interval estimate of the population parameter may be expressed as follows:

When s = sample mean ($\bar{x}$), then σ_s becomes $\sigma_{\bar{x}} = \sigma/\sqrt{n}$, and the estimate for the population parameter (μ) from a large sample would be

$$\bar{x} - 1.96\frac{\sigma}{\sqrt{n}} < \mu < \bar{x} + 1.96\frac{\sigma}{\sqrt{n}}, \qquad \text{(B-28)}$$

and that from a small sample would be

$$\bar{x} - t_{.025}\frac{s}{\sqrt{n}} < \mu < \bar{x} + t_{.025}\frac{s}{\sqrt{n}}, \qquad \text{(B-29)}$$

where negative and positive $t_{.025}$ are the values of t to the right and left of which 2.5 percent of the area under the curve is found, and which vary depending upon the degrees of freedom, i.e., n - 1.

When s = sample proportion, x/n, then σ_s becomes $\sigma_{x/n} = \sqrt{pq/n}$, and the interval estimate of the population parameter (p) would be

$$\frac{x}{n} - 1.96\sqrt{pq/n} < p < \frac{x}{n} + 1.96\sqrt{pq/n}. \qquad \text{(B-30)}$$

When s = sample standard deviation, then σ_s becomes $\sigma/\sqrt{2n}$, and the interval estimate for the population parameter σ is

$$\frac{s}{1 + 1.96/\sqrt{2n}} < \sigma < \frac{s}{1 - 1.96/\sqrt{2n}} \qquad \text{(B-31)}$$

For the small sample, Chi-square is used, and the equation is constructed as

$$\sqrt{\frac{(n-1)s^2}{\chi^2_{.025}}} < \sigma < \sqrt{\frac{(n-1)s^2}{\chi^2_{.975}}} \qquad \text{(B-32)}$$

8. *Test of hypotheses*

The task involved in the test of hypotheses is that of determining whether a sample resulting in a given statistic (e.g., $\bar{x}$) could have been drawn from a population for which the corresponding parameter is specified. In other words, it involves the question of the test of significance, whether the difference between the observed statistic and what is expected (population parameter) can be attributed to chance or not. In the test of hypotheses, there is a possibility of facing two kinds of errors, namely the Type I error and the Type II error. The error of the first kind is committed by rejecting a hypothesis which should have been accepted, and the second kind is committed by accepting a hypothesis when it should have been rejected. For a fixed size of sample, a decrease in the probability of Type I error will increase that of Type II error. In many statistical applications only the first type of error is controlled. The following are general rules to be taken into consideration in the construction of the text.

(1) Formulate a hypothesis in such a way that the computation of a statistic is possible. The hypothesis is formulated in null form, designated by H_0.

(2) Formulate an alternative hypothesis in such a way that the rejection of H_0 is equivalent to the acceptance of the alternative hypothesis, designated as H_1.

(3) Specify the level of significance of errors. The symbol α is used for the Type I error, the conventional level for which is 0.05 or 0.01. The symbol β is used for the Type II error.

(4) Specify whether the alternative to the null hypothesis is to reject it or to reserve judgement. While rejection of the null hypothesis results in the conclusion that an alternative hypothesis is true, failure to reject it does not result in the positive conclusion that the null hypothesis is true.

There are two types of tests, the one-tailed and two-tailed tests. In the one-tailed test, the alternative hypothesis indicates the difference in only one direction. For instance, when $H_0: \mu_1 \leq \mu_2$, then $H_1: \mu_1 > \mu_2$. In the two-tailed test, the alternative hypothesis indicates the difference in both directions; thus, when $H_0: \mu = 50$, then $H_1: \mu \neq 50$.

The following are formula and tests of significance concerning mean and proportion based upon the random sample drawn from a normal population, in which z' and t' are the computed values from the formula and z and t are given values for specific α (e.g., when $\alpha = 0.05$, z in a one-tailed test is 1.64, either positive or negative, depending upon how H_0 is stated; z in a two-tailed test is both ± 1.96; t in a one-tailed test is $t_{.05}$ for the specified degrees of freedom, $n-1$; and t in a two-tailed test is both $\pm t_{.025}$ for the specified degrees of freedom).

(a) Test concerning proportions. One-tailed test: When $H_0: P_1 \leq P_2$, reject the null hypothesis if $z' > z$; accept the null hypothesis or reserve judgement if $z' \leq z$, where

$$z' = \frac{x - np}{\sqrt{npq}} \qquad \text{(B-33)}$$

Two-tailed test: The same formula is applied. Reject the null hypothesis if $z' < -z$ or $z' > z$; accept the null or reserve judgement if $-z \leq z' \leq z$.

(b) Test concerning difference between proportions. This is a two-tailed test. When $H_0 : P_1 = P_2$, reject the null if $z' < -z$ or $z' > z$; accept the null or reserve judgement if $-z \leq z' \leq z$, where

$$z' = \frac{\frac{x_1}{n_1} - \frac{x_2}{n_2}}{\sqrt{pq(\frac{1}{n_1} + \frac{1}{n_2})}} \qquad \text{(B-34)}$$

in which $\sqrt{\frac{p_1q_1}{n_1} + \frac{p_2q_2}{n_2}}$ = standard error of the difference between two proportions and $p = \frac{x_1}{n_1} + \frac{x_2}{n_2}$.

(c) Tests concerning means. One-tailed test for a large sample: When $H_0 : \mu_1 \leq u_2$, reject the null if $z' > z$; accept the null or reserve judgement if $z' \leq z$, where

$$z' = \frac{\bar{x} - \mu}{s/\sqrt{n}}. \qquad \text{(B-35)}$$

Two-tailed tests for a large sample: The same formula is employed; reject the null if $z' < -z$ or $z' > z$; accept the null or reserve judgement if $-z < z' < z$.

In both the one-tailed and two-tailed tests for the small sample: the formula with the t-distribution is used as below, and t' and t replace the z' and z, respectively.

$$t' = \frac{\bar{x} - \mu}{s}\sqrt{n} \qquad \text{(B-36)}$$

(d) Tests concerning difference between means. When $H_0 : \mu_1 = \mu_2$, the same statement concerning the two-tailed test of the mean is employed for the large sample where

$$z' = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \qquad \text{(B-37)}$$

in which $\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}$ = standard error of the difference between two means. For the small sample, and if $s_1 = s_2$, then

$$t' = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}(\frac{1}{n_1} + \frac{1}{n_2})}} \qquad \text{(B-38)}$$

in which $n_1 + n_2 - 2$ = degrees of freedom.

(e) Tests concerning differences among more than two means. The problem here is whether differences among more than two sample means can be attributable to chance variation, or, in other words, whether all populations from which different samples come could have identical means. For the test of significance, the F-distribution is used, upon the assumption that all samples concerned come from populations having a normal distribution with some standard deviation σ. The test eventually involves the comparison of F' derived from observations, with the theoretical F value at specified levels of significance, for two degrees of freedom. The following symbols, given only for completely random design, are employed for the F-distribution test:

- $\bar{X}$ is the over-all mean of all samples.
- $\bar{x}_j$ is the jth sample mean.
- k is the number of samples.
- n is the number of cases in a sample.
- F' is the value of F derived from the observed data.
- F is the theoretical value of the F-distribution obtained from the F-distribution table.

When the level of significance is assigned as $\alpha = .05$, it is written as $F_{.05}$, and for $\alpha = .01$, it is written $F_{.01}$. The variation of the value depends upon the degrees of freedom.

- df is the number of degrees of freedom for the numerator of F, k - 1.
- df' is the number of degrees of freedom for the denominator of F, k(n - 1).

A null hypothesis to be tested may be stated as $\mu_1 = \mu_2 = \mu_3 = \ldots = \mu_k$ against an alternative hypothesis that the μ's are not all the same, and the criterion below is applied.

Reject the null hypothesis if $F' > F$; accept the hypothesis or reserve judgement if $F' \leq F$, where the exact value of F is to be determined by the assigned level of significance and by degrees of freedom, and F' is to be calculated as

$$F' = \frac{kn(n-1) \cdot \sum_{j=1}^{k} (\bar{x}_j - \bar{x})^2}{(k-1) \cdot \sum_{i=1}^{n} \sum_{j=1}^{k} (x_{ij} - \bar{x}_j)^2} \qquad \text{(B-39)}$$

Up to this point, the relations between the standard deviation, σ, mean deviation, $\bar{d}$, and probable error of the mean, e (i.e., $e = \sigma/\sqrt{2n} = 0.6745\frac{\sigma}{n}$) can be summarized and simplified as

$$\begin{aligned} \sigma &= 1.25331\,\bar{d} = 1.48260\,e \\ \bar{d} &= 0.79778\,\sigma = 1.18295\,e \\ e &= 0.67449\,\sigma = 0.84535\,\bar{d} \end{aligned} \qquad \text{(B-40)}$$

Equation (B-40) can be further approximated as

$$\begin{aligned} \sigma &= 1.25\,\bar{d} = 1.5\,e \\ \bar{d} &= 0.8\,\sigma = 1.2\,e \\ e &= 2/3\,\sigma = 5/6\,\bar{d} \end{aligned} \qquad \text{(B-41)}$$

9. *Linear correlation and multiple correlation*

When two variables, X and Y, have a straight-line relationship, it can be expressed as

$$Y = aX + b, \tag{B-42}$$

where a and b are constants. The degree of the relationship of X and Y can be expressed by

$$r_{xy} = \frac{\Sigma[(X_i - \bar{X})(Y_i - \bar{Y})]}{\sqrt{\Sigma(X_i - \bar{X})^2 \, \Sigma(Y_i - \bar{Y})^2}}, \tag{B-43}$$

where r_{xy} (or simply r) is the coefficient of correlation, $\bar{X}$ and $\bar{Y}$ are the arithmetic means of the X_i and Y_i; and $(X_i - \bar{X})$ and $(Y_i - \bar{Y})$ are the departures from the means. Let $(X_i - \bar{X})$ be x and $(Y_i - \bar{Y})$ be y; then Equation (B-43) becomes

$$r = r_{xy} = \frac{\Sigma xy}{\sqrt{\Sigma x^2 \, \Sigma y^2}}. \tag{B-44}$$

The short-cut in computing the formula for Equation (B-44), though it looks bulky, is

$$r = \frac{n \cdot \Sigma X_i Y_i - (\Sigma X_i)(\Sigma Y_i)}{\sqrt{n \cdot \Sigma X_i^2 - (\Sigma X_i)^2 \, n \cdot \Sigma Y_i^2 - (\Sigma Y_i)^2}}. \tag{B-45}$$

Equation (B-45) is much simpler to compute than Equation (B-44) because we do not need to compute the departures of X and Y.

In order to determine the constants, a and b, we have

$$a = \frac{\Sigma Y_i - b(\Sigma X_i)}{n}, \tag{B-46}$$

where b can be obtained from the following expression:

$$b = \frac{n(\Sigma X_i Y_i) - (\Sigma X_i)(\Sigma Y_i)}{n(\Sigma X_i^2) - (\Sigma X_i)^2}.$$

By substituting a and b into Equation (B-42), it is possible to make a regression line to fit the linear relationships of the two variables X and Y in a chart.

The coefficient of correlation (r) obtained from Equation (B-43), (B-44), or (B-45) can be interpreted statistically as below:

If the two variables have a coefficient of correlation (r), then $(100 \cdot r^2)$ percent of the variation of the Y's is accounted for by the differences in X; that is, by the relationship with X. For example, when r = 0.80, then $100 \cdot r^2$ is 64 %; and when r = 0.40, then $100 \cdot r^2$ is 16 %. This means that a correlation of r = 0.80 is four times as "strong" as a correlation where r = 0.40. The probable error of the mean (e) in terms of the coefficient of correlation (r) is

$$e = \frac{1 - r^2}{\sqrt{2n}} \tag{B-47}$$

Further interpretation of r values depends upon the number of pairs of observations made for the computation. In other words, the larger the number of observations, the closer the approximation and the higher the significance. Thus, the significance level (P) has been designated to show the validity of the data. When P = .050, this designates that 95 percent of the time the correlation is significant, and when P = .010, this means that 99 percent of the time the correlation is significant.[1] In the interpretation of linear correlation, it is very important to know that the coefficient of correlation is not only the most widely used, but also the most widely abused of statistical formulas. It is often overlooked that r measures only the strength of linear relationships. When a case of nonlinearity arises, r does not adequately describe the condition. It is then misleading to use it.

When more than two variables exist, a linear equation similar to Equation (B-42) can be expressed as

$$Y = a + bX_1 + cX_2 + dX_3 \ldots \qquad \text{(B-48)}$$

where Y is the dependent variable, X_1, X_2, X_3 . . . are the independent variables, and a, b, c, d, . . . are constants. Equation (B-48) is the multiple linear regression equation. The partial correlation coefficient may be written

$$r_{12\cdot 3} = \frac{r_{12} - r_{13}r_{23}}{\sqrt{(1 - r_{13}^2)(1 - r_{23}^2)}} \qquad \text{(B-49)}$$

where $r_{12.3}$ designates the partial correlation between 1 and 2 when variate 3 has been eliminated, and r_{12}, r_{13}, and r_{23} indicate the correlations found directly between the members of each pair of variates. Equation (B-43), (B-44), or (B-45) can be used to find r_{12}, r_{13}, and r_{23}, and thus the partial correlation $r_{12\cdot 3}$ can be computed.

10. *Nonparametric approach*

So far our attention has been concentrated on the assumption that the population had some known form. For instance, we assume the existence of a normal distribution in which testing of hypotheses is based upon certain parameters, such as mean and variance. This type of classical statistics is known as parametric statistics. But not all forms of population are known or normally distributed, and therefore nonparametric statistics is needed. In nonparametric studies, one attempts to find test statistics which would compare distributions without specifying the form of the distributions. In short, this involves no assumptions whatever about the parameters of the population sampled. Recent advances in statistics have been in the direction of using more and more nonparametric approaches for large distributions. Thus nonparametric methods become an indispensable technique in modern statistics. One advantage of their use is that they are not only "quick and easy," or a "short-cut" in statistics, but nonparametric statistics are also easy to interpret and grasp. A small sample

[1]The value P can be obtained from statistical tables, e.g., R.A. Fisher & F. Yates, 1952, Statistical tables for biological, agricultural and medical research, 4th ed., London and Edinburgh, 126 pp.

of 10 to 15 cases or a sample with only qualitative values can be handled by nonparametric methods. In addition, they can be used to solve some problems which standard parametric methods fail to handle. However, in the case when the distribution is normal or the null hypothesis is false, the nonparametric method cannot extract as much information from the data as can the standard parametric method.

Nonparametric statistics involve rank correlation, the Chi-square test, the sign test, tests based on runs, nonparametric tolerance limits, test for randomness, Chebyshev's inequality, corner test for association, and many others. The rank correlation, Chi-square, and corner test for association are used as illustrations.

(a) Rank correlation. When n pairs of observations of two sets of data x_i and y_i, such as (x_1, y_1), (x_2, y_2), . . . (x_n, y_n) are arranged according to the order of the size of each individual set, the rank-correlation coefficient can be obtained. In each set, the largest value is assigned a rank of 1, the second largest a rank of 2, and so on. The difference in rank between a pair of data of the two sets is d_i. According to Spearman's rank coefficient, r_s, we have

$$r_s = 1 - 6 \sum_i d_i^2/n(n-1)(n+1) . \quad \text{(B-50)}$$

The criterion,

$$t = r_s\sqrt{(n-2)/(1-r_s^2)} ,$$

is distributed as the Student's t with (n - 2) degrees of freedom. For example, in Table B-2, columns (2) and (3) are the original sets of data x_i and y_i; columns (4) and (5) are the corresponding ranking of x_i and y_i; column (6) is the difference between columns (4) and (5), i.e., d_i; and column (7) is the square of d_i. In this example, the Spearman coefficient (r_s) is 0.50, i.e., $r_s = 1 - (\frac{6 \times 10}{5(5-1)(5+1)})$, where $\sum_i d_i^2 = 10$, and n = 5.

Table B-2. Illustration for the Computation of Spearman's Rank Coefficient

Contestant	x_i	y_i	Rank of x_i	Rank of y_i	Difference in Rank d_i	d_i^2
(1)	(2)	(3)	(4)	(5)	(6)	(7)
A	78	99	2	1	1	1
B	94	91	1	2	-1	1
C	23	24	4	4	0	0
D	35	19	3	5	-2	4
E	12	77	5	3	2	4

If the rank order of x_i, y_i is exactly the same, d_i^2 is zero; hence, $r_s = 1$. If the rank order of x_i is just the opposite for y_i, namely, the order of x_i is 1, 2, 3, 4, 5, and the order of y_i is 5, 4, 3, 2, 1, then $r_s = -1$. Thus the Spearman coefficient is similar to the coefficient of linear correlation in that r_s lies between -1 and 1. There is another rank correlation coefficient, known as Kendall's coefficient, which is used for the purpose of inference. Since sampling distribution for certain values of n is not known, the tests of significance upon Spearman's coefficient, r_s, would be possible by means of Kendall's coefficient of rank correlation, τ. Kendall's coefficient of concordance, W, deals with several variables simultaneously, and is of wider applicability. For details, the reader may refer to M. G. Kendall, 1948, Rank Correlation Methods, London, Griffin.

(b) Chi-square distribution. Chi-square is defined as the sum of the squares of n independent normally-distributed variables having zero mean and unit standard deviation. The use of the chi-square (χ^2) test involves no assumption about the distribution of the parent population from which the sample is drawn. Like the t-distribution, the χ^2 distribution depends on the number of degrees of freedom; as the number of degrees of freedom increases, the distribution approximates the normal curve.

It is used in problems where a set of theoretical frequencies is compared with observed frequencies, chiefly for the test of hypotheses of independence and the test of goodness of fit. The χ^2 test involves the selection of a significance level (α), the determination of a critical value of χ^2 at this chosen level of significance for a specific number of degrees of freedom, and the computation of the χ^2 value for observed frequencies, which is to be compared with the critical value.

The following symbols are employed in the discussion of the χ^2 test:

χ^2_o is the observed value of χ^2.

$\chi^2_{.05}$ is the value of χ^2 at $\alpha = .05$ for varying numbers of degrees of freedom. Analogous to $t_{.05}$, it is a value of χ^2 to the right of which 5 percent of the total area under the curve falls. The exact value is obtained from a prepared χ^2 table.

F_O is the observed frequency.

F_E is the expected frequency.

n is the number of cells or classes in which O and E are compared.

n_r is the total frequency of a row.

n_c is the total frequency of a column.

N is the total of all n_r and n_c, or the grand total of frequencies.

r is the number of rows.

c is the number of columns.

df is the number of degrees of freedom for the χ^2, derived from observation.

Some of the conditions for the use of the χ^2 test are:

(a) absolute rather than relative frequencies;

(b) independence and randomness of separate observations in a sample; for small expected frequencies, tests are applicable to individual cell entries as small as 5, but some writers suggest 10. For large expected frequencies, there is no such restriction.

(1) Test of independence. This is the test of significance of the differences among more than two proportions, where each trial permits more than two possible outcomes. The necessary information can be classified into a so-called "contingency table," which is a two-way classification table which specifies varying numbers of discrete categories in each of two dimensions. Here we have a contingency table of four cells into which the observed frequencies (underlined figures) are entered. The figures in parentheses are the corresponding expected frequencies.

Contingency Table

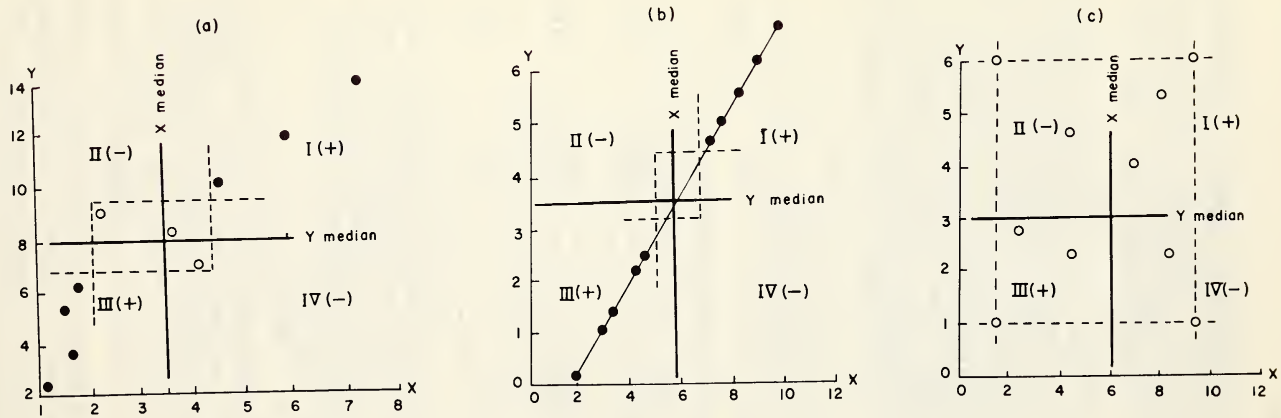
Row / Column	A_1	A_2	Total
B_1	$\underline{75}$ (94.3)	$\underline{120}$ (90.7)	195
B_2	$\underline{70}$ (50.7)	$\underline{35}$ (64.3)	105
Total	145	155	300

The question here is whether the observed differences among the proportions are indicative of a significant relationship between A and B, or whether the differences may be attributed to chance. The calculation of an expected frequency in each cell is obtained by

$$F_E = \frac{(n_r)(n_c)}{N} \qquad \text{(B-51)}$$

where n_r and n_c are the total frequencies of a specific row and column, respectively, to which a particular cell belongs. Substituting the figures in the above table into this equation, the expected frequency for the cell No. 1 (the cell in the first row, first column) will be $\frac{195 \times 145}{300} = 94.3$. Since the sum of the expected cell frequencies of any row or column must be equal to the sum of the observed frequencies of the corresponding row or column, the remaining expected cell frequencies can be obtained by subtracting them from n_r and n_c.

On the basis of both sets of frequencies, the observed value of χ^2 can now be computed as



(a)

Direction	Score
Up	3
Down	4
Right	3
Left	4
Quad Sum	14

(b)

Direction	Score
Up	5
Down	3
Right	5
Left	5
Quad Sum	20

(c)

Direction	Score
Up	0
Down	0
Right	0
Left	0
Quad Sum	0

Fig. B-2. The corner test of association.

$$\chi_o^2 = \Sigma \left(\frac{F_O - F_E}{F_E}\right)^2 \qquad \text{(B-52)}$$

The criterion for the test of significance is stated, for example, at $\alpha = .05$ as: Reject the hypothesis if $\chi_o^2 > \chi^2$; accept the hypothesis or reserve judgement if $\chi_o^2 \leq \chi^2$ where χ_o^2 is calculated with the above formula and the number of degrees of freedom (for χ^2) equals (r-1) (c-1). In our example, the value of χ_o^2 is 34.12, and the value of $\chi^2_{.05}$ for df = (2-1)(2-1) is 3.84 Since the observed value of χ^2 is larger than the expected value of χ^2, we can reject the hypothesis and state that there is a relationship existing between A and B.

(2) Test of goodness of fit. This test is used when an ideal curve is fitted to an observed distribution, or vice versa. The question here is whether the ideal curve provides a good approximation to the observed data. It involves a comparison of two sets of frequencies, observed and expected, arranged in a single column instead of a two-way table. The equation and criterion applied here for the rejection or acceptance of a hypothesis are the same as those for the hypothesis of independence, except that the degrees of freedom are determined by (n - k). The symbol k stands for the number of constants used to calculate the expected frequencies, which are determined from the observed data. For example, when the process of calculating the expected frequency distribution requires the mean, the standard deviation, and the total frequencies of the original data, the number of constants equals three.

(3) The corner test for association. The significance of the correlation of two continuous variables can be approximated by the corner test for association, also known as the "quadrant sum" test. This can be done by a simple scatter diagram as shown in Fig. B-2. After the paired observations have been plotted, the x-median and the y-median are drawn so as to divide the scatter diagram into four quadrants which are labeled I, II, III, and IV. Obviously, the total number of observations on each side of the median should be the same.[2] Then enter the dash lines for the purpose of eliminating those observations (shown as blank circles) which encounter each other with respect to the median. The quadrant sum can be obtained by counting the number of observations outside the block (which is constructed by the dash lines) in four directions. In Figure B-2a, 3 observations above the upper dash line, 4 observations below the lower dash line, 3 observations to the right of the vertical dash line, and 4 observations to the left are indicated. A total of 14 quadrant sums resulted; sign expressions can be ignored. Two extreme cases are shown in Figs. B-2b and B-2c.

[2]For an odd number of pairs, we can either draw both the medians x and y through one point, if possible, or we can draw these two medians through two different points with coordinates of $(x_i y_j)$ and $(x_m y_n)$, and then replace the two points by a single point with a coordinate of $(x_i y_n)$.

Table B-3. Significance Levels for Magnitude of Quadrant Sums*

Magnitudes of Quadrant Sums**	Significance Level (%)
9	10
11	5
13	2
14-15	1
15-17	0.5
17-19	0.2
18-21	0.1

*This table was prepared by Olmstead and Tukey in the Bell Telephone Laboratories and Princeton University, and published in the Ann. Math. Statistics 18: 498.

**A magnitude which is equal to or greater than twice the sample size less 6 should not be used.

The former has the highest correlation with a quadrant sum of 20, while the latter has no correlation at all and the quadrant sum is zero. It is now seen that the larger the quadrant sum, the higher the correlation tends to be. The significance level can be obtained from Table B-3.

APPENDIX C

Some Fundamental Mathematics

Subjects which include arithmetic, algebra, geometry, and analytic geometry are customarily recognized as the fundamentals of mathematics. More advanced treatments of mathematics are calculus, differential equations, and vector analysis. All of these subject areas overlap each other. The stress on definition and the order and emphasis accorded the areas are based largely on mathematical applications in agrometeorology. Inevitably, some terms related to physics and biology are introduced from time to time.

1. *Number, notation, and dimensions*

A biological or physical quantity or system is measured and expressed in terms of numbers, notations, and finally in equations.

Two types of numbers are used: the real and the imaginary numbers. The real numbers consist of the positive and negative integers and the rational and irrational numbers. The numbers . . . −4, −3, −2, −1, 0, 1, 2, 3, 4, . . . are a complete set of positive and negative integers. Any number that can be written as the quotient of two integers is called a rational number, for example, 1/2 or 0.5. Any number that is not rational is an irrational number, for example, $\sqrt{2}$ and $\sqrt{3}$. The ratio of the circumference and radius of a circle is also irrational. The number $\sqrt{-1}$ is not a real number and has been designated "i" by mathematicians, an imaginary number. Thus, $i^2 = -1$. When a number system involves both real and imaginary numbers or imaginary numbers alone, it becomes a complex number system. The elementary arithmetic operations of all numbers, such as addition, subtraction, multiplication, and division, as well as the associative, commutative, and distributive laws, are assumed to be familiar to the reader. These laws remain valid for the system of complex numbers. This means that the arithmetic of complex numbers is similar to the arithmetic for real numbers. Thus, the rules of arithmetic for the complex numbers follow:

If $u = a + bi$ and $v = c + di$ are two complex numbers that are expressed in terms of the real numbers a, b, c, and d, then according to

(a) the definition of equality, we have $u = v$, which means $a = c$ and $b = d$;

(b) the definition of addition, we have $u + v = (a + c) + (b + d)i$; and

(c) the definition of multiplication, we have $u \times v = (ac + bd) + (bc + ad)i$.

The order relations of real numbers a, b, and c (which can be positive, negative, or zero) have the following fundamental properties:

(a) If any two real numbers a and b exist, one and only one of the following three relations is true: $a < b$; or $a = b$; or $a > b$. (This is read, "a is less than b; or a is equal to b; or a is greater than b," and is known as a "trichotomy.")

(b) If $a < b$ and $b < c$, then $a < c$. This is known as "transitivity."

(c) If $a < b$, then $a + c < b + c$.

(d) If $c > 0$ (c being positive) and $a < b$, then $ac < bc$.

(e) If $c < 0$ (c being negative) and $a < b$, then $ac > bc$.

Ordinarily, the symbol "<" is not used with complex numbers; symbols such as $1 < i$ are not defined. The notation $a \leq b$ means that a is either less than b or equal to b.

The "significant figures" or "significant digits" represent the accuracy to which the data can be measured or observed. For example, the temperature (T) on a thermometer can be read to the degree and can be estimated to the tenth of a degree thus, when an observation of T = 85.0°F is recorded, there are three significant digits. The absolute error is less than 0.1°F, and the relative error is less than one part in 850. The true value of T lies between 84.95 and 85.05. In an arithmetic operation, it is necessary to apply the "rule for rounding-off" according to the accuracy of the data desired. For example, the ratio of the circumference to the diameter of a circle is 3.1415927, and the decimals can be carried as far as desired. When the rule for rounding-off is applied, this ratio becomes 3.1416 if 5 significant figures are desired, and 3.142 if 4 significant figures are needed. The repetition of rounding-off is not allowed; thus, the cube root of π (1.46459) is expressed as 1.464 instead of 1.465, if 4 significant figures are needed. In case a number lies exactly half-way between the units, we round-off the last remaining digit on the right to an even number, namely 0, 2, 4, 6, or 8. Thus a temperature of exactly 84.5° and another temperature of exactly 83.5° would be expressed in the same way, i.e., 84°, if accuracy to the whole degree is required.

The benefits of using significant figures in arithmetic operations or simple calculations with rounded numbers are (1) in avoiding the erroneous impression of the accuracy of results and (2) in saving labor from superfluous computation. However, a figure should not be rounded too much if it is subsequently to be multiplied by a large number. For example, in an over-all estimate of the irrigation cost in a certain area, we may arrive at a figure of 76.29 cents per ton of water; if we round this off as 76 cents, or .76 dollars, the difference in cost for 100,000 tons of water would be 76290 - 76000 = $290.

The scientific notation by powers of 10 simplifies the expression and manipulation of figures. Thus 230,000 + 50,000 can be written as $(23 \times 10^4) + (5 \times 10^4)$, and 0.00023 - 0.00005 can be written as $(23 \times 10^{-5}) - (5 \times 10^{-5})$. Any number to the zero power is 1, e.g., $10^0 = 1$.

When a number is designated as an "absolute value," it is said that the number is neither positive nor negative. In other words, neither the positive nor the negative sign is needed for the absolute value. The symbol used for the absolute value of a number 2 is $|2|$.

So far we have discussed the pure numbers. In physics, the mechanical qualities — namely mass, length, and time — are the three fundamental units.[1] Other units can be derived from these. The algebraic expression of a unit is the dimension of that quantity (see column 2, Table C-1). A dimensional letter in brackets can be assigned to each of the three fundamental quantities as below:

[mass] = [M]
[length] = [L]
[time] = [T]

Thus, a pure number can be assigned as [1], the dimension unity, for example,

$$[\text{pure number}] = [L^0\ M^0\ T^0] = [1].$$

Some commonly derived units in meteorology are listed in Table C-1.

A dimensional check is necessary for all equations. For example, the relation between force and the rate of change of momentum with time can be expressed dimensionally by

$$[M\ L\ T^{-2}] = [M\ L\ T^{-1}] \div [T].$$

Sometimes the coefficients of an equation can be assigned any dimension which results in dimensional consistency for that equation.

2. *Basic mathematical operation*

The language of algebra uses symbols rather than the usual numerals to stand for numbers. Since positive and negative signs of the symbols are introduced in algebra for the separation of algebraic terms, the words "algebraic sum" refer to both addition and subtraction in the arithmetical sense. A one-term expression, such as ab, is a monomial; two-term expressions, such as (ab + ac), are called binomials.

[1]A fourth fundamental unit, namely temperature, is used for the study of thermodynamics. Thus, the dimension of temperature can be expressed as $[\theta]$. In engineering, "force," instead of "mass," is used for one of the three fundamental quantities; it can be expressed as [F].

Table C-1. Units and Dimensions of Some Physical Quantities

Quantity	Dimension	C.G.S. System[2]	F.P.S. System[3]
Length	L	1 cm	1 ft
Mass	M	1 gm	1 lb
Time	T	1 sec	1 sec
Area	L^2	1 cm^2	1 sq ft
Volume	L^3	1 cm^3	1 cu ft
Density	$M L^{-3}$	1 gm cm^{-3}	1 lb ft^{-3}
Specific volume[4]	$L^3 M^{-1}$	1 cm^3 gm^{-1}	1 ft^3 lb^{-1}
Velocity	$L T^{-1}$	1 cm sec^{-1}	1 ft sec^{-1}
Acceleration	$L T^{-2}$	1 cm sec^{-2}	1 ft sec^{-2}
Force	$M L T^{-2}$	1 gm cm sec^{-2} (1 dyne)	1 ft lb sec^{-2} (1 poundal)
Pressure	$M L^{-1} T^{-2}$	1 dyne cm^{-2} (10^{-3} mb)	1 ft^{-1} lb sec^{-2}
Work or Energy	$M L^2 T^{-2}$	1 dyne cm (1 erg)	1 foot-poundal
Angular velocity	T^{-1}	1 rad sec^{-1}	1 rad sec^{-1}
Momentum	$M L T^{-1}$	1 dyne sec	1 lb sec
Power	$M L^2 T^{-3}$	1 dyne cm sec^{-1}	1 ft lb sec^{-1}

Three-term expressions are trinomials, and expressions of two or more terms are polynomials.

Exponents provide a foundation for the theory of logarithms. The laws of operations with logarithms, given below in Equations (C-2), (C-4), and (C-6), are translations from the language of exponents to the language of logarithms. Any positive number b can be used as a base for logarithms; thus, if $M = b^x$ and $N = b^y$, then

$$M N = b^x b^y = b^{x+y} . \qquad \text{(C-1)}$$

From the definition of logarithm,[5] we have

$$\log_b (MN) = \log_b M + \log_b N = x + y . \qquad \text{(C-2)}$$

When two real numbers are divided,

$$\frac{M}{N} = \frac{b^x}{b^y} = b^{x-y} . \qquad \text{(C-3)}$$

[2]The C. G. S. system denotes the centimeter-gram-second system.

[3]The F. P. S. system denotes the foot-pound-second system.

[4]The word "specific" always stands for "per unit mass," such as specific energy, specific heat, etc.

[5]The logarithm of a number (N) to the base (b) is the exponent (y) which must be applied to (b) to give (N), i.e., $\log_b N = y$.

Logarithmically, this law is expressed as

$$\log_b\left(\frac{M}{N}\right) = \log_b M - \log_b N = x - y. \qquad \text{(C-4)}$$

It follows that when $x = y$, Equation (C-3) becomes

$$\frac{M}{N} = \frac{b^x}{b^y} = 1 = b^0.$$

This shows that $\log_b 1 = 0$.
When $M = b^{x/y}$, M can be expressed exponentially by one of the following:

$$(b^{1/y})^x \text{ or } (b^x)^{1/y} \text{ or } (\sqrt[y]{b})^x \text{ or } \sqrt[y]{b^x},$$

for they are identical. Logarithmically,

$$\log_b M = \frac{x}{y}. \qquad \text{(C-5)}$$

When $M^p = b^{xp}$, then

$$\log_b M^p = p \log_b M = xp. \qquad \text{(C-6)}$$

In a case where $p = \frac{1}{n}$, $M^{1/n} = \sqrt[n]{M} = b^{x/n}$, thus

$$\log_b M^{1/n} = \log_b \sqrt[n]{M} = \frac{1}{n}\log_b M = \frac{x}{n}. \qquad \text{(C-7)}$$

In the case where $M = b$, then $b^p = b^{xp}$, or $x = 1$, thus,

$$\log_b b^p = p \log_b b = xp = p. \qquad \text{(C-8)}$$

The above equations, (C-2), (C-4), (C-6), (C-7), and (C-8), are the five fundamental properties of logarithms. When the base (b) for all these five fundamentals is substituted by 10, then we have the common system of logarithms, or simply "common logarithms." Symbolically, $\log_{10} = \log$. Since $10 = 10^1$, from Equation (C-8) we have

$$\log 10 = 1.$$

Similarly,

$\log 0.01 = -2$, since $10^{-2} = 1/10^2 = 0.01$;
$\log 0.10 = -1$, since $10^{-1} = 1/10 = 0.10$;
$\log 1 = 0$, since $10^0 = 10/10 = 1$;
$\log 10 = 1$, since $10^1 = 10$;
$\log 100 = 2$, since $10^2 = 100$;
$\log 200 = 2.30103$, since $10^{2.30103} = 200$ (approximately),[6] and so on.

By use of common logarithms and their properties, we can do multiplication, division, and exponential operations easily. For example, in Equation (C-2), if we insert $M = 100$ and $N = 1000$, then $\log(100 \times 1000) = \log 100 + \log 1000 = 2 + 3 = 5$. The result 5 is a logarithmic value and should be referred back to the original number, i.e., 100,000 or 10^5. Stated another way, the number that corresponds to a given

[6] The logarithmic value for any number can be obtained from the "Common Logarithms Table," which usually carries 4 or 5 place decimals. Common logarithms are also known as the decimal denary, or Briggsian logarithms. The reader should be familiar with their use.

logarithm is often referred to as the "antilogarithm" or simply "antilog." Thus if $\log 10^5 = 5$, then antilog $5 = 10^5$.

Computations involving division can be simplified by acknowledging the fact that division by a number is equivalent to multiplication by its reciprocal. Thus, Equation (C-4) can be rewritten as

$$\log_b (M)(\frac{1}{N}) = \log_b M + \log_b (\frac{1}{N}) = x - y,$$

where the logarithm of the reciprocal of a number N, namely $\log_b(\frac{1}{N})$, is called the "cologarithm," or simply "colog," of the number, that is $\log_b (\frac{1}{N}) = \text{colog}_b N = \log_b 1 - \log_b N = 0 - \log_b N = -\log_b N$. Thus Equation (C-4) can also be written as

$$\log_b (M)(\frac{1}{N}) = \log_b M + \text{colog}_b N = x - y.$$

Aside from common logarithms with the base 10, the natural logarithm with a base of e is used in mathematical operations. The value $e = 1 + 1 + \frac{1}{2!} + \frac{1}{3!} + \frac{1}{4!} + \ldots = 2.71828$. If we know the logarithm of a number to the base 10, and wish to find its logarithm referred to the base e, we simply multiply the known logarithm by the $\log_e 10$. Thus, if we know $\log_{10} M$ and wish to find $\log_e M$, the conversion formula is

$$\log_e M = (\log_e 10)(\log_{10} M) = 2.3026 \log_{10} M. \qquad \text{(C-9)}$$

In mathematical operations the concept of the function is extremely important. We may borrow the famous theorem of Pythagoras (545 B. C.) for illustration. Consider a right angle as shown in Fig. C-1, where the hypotenuse r (constant) and the two adjacent sides x and y (variables) have an algebraic functional relationship. Thus,

$$x^2 + y^2 = r^2. \qquad \text{(C-10)}$$

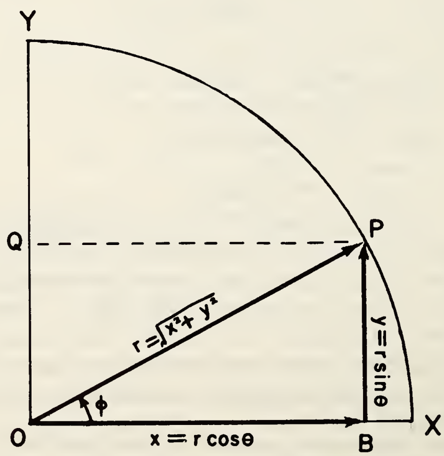


Fig. C-1. Pythagorean theorem.

This may be considered as the algebraic equation of a circle with a fixed radius (r). When Equation (C-10) is solved for x,

$$x = \pm(r^2 - y^2)^{\frac{1}{2}}.$$

When y is given, x is determined; thus, x is a function of y. In this case, x is given explicitly as a function of y and is said to be an explicit function of y. The latter is the independent variable, while the former is the dependent variable. Then y is an implicit function of x. When interest lies in the trigonometric function, we may rewrite Equation (C-10) as $\frac{x^2}{r^2} + \frac{y^2}{r^2} = 1$, and substitute this with $\text{Sin}\,\phi = \frac{y}{r}$ and $\text{Cos}\,\phi = \frac{x}{r}$, then we have

$$\text{Sin}^2\,\phi + \text{Cos}^2\,\phi = 1. \qquad \text{(C-11)}$$

The sine, cosine, tangent, cotangent, secant, and cosecant of an angle are known as the trigonometric functions of that angle. This includes $\text{Sin}^{-1}\phi$, $\text{Cos}^{-1}\phi$, and so forth.[7] When a logarithmic function of $y = \log_e x$ has been expressed as $x = e^y$, where y is a variable and e a constant, e^y would be the exponential function. The trigonometric, logarithmic, and exponential functions and their combinations are called transcendental functions. The transcendental functions are useful in both applied and pure mathematics. In basic mathematical operations, students should become acquainted with the functional relationships of algebra, trigonometry, geometry, and analytical geometry.

3. *Advanced mathematical operation*

In advanced mathematics, we are interested only in applied mathematics, such as calculus (both differential and integral), differential equations, vector analysis, and Fourier series.

(a) Calculus. The linear or constant rate of growth of a plant (G) may be expressed in terms of the stem elongation by measuring the height from time to time. At time t_1, the height of the plant is h_1 above the ground, and at time t_2, it is h_2. Then the average rate of growth for the interval from $t = t_1$ and $h = h_1$ to $t = t_2$ and $h = h_2$ is defined as

$$G = \frac{h_2 - h_1}{t_2 - t_1} = \frac{\Delta h}{\Delta t}, \qquad \text{(C-12)}$$

where $\Delta h = h_2 - h_1$ is the change in height (h) in the time interval $\Delta t = t_2 - t_1$. Δh is read "delta h," and is the average rate of growth in the interval from t_1 to $(t_1 + \Delta t)$. In Fig. C-2, h is plotted against t. The average rate of growth for the time interval $t_2 - t_1$ is $\frac{\Delta h}{\Delta t}$ and this is represented by $\frac{MP_2}{P_1M} = \tan\theta$, the slope of the chord joining the

[7] $\text{Sin}^{-1}\phi$ is read as arc sine ϕ, and is defined as "the angle whose sine is ϕ."

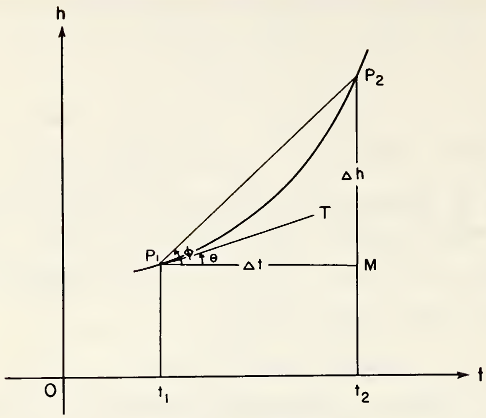


Fig. C-2. The concept of differentiation.

point $P_1(t_1h_1)$ to $P_2(t_2h_2)$. What may be called the instantaneous rate of growth at $t = t_1$ is clearly the limit of the ratio $\frac{\Delta h}{\Delta t}$ as Δt approaches zero. This is denoted by the symbol $\frac{dh}{dt}$. That is, $\lim_{t \to 0} \frac{\Delta h}{\Delta t}$. Here $\frac{dh}{dt}$ is called the derivative of h with respect to t. Clearly the derivative $\frac{dh}{dt}$ represents the slope tan θ of the tangent P_1T in Fig. C-2. The derivative of h with respect to t is also denoted by the symbol f(t) where h is a function of t. We recognize that

$$G = \frac{dh}{dt} = f'(t)$$

is a definition of the derivative of the function h = f(t). With the aid of the symbol f'(t), we are able to define a new quantity dh by the equation

$$dh = f'(t)\,dt. \qquad \text{(C-13)}$$

dh is called the differential of h, and for convenience, the increment Δt of the independent variable t is called the differential of t. dh is an approximation of h resulting from the increment Δt.

The application of differentiation in practical problems is imperative Problems in maxima and minima are used as illustrations:

(1) How would you cut a 1-foot-square galvanized metal sheet in order to make an open-top square box that holds the maximum amount of soil for experimental purposes?

Solution. Let the depth of the box be h inches; then the bottom of the box is $(12 - 2h)^2$ square inches, and the volume (V) of the box is $(12 - 2h)^2h$, as shown in Fig. C-3. Hence

$$V = 4h(6 - h)^2 \qquad \text{(C-14)}$$

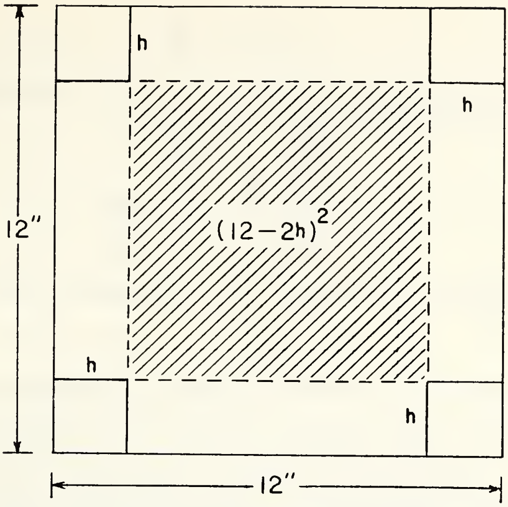


Fig. C-3. An illustration of a problem in maxima and minima.

Differentiating Equation (C-14) with respect to h, we have

$$\frac{dV}{dh} = 4[(6 - h)^2 - 2h(6 - h)]$$

or

$$\frac{dV}{dh} = 12(6 - h)(2 - h)$$

For V to be a maximum, $\frac{dV}{dh}$ must be zero; then

$$12(6 - h)(2 - h) = 0 \qquad \text{(C-15)}$$

From Equation (C-15) we know that h = 6 or h = 2 are the two possible values of h (or depth of the box) that make V (volume of the box) a maximum. It is obvious that h = 6 is impossible: therefore h = 2 is the only answer. Substituting this value into Equation (C-15) we have V = 128. Thus, this box has a capacity of $2 \times 8 \times 8 = 128$ cubic inches for the soil.

Example 2. What is the most economical way to use galvanized iron sheets to build a cylindrical can that holds a known capacity of water?

Solution. Let the volume be V, the height H, the diameter D, and the total surface S; then

$$V = \frac{1}{4}\pi D^2 H \qquad \text{(C-16)}$$

and

$$S = \pi(\frac{1}{2}D^2 + DH). \qquad \text{(C-17)}$$

Solve Equation (C-16) for H (i.e., $H = \frac{4V}{\pi}\frac{1}{D^2}$) and substitute in Equation (C-17); when simplified, we have

$$S = \frac{1}{2}\pi D^2 + \frac{4V}{D} \qquad \text{(C-18)}$$

Thus, S is a function of D and V, and π is a constant. Differentiating Equation (C-18), we get

$$\frac{dS}{dD} = \pi D - \frac{4V}{D^2} \qquad \text{(C-19)}$$

For S to be a minimum, $\frac{dS}{dD} = 0$; hence

$$\pi D - \frac{4V}{D^2} = 0, \text{ or } D^3 = \frac{4V}{\pi}. \qquad \text{(C-20)}$$

Substituting Equation (C-16) in Equation (C-20) to eliminate V, then

$$D^3 = D^2H \text{ or } D = H.$$

The result means that the most economical way of making a cylindrical can is to have the height and the diameter the same.

Some common rules for differentiation are chosen for the convenience of the reader. Let a and b be the constants, and y and z the variables which are a function of x. The derivative, $\frac{dy}{dx}$ or $\frac{dz}{dx}$, can be obtained by dividing through the following equations:

$d(a) = 0$

$d(a + y) = dy$

$d(ay) = ady$

$d(y + z) = dy + dz$

$d(y^n) = ny^{n-1}\,dy$

$d(a^y) = a^y \ln a dy$

$d(e^y) = e^y\,dy$

$d(\ln y) = \frac{1}{y}dy$

$d(\frac{1}{y}) = -\frac{dy}{y^2}$

$d(\log_{10} y) = \log_{10} e \frac{dy}{y} = 0.4343 \frac{dy}{y}$

$d(\sin y) = \cos y\,dy$

$d(\cos y) = -\sin y\,dy$

$d(\tan y) = \sec^2 y\,dy$

$d(\cot y) = -\csc^2 y\,dy$

$d(\sec y) = \tan y \sec y\,dy$

$d(\csc y) = -\cot y\ \text{scs}\ y\,dy$

Integration is the reverse process of differentiation. When a differential is f(x)dx, its integral is the summation of f(x)dx, and is denoted by

$$\int_a^b f(x)dx + C,$$

where a is the lower limit of the integration, b is the upper limit, and C is an arbitrary constant. Some common rules for integration are set forth below:

$\int ady = ay + C$

$\int (dy + \ldots dz) = y + \ldots z + C$

$\int y^n\,dy = \frac{y^{n+1}}{n+1} + C, \; n \neq -1$

$$\int \frac{dy}{y} = \ln y + \ln C$$
$$\int a^y\,dy = \frac{a^y}{\ln a} + C$$
$$\int e^y\,dy = e^y + C$$
$$\int \ln y\,dy = y \ln y - y + C$$
$$\int \sin y\,dy = -\cos y + C$$
$$\int \cos y\,dy = \sin y + C$$
$$\int \tan y\,dy = \ln \sec y + C$$
$$\int \cot y\,dy = \ln \sin y + C$$
$$\int \sec y\,dy = \ln(\sec y + \tan y) + C = \ln \tan\left(\frac{\pi}{4} + \frac{y}{2}\right) + C$$
$$\int \csc y\,dy = \ln(\mathrm{scs}\, y - \cot y) + C = \ln \tan \frac{y}{2} + C$$

(b) Differential equations. A differential equation is an equation containing differentials or derivatives. When there is only one independent variable, it is an ordinary differential equation, and when there is more than one independent variable, it is a partial differential equation. The order is the order of the derivative of the highest order, and the degree is the power to which that derivative is raised. Thus,

$$\frac{d^2y}{dx^2} + a^2y = 0 \tag{C-21}$$

is a second-order, first-degree ordinary differential equation;

$$x\frac{\partial z}{\partial x} + y\frac{\partial z}{\partial y} - z = 0 \tag{C-22}$$

is a first-order, first-degree partial differential equation; and

$$\left(x\frac{dy}{dx} - y\right)^2 = x^2 + y^2 \tag{C-23}$$

is a first-order, second-degree ordinary differential equation. A ***solution*** is a function that satisfies the equation. Thus a solution of Equation (C-21) is $y = \sin ax$. An ordinary differential equation of order n will usually have a solution containing n arbitrary or disposable constants. The constants may often be chosen to make the particular solution so obtained satisfy desirable initial or boundary conditions. Not all differential equations have solutions. Further applications of partial differential equations in agrometeorology are illustrated in Section 7.5.2.

(c) Vector analysis. Some quantities, such as mass, length, and speed are characterized by ***magnitude*** only, and are known as scalar quantities. Vector analysis is the mathematical treatment of quantities such as velocity, acceleration, and force, which have both ***magnitude*** and ***direction***. These directed quantities are known as ***vectors***. This discussion is concerned with both 2- and 3-dimensional vectors.

Two-dimensional vectors can be interpreted as points in a plane, while three-dimensional vectors take us into space. Vectors have two operations, ***vector addition*** sometimes called parallelogram addition, and ***scalar multiplication.*** To add vectors A and B, we must choose an origin O and a coordinate scale. Then draw an arrow from O to A, and one from O to B. The addition can now be done by completing the parallelogram. Draw a line (that is, the length of OB) from the tip of OA running parallel to OB. Now draw another line (that is, the length of OA) from the tip of OB running parallel to OA. These two lines intersect at a point C, and thus OC, or the diagonal of the parallelogram, is the vector sum of OA and OB. Thus we have

$$A + B = C, \tag{C-24}$$

where the first coordinate of C is the sum of the first coordinate of A and the first coordinate of B, and the second coordinate of C is the sum of the second coordinate of A and the second coordinate of B. For example, let $A = (x_1, x_2)$ and $B = (y_1, y_2)$; then $A + B = (x_1 + y_1, x_2 + y_2)$. Similarly, for Equation (C-24) we have

$$A + B + C = D,$$

and if we let $A = (x_1, x_2, x_3)$, $B = (y_1, y_2, y_3)$, and $C = (z_1, z_2, z_3)$, then $A + B + C = (x_1 + y_1 + z_1, x_2 + y_2 + z_2, x_3 + y_3 + z_3)$. For vector difference, we have

$$A - B = C. \tag{C-25}$$

In a rectangular system of coordinates, the three ***unit vectors*** along the positive axis of x, y, z will be denoted by $\bar{i}$, $\bar{j}$, $\bar{k}$, as shown in Fig. C-4. Thus, the three dimensional components of A are $A_X \bar{i}$, $A_Y \bar{j}$, and $A_Z \bar{k}$; hence

$$A = A_X \bar{i} + A_Y \bar{j} + A_Z \bar{k}.$$

Similarly, for Equation (C-24) we have

$$C = A + B = (A_X + B_X)\bar{i} + (A_Y + B_Y)\bar{j} + (A_Z + B_Z)k.$$

The multiplication of vectors can be expressed by the scalar product. The scalar product, known also as the dot product, of two vectors A and B, is defined as the scalar quantity $AB \cos \phi$, where ϕ is the angle between vectors A and B. Hence, according to definition, we have

$$A \cdot B = AB \cos \phi. \tag{C-26}$$

When ϕ is 90°, then $AB = 0$ or A is perpendicular to B; when ϕ is 0°, then $A \cdot B = AB$. Thus the scalar product of two vectors is a scalar. The vector product, known as the cross-product of two vectors A and B, is defined as the vector whose length is $AB \sin \phi$ (where ϕ is the angle between vectors A and B), and whose direction is perpendicular

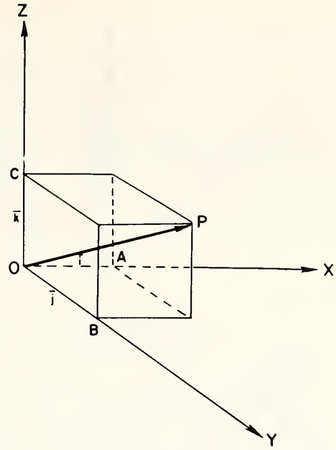


Fig. C-4. The concept of unit vector in three dimensions.

to the plane of A and B. The perpendicular line is on a direction that a right-handed screw advancing along AXB would turn A toward B. Hence

$$A X B = - B X A.$$

One of the important expressions of vector differentiation of a vector quantity, Q, is the gradient of Q denoted by the notation ∇Q (read "del Q"), which is defined as

$$\nabla Q = i\frac{\partial Q}{\partial x} + j\frac{\partial Q}{\partial y} + k\frac{\partial Q}{\partial z}. \qquad \text{(C-27)}$$

This notation gives the three-dimensional treatments of the quantity Q and simplifies the vector operation a great deal.

(d) Fourier series. The Fourier series for $y = f(x)$ where $-k \leq x \leq k$ is

$f(x) =$

$$\frac{1}{2}a_0 + a_1\cos\frac{\pi x}{k} + a_2\cos\frac{2\pi x}{k} + a_3\cos\frac{3\pi x}{k} + \ldots + b_1\sin\frac{\pi x}{k} + b_2\frac{2\pi x}{k} + b_3\sin\frac{3\pi x}{k} + \ldots, \qquad \text{(C-28)}$$

where the constant coefficients are determined by

$$a_n = \frac{1}{k}\int_{-k}^{k} f(t)\cos\frac{n\pi t}{b}dt; \quad b_n = \frac{1}{k}\int_{-k}^{k} f(t)\sin\frac{n\pi t}{k}dt.$$

For the special Fourier series for $-\pi < x < \pi$, we have

$$x = 2(\sin x - \frac{\sin 2x}{2} + \frac{\sin 3x}{3} - \frac{\sin 4x}{4} + \ldots);$$

$$x^2 = \frac{\pi^2}{3} - 4(\cos x - \frac{\cos 2x}{2^2} + \frac{\cos 3x}{3^2} - \ldots).$$

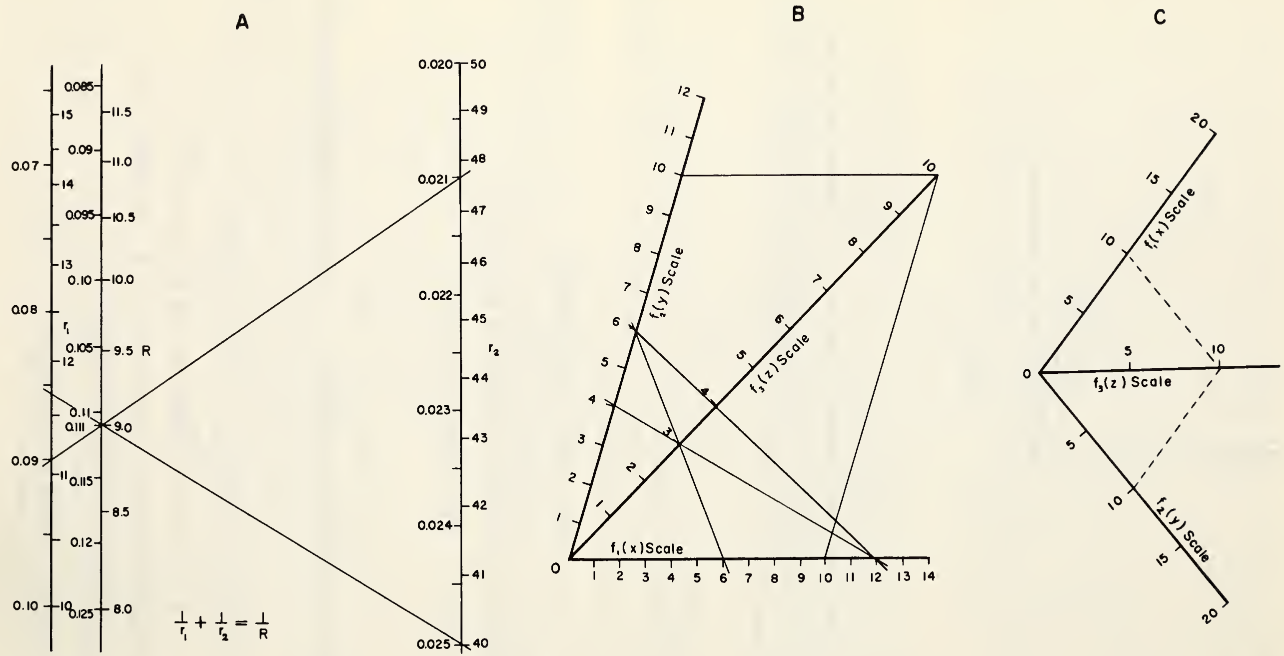


Fig. C-5. Nomogram for $\frac{1}{f_1(x)} + \frac{1}{f_2(y)} = \frac{1}{f_3(z)}$.*

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For $0 < x < \pi$, we have

$$1 = \frac{4}{\pi}(\sin x + \frac{\sin 3x}{3} + \frac{\sin 5x}{5} + \ldots);$$

$$x = \frac{\pi}{2} - \frac{4}{\pi}(\cos x + \frac{\cos 3x}{3^2} + \frac{\cos 5x}{5^2} + \ldots)$$

$$x^2 = \frac{2}{\pi}[(\pi^2 - 4)\sin x - \pi^2 \frac{\sin 2x}{2} + (\pi^2 - \frac{4}{3^2})\frac{\sin 3x}{3} - \pi^2 \frac{\sin 4x}{4} + (\pi^2 - \frac{4}{5^2})\frac{\sin 5x}{5} - \ldots]$$

4. *Graphical representation*

In agrometeorology, graphical expression is superior to mathematical formulation because it is easier to manipulate, interpret, and check for error. Some simple graphical manipulations are summarized.

(a) Coordinate system. The customary coordinate system used is the Cartesian system, known as the rectangular system. In this system, the coordinates are the X and Y axes, which are perpendicular to each other. The X-axis is called the abscissa, and the Y-axis, the ordinate. Both are linear scales. Any point (P) in the rectangular coordinate system can be located by P(x, y). A coordinate system expressed by a movable radius vector, r, and the angle, ϕ, which is subtended between the movable radius vector r and the X-axis, as shown in Fig. C-1, is a polar coordinate system. Any point in a polar coordinate system is thus expressed by (r, ϕ). Let (x, y) be the rectangular and (r, ϕ) the polar coordinates of a given point P. Then $x = r \cos \phi$; $y = r \sin \phi$; and $r^2 = x^2 + y^2$. Point P can be expressed as P(x, y) for the rectangular coordinate, and by $P(r, \phi)$ for the polar coordinate. When the ordinate is replaced by a pressure unit such as the millibar (mb), the the abscissa remains in a linear scale, it is a pressure coordinate system. The pressure coordinate is useful in meteorology. The ecological coordinate system has both axes indicated by the unit of the crop-environment relationship. This system is explained in Section 7.4.3 (Figs. 7-2 and 7-3), and is useful in agrometeorological studies. If the axes of a rectangular coordinate are expressed by the logarithmic scale, it is a logarithmic coordinate. If only the ordinate is replaced by the logarithmic scale, it is the semi-logarithmic coordinate. The graph for the former is known as log-log paper, while that for the latter is semi-log. There is still another kind of graph paper, known as the percentage probability scale, where the ordinate is a cumulative percentage scale and the abscissa remains linear. Various coordinate systems serve different purposes of their own.

(b) Graphical solution of relations among three variables. The graphical presentation of three variables, linear or non-linear, is given by Equations (C-29) to (C-31), and Figs. C-5 to C-9. These figures are by no means representative of the present subject, because

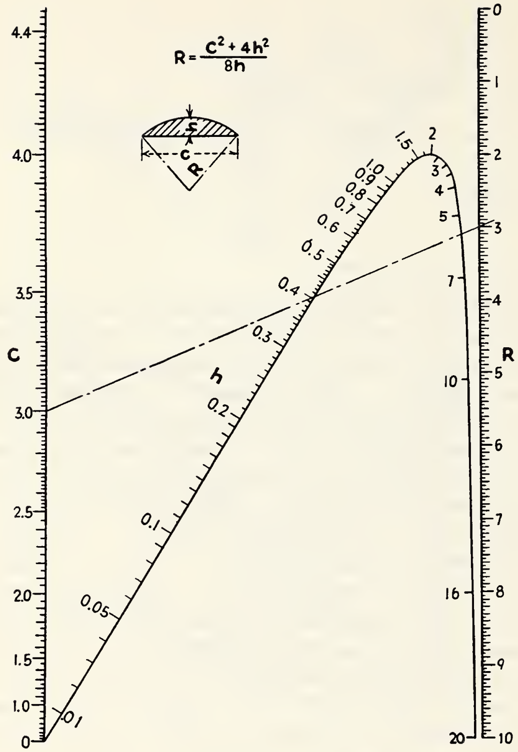

Fig. C-6. Nomogram for the relationship of radius, chord, and sagitta.*

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there are many graphical presentations in various publications.[8] Neither do we intend to describe the theory underneath, nor do we intend to explain the method of graphical construction. Our intention is to guide the reader into realizing the advantage of graphical methods so that he will make use of them whenever possible. In graphical construction the theoretical approaches are based upon either the plane and analytical geometry or the determinants. A knowledge of these

[8]Some suggested books are:

M. G. van Voorhis. 1937. How to make alignment charts. McGraw-Hill Book Co., Inc., New York. 114 pp.

E. V. Huntington. 1943. Graphical representation of functions. In: Handbook of Mathematics, 3rd ed. McGraw-Hill Book Co., Inc., New York. pp. 173-187.

J. B. Peddle. 1919. The construction of graphical charts, 2nd ed. McGraw-Hill Book Co., Inc., New York. 155 pp.

F. A. Berry, E. Bollay, & N. R. Beers. 1945. Numerical and graphical data. In: Handbook of Meteorology. McGraw-Hill Book Co., Inc., New York. pp. 3-121.

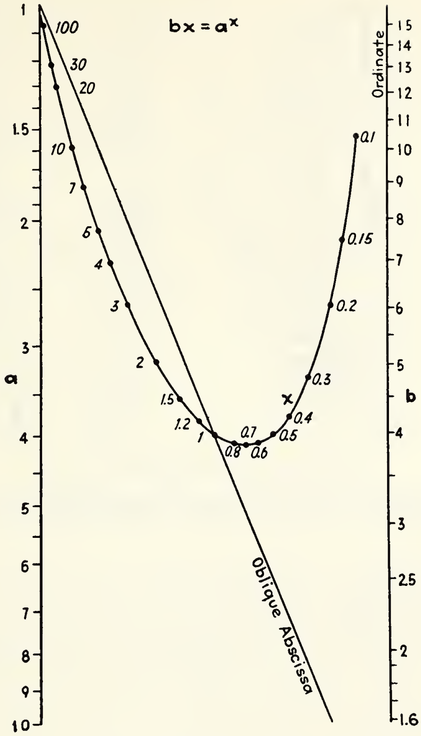

Fig. C-7. Nomogram for $bx = a^x$.*

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subjects would be helpful. A few graphs and equations are presented below for illustration; thus we have

$$\frac{1}{x} + \frac{1}{y} = \frac{1}{z} \tag{C-29}$$

This equation can be represented by three different graphs, as shown in Figs. C-5a, C-5b, and C-5c. In Fig. C-5a, we have the equation for the electrical resistance of conductors connected in parallel,

$$\frac{1}{r_1} + \frac{1}{r_2} = \frac{1}{R},$$

where r_1 (ranging from 10 to 15 ohms) and r_2 (40 to 50 ohms) are the resistances of parallel conductors, and R (0.0867 to 0.125 ohms) is the total or effective resistance. When the resistance of r_1 and r_2 are given in ohms, we can read R readily from the intersection of a straight line, and the scale line for R is shown in Fig. C-5a. The right-hand side of each scale line indicates the actual values of r_1, r_2, and R, respectively, while the left-hand side of each scale line

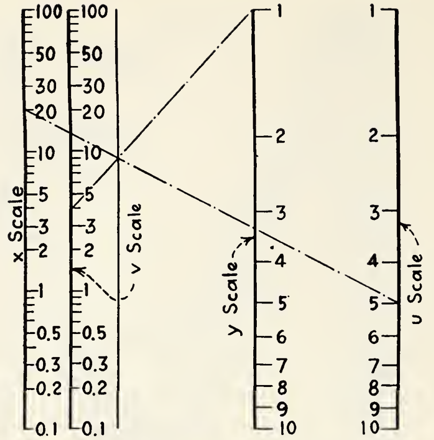

Fig. C-8. Nomogram for $\frac{x}{u} = \frac{v}{y}$.*

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indicates their reciprocals, i.e., $\frac{1}{r_1}$, $\frac{1}{r_2}$, and $\frac{1}{R}$. All lines for this figure are drawn in a linear scale.

Equation (C-29) can also be used for the study of optical paths of lenses and mirrors. For example, in the case of a concave mirror, we have

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f},$$

where u is the distance of the object from the mirror, v is the distance of the image, and f, the focal length.

A general equation can be assigned to Equation (C-29) as

$$\frac{1}{f_1(x)} + \frac{1}{f_2(y)} = \frac{1}{f_3(z)},$$

and is represented by either an acute or obtuse angle between the $f_1(x)$ and $f_2(y)$ scale lines. Then the $f_3(z)$ scale line is the diagonal of the parallelogram, as shown in Figs. C-5b and C-5c. If a right angle, instead of an acute or obtuse angle, is used, then $f_3(z)$ is the bisector of the right angle.

The relationship between the length of a chord (c), the sagitta of an arc (h), and the radius of a circle (R) can be formulated as

$$R = \frac{C^2 + 4h^2}{8h}. \qquad \text{(C-30)}$$

The nomogram of Equation (C-30) is given in Fig. C-6, where the straight line passes across two points on the curve scale h. The small value of these two points is h, while the larger value is the diameter minus h, namely, 2R - h. For example, if R = 3 and C = 3,

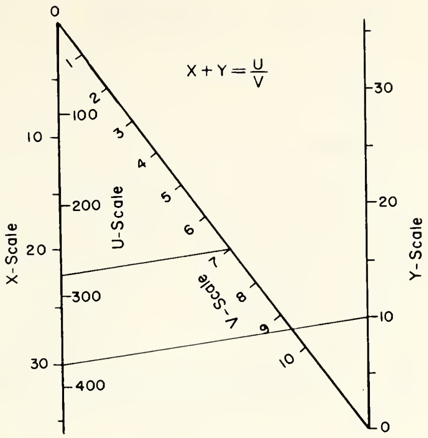

Fig. C-9. Z chart.*

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then $h = 0.4^+$ or 5.6^-, where the small value of 0.4 is h, approximately, and the larger value 5.6 is not h, but 2R - h, approximately.

When a formula is in the form of

$$bx = a^x, \tag{C-31}$$

the two values of x are determined in the nomogram of Fig. C-7.

(c) Graphical solution of more than three variables. When four variables, x, y, u, and v, are in the form of

$$\frac{x}{u} = \frac{v}{y}, \tag{C-32}$$

we have the nomogram layout as has been shown in Fig. C-8. When the four variables are in the relationship of

$$x + y = \frac{u}{v}, \tag{C-33}$$

we have the Z chart as shown in Fig. C-9. For a nomogram of more than four variables, the reader may refer to references in Footnote 8 of this appendix.

(d) Graphical analyses of scalar quantities. The addition, subtraction, multiplication, and division of scalar quantities could be performed graphically, provided the gradients of these quantities are given. When two quantities Q and Q' are drawn on a map as Q_1, Q_2 . . . Q_n, and Q_1', Q_2', . . . Q_n', the descending order of the gradient can be specified by vectors $\overline{Q}$ and $\overline{Q'}$. This is given in Fig. C-10a, which is a schematic diagram. The solid arrow indicates the gradient of Q, and the blank arrow shows that of Q'. The cross diagonal lines are the vector sum of quantities Q and Q', thus

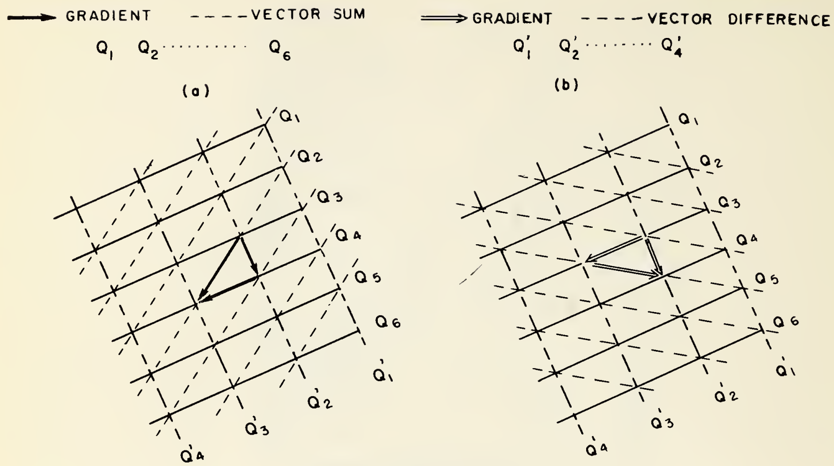

Fig. C-10. Schematic diagram of vector sum and vector difference.

$$\overline{Q} + \overline{Q'} = \overline{R}. \qquad \text{(C-34)}$$

Similarly, the vector difference is shown schematically in Fig. C-10b.

When graphical multiplication and division are needed, one can simply re-label the original quantity with a new value. For example, the isotherms (T) can be re-labeled with corresponding values of saturation vapor pressure (e_s), because (e_s) is a function of (T). Also, an isotherm pattern which was originally analyzed in the Fahrenheit scale can be re-labeled by converting Fahrenheit into Centigrade. Thus multiplication and division in graphical analysis occurs in the transformation of a quantity into a new quantity by re-labeling.

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