WHEAT STUDIES

OF THE

FOOD RESEARCH INSTITUTE

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FORECASTING WHEAT YIELDS FROM THE WEATHER

ELEMENTS OF AN UNSOLVED PROBLEM

CUSTOMARY methods of forecasting crop yields are based on the exercise of judgment and are subject to errors inherent in judgments, especially to bias. Hence methods involving the least possible exercise of judgment are needed, if only as checks upon current methods.

Forecasting yields from the weather would satisfy this need. Proposed methods assume that a given crop plant in a given region always reacts in the same way to a given kind of weather. Mathematical formulae have been developed to predict crops in a given year from weather and crop data of earlier years, and weather data of the year in question. Sometimes such forecasts are reasonably good, sometimes not. They would be better if data for past crops were not often inaccurate; if weather data, though reasonably exact, did not sometimes lack important weather factors; and if more were known of the laws of growth and of the influence of environmental factors on crop formation.

To remedy these deficiencies, crop yield statistics and weather records must be improved, and much scientific research upon the laws of plant growth must be conducted. Investigations by physiologists designed especially to determine at what stages of the crop plant's growth the weather exerts the greatest influence, and why, will prove particularly important. If these various gaps in knowledge are filled—and there is no reason why they cannot be—forecasting yields from the weather should become a valuable tool for agricultural statisticians. In all probability the process must always depend in part upon statistical analysis. Experimental work promises to make its greatest contributions toward the problems of forecasting by furnishing improved bases for statistical analysis.

STANFORD UNIVERSITY, CALIFORNIA

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The central feature of the series is a periodic analysis of the world wheat situation, with special reference to the outlook for supplies, requirements, trade, and prices. Each volume includes a comprehensive review of the preceding crop year, and three surveys of current developments at intervals of about four months. These issues contain a careful selection of relevant statistical material, presented in detail in appendix tables for reference purposes, and in summary form in text tables and charts.

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FOOD RESEARCH INSTITUTE

STANFORD UNIVERSITY, CALIFORNIA

The Food Research Institute was established at Stanford University in 1921 jointly by the Carnegie Corporation of New York and the Trustees of Leland Stanford Junior University, for research in the production, distribution, and consumption of food.

FORECASTING WHEAT YIELDS FROM THE WEATHER

ELEMENTS OF AN UNSOLVED PROBLEM

I. PRELIMINARY CONSIDERATIONS

Man's progress, at least materially, has been won by achieving ever greater independence of his surroundings. With advancing material civilization he has become less and less subject to injury from the numerous factors that tend to hamper his development. Some of these, such as diseases and predatory animals, he has succeeded, more or less perfectly, in controlling or eliminating. Others, like climate or the weather, he is unable to control, but to them he has succeeded in making adaptations so as to nullify many of their adverse effects. To this end he has developed housing, clothing, and heating, and also special forms of agriculture. Crop plants and domesticated animals have been adapted to different climates. Different soil conditions have been met by different forms of tillage and by the use of fertilizers. Nevertheless, in spite of all that has been achieved in these ways, agricultural production remains extremely variable and hazardous, chiefly because of fluctuations in the weather.

CONTENTS

Having been unable as yet to overcome to any great degree the hazards of the weather, man has turned his attention to forecasting its probable effects, for it is obvious that next to eliminating or controlling hazards the best procedure is to foresee them. To be forewarned is to be forearmed. If it is possible to foresee a crop failure, or even a short crop, steps may be taken at least to minimize the evil effects.

Famines were perhaps the evil effects that man first attempted to minimize by forecasting crops. To mitigate their horrors men must from the earliest times have endeavored to forecast harvests. Except here and there, this is no longer an important object of crop forecasting, for the excellence of transportation facilities in the modern world permits the shipment of sufficient volumes of food into deficiency areas. If famines nevertheless occur, it is most frequently because the victims lack sufficient purchasing power. Moreover, crop forecasts are of limited use in predicting famines, partly because it is not yet possible to make them far enough in advance of the harvest, but principally because it is especially difficult to forecast more or less complete crop failures. It is to crop failures that famines are usually due. Such failures are commonly the consequence of quite abnormal conditions or even catastrophes, such as hurricanes, hail, unseasonable frosts, prolonged drought, and the like. These can hardly be foreseen until they happen. One can, however, estimate the probability of the occurrence of these catastrophes by studying the weather records of the past. Such knowledge enables governments, with a minimum of waste, to accumulate in times of plenty the resources for famine relief. In ancient times, this took the form of the accumulation of reserve stores of food; in modern times, it takes the form of the accumulation of money reserves or credits to be used for the work of relief or for the prosecution of public works to enable citizens to earn the money with which to purchase imported food.

Another method of minimizing the evil effects of bad harvests, which has begun to be practiced only in recent years, is to distribute the risk by insuring the crop. To any reasonably perfect system of crop insurance forecasts of yields are basic. At the present time crop insurance has been limited largely to the effects of such catastrophes as hail, hurricanes, or unseasonable frosts, involving the more or less complete destruction of crops. In such cases, the underwriters are interested primarily in the comparatively simple actuarial problem of determining the probability of such catastrophes and in adjusting to the probabilities the premiums demanded for assuming the risk. When, however, injury rather than complete destruction of the crop is involved, forecasting the yield becomes fundamental to any scheme of insurance. In such instances, the adjuster must determine the extent of the damage done by the hail, the hurricane, or the frost, as the case may be. To do so, he must first form some estimate of what the crop would have been had there been no hail, no hurricane, no frost. This involves estimating the yields that would have prevailed under the weather conditions in that season had no catastrophe occurred. Since, as we shall see, the methods of forecasting crop yields are as yet quite imperfect, most plans of crop insurance recently proposed have been based not on the actual amount of damage done but rather upon the investment of the farmer in the crop or upon the ten-year-average crop yield. Neither of these plans is, of course, as equitable as that of basing the contract upon actual damage, the plan now almost universally adopted in the insurance of property against loss from fire and the like.

More important to modern states than the forecasting of famines is the forecasting of crops in connection with the preparation of budgets, for crops are important sources of the national income, which in the last analysis determines the capacity of a large part of the people to pay taxes. Crop forecasting becomes especially important when the crop itself is taxed or when, as is the practice on some of the sugar islands, the tax upon the export of agricultural produce is an important source of revenue. Forecasting the crop is furthermore important in predicting a nation's balance of trade. If the nation produces a surplus, the probable size of the exportable fraction must be known in order that its value may be placed on the credit side of the balance sheet. If the nation produces only a fraction of its own requirements, the volume of imports that will be required, the value of which must be placed on the debit side, will be determined in large measure by the size of the domestic crop. Finally, crop forecasting at the earliest possible moment is, obviously, important also for those countries that subsidize or propose to subsidize agriculture directly or to protect the farmer more indirectly by some such plan as the equalization fee of the McNary-Haugen bill, government-operated pools, special freight tariffs, government crop insurance, and the like.

To private citizens and to corporations the forecasting of harvests is of manifest importance. If they are farmers, they will want to take into consideration such forecasts in planning their harvesting and marketing operations. If they are dealers in the crop, the forecasts directly affect their current policies and plans, for crop prospects are of very great influence in determining the course of prices. If they are merchants of other sorts, they will want to use forecasts in determining the probable future purchasing power of the different elements of the population that consume their goods or services. Manufacturers using agricultural raw materials, for example millers or cotton spinners, will use forecasts to learn how much raw material is likely to be available. Railroad executives will use them to make preparations for the transportation of the crops. Bankers will be able to employ them in forecasting future economic conditions in general as well as in preparing to finance the movement of crops.

It is obvious, then, that accurate forecasting of crops is a matter of great importance to the economic life of any nation. If it were possible to make accurate forecasts well in advance of harvest, multifarious adjustments would be made with far greater ease than at present, and there would be far greater opportunities to moderate the movements of agricultural prices and production, and to minimize the violent fluctuations in economic conditions which hitherto have been found unavoidable.

Common Methods of Crop Forecasting

Crop forecasting of a sort has been practiced since time immemorial. Experienced men have always given their opinion on the probable crop outturn of a field or a district; and such opinions, modified in certain ways, still form the basis of the principal methods of crop estimating now in use. Such forecasts involve two quantities: the area planted to the crop, and the yield per unit of area. The prospective volume of the crop is computed by multiplying one quantity by the other. The farmer who forecasts the outturn of a given field either knows its area or estimates it; he estimates the probable yield per unit area and, consciously or subconsciously, makes the computation.

Now the two factors, acreage and yield, present quite different problems in estimating. Acreage is static; ordinarily it is constant after the end of the planting season.[1] Where acreage in a particular crop is abandoned, an allowance for this reduction can be made. The acreage to be harvested may, therefore, be determined in advance of the harvest with reasonable exactness by taking a census, i.e., by actual count or enumeration.[2] Few countries, however, do this because of the great expense[3] and because it ordinarily takes so long that the results are obtained too late for forecasting purposes. Most countries are compelled to resort to an enumeration of representative samples of the total area, to reports furnished by experienced farmers, or to other methods of estimating.[4] Errors in estimates of acreage are by no means negligible, and they may be cumulative over a period of years.[5] As a rule, however, the variations in acreage from year to year are much smaller, and more closely calculated some months before harvest, than is the case with yields per acre.

Unlike the acreage, the yield per acre is not fixed but highly variable. It cannot be determined by census methods in advance of the harvest, for one cannot enumerate or measure what does not yet exist. One can take a census and make an enumeration only at the time of harvest or thereafter. Few countries take such a census because of the expense; hence, official estimates of crops actually harvested commonly rest upon a census of a more or less representative sample, on the reports of experienced farmers, and on supplemental methods of estimating. The resulting data are by no means perfect, and even the comprehensive census reports of harvested crops, when they are taken, are subject to special kinds of error. Such defects as these figures contain constitute an often-unappreciated weakness in statistical attempts to derive forecasting formulas from past yields. Obviously, however, such estimates after harvest afford no substitute for the forecasts of crops before harvest.

The almost universal method of forecasting yields is to gather the opinions of a large number of experienced agriculturists and to form some sort of composite of the opinions so gathered. This may be termed

[1] However, a portion of the acreage of certain crops in certain regions may be abandoned on account of destruction of or serious damage to the crop by bad weather, and then sown to some other crop or left fallow. Thus in the hard-winter-wheat belt of the United States a variable portion of the acreage sown is winterkilled. This land may be plowed up in the spring and sown to corn (maize) or other spring crops.

[2] For a discussion of some of the sources of error in the taking of a census of acreage, see L. G. Powers, "Degree of Accuracy in Census Statistics of Agriculture," *Publications of the American Statistical Association*, 1910–11, XII, No. 93.

[3] The United States Secretary of Agriculture stated in 1920 that the entire cost of the Bureau of Crop Estimates for furnishing information (60 crops, 6 classes of live stock) was at that time about the same as the cost of the cotton-ginning reports of the Bureau of the Census.—*Weekly News Letter of the Department of Agriculture*, June 16, 1920, VII, 5 f.

[4] In this connection, it is of interest to note that weather factors may sometimes be used. Thus in some regions the acreage of winter wheat depends in some measure upon autumn rainfall. If it is so heavy that the number of days when the ground is in condition for plowing is small, acreage is reduced. (Cf. R. H. Hooker, "Correlation of the Weather and Crops," *Journal of the Royal Statistical Society*, 1907, LXX, 1 ff.) Another example is the effect of winterkilling cited above. Still another example is found in regions where, if possible, two crops per annum are grown, as in India. The time of maturity and the character of the summer crop, which depend upon the summer weather, determine the acreage of winter crops it is possible to put in. (Cf. Conrad P. Wright *et al.*, "India as a Producer and Exporter of Wheat," Wheat Studies, 1927, III, 352 ff.; and S. M. Jacob, "Correlation of Rainfall and the Succeeding Crops with Special Reference to the Punjab," *Memoirs of the Indian Meteorological Department*, 1916, XXI, pt. xiv, 131 ff.

[5] Cf. Holbrook Working, "Wheat Acreage and Production in the United States since 1866: A Revision of Official Estimates," Wheat Studies, 1926, II, 237 ff.

a subjective method, since it rests upon judgments. Each agriculturist or crop reporter who gives his opinion bases it more or less consciously on his personal recollection of the appearance of the standing crop in former years and the yield in those years. The person or board that synthesizes these opinions uses judgment, individual or collective, in giving different weights to the individual opinions of the agriculturists. Tacitly this method assumes that mistakes made by the individual observers will as often underestimate as overestimate the probable yield; that there is no bias on the part of the observers; and that, if only there be enough of them, their mistakes will cancel out, so that the final average obtained will be very close to the truth.

Yet it may be doubted that there is no unconscious bias on the part of the observers.[1] It may be questioned that the psychological factor can be ignored. One may doubt that as many farmers will be pessimists as optimists. It is not necessarily true that farmers' opinions will vary purely as a matter of chance like the flipping of a coin. The psychology of the farmer is a factor and may not obey a simple law of probability. It remains to be determined that the widespread reading of newspapers in which the weather and its supposed effects upon crops are discussed is without systematic influence upon the farmers' frame of mind. The psychological factor is very possibly different from year to year; it may conceivably vary with the farmers' economic position or with the prevailing level of crop prices or both. It may be that in a year of agricultural depression with low prices the wish is more often father of the thought than in years of agricultural prosperity. Under some circumstances it is quite possible that in some years farmers consciously or unconsciously are more prone to underestimate and in others to overestimate. That there may be bias in the reports of crop estimators is now recognized by the United States Department of Agriculture, and methods have been devised for making appropriate corrections,[2] although these methods do not seem as yet to have been published.

The inherent defects of this method of crop estimating are now so well recognized that many countries make no official forecasts of the volume of crops in advance of harvest. They limit themselves to the publication of so-called condition reports. In many countries this is done on a purely arbitrary scale of numbers, e.g., 1, 2, 3, 4, 5, one end of the scale representing a bumper crop, the other a failure. Some countries are not even as precise as this but describe the condition by such words as excellent, good, average, below average, poor, etc.[3] In the United States condition figures have for a great many years been expressed as percentages of a hypothetical normal.[4] There exists a difference of opinion whether condition figures are best expressed in percentages of such a normal or of the ten-year average. Since 1912 the United States has been issuing not merely condition figures but also forecasts of yields which are derived by calculation from the condition figures.[5]

The improvement in crop estimating by this method in recent years has taken the form of increasing the number of crop reporters, i.e., in increasing the size of the sample; in securing better crop reporters or their better distribution either geographically or in regard to the character of their farm holding or their farm operations, etc.; in the elimination of bias; and notably in devising methods of checking the reports in various ways. But in the ultimate analysis the method is based on judgments, and the very notable improvements that have been made are for the most part designed to reduce errors that are inherent in judgments. All students of the subject are agreed that another method would be extremely valuable if only as a check upon the current method; and this is recognized in the United States Department of Agri-

[1] Cf. H. Parker Willis, "The Adjustment of Crop Statistics, III," *Journal of Political Economy*, 1902–3, XI, 540–67.

[2] W. F. Callander, "Problems in Crop and Live Stock Estimating," *Journal of Farm Economics*, 1928, X, 232 ff.

[3] C. C. Clark, "International Crop Reporting Service," *Publications of the American Statistical Association*, 1910–11, XII, No. 91. For a criticism of condition figures, cf. L. March, "La statistique des états de culture," *Bulletin de l'Institut Internationale de Statistique*, 1915, XX, 649.

[4] For details see Callander, *op. cit.*

[5] *Idem.*

culture as well as elsewhere. Such a check method would be valuable in proportion to the degree to which it is objective, i.e., not based on opinion. Forecasting yields from the weather, if it is feasible, would offer such an alternative method, and research is in progress in the United States (chiefly in the Bureau of Agricultural Economics), and in some other countries, to provide a firm foundation for such procedures.

Purpose of the Present Study

In the course of the last forty years a fairly considerable literature on methods of forecasting yields from the weather has been published. Study of this literature leaves the reader baffled and confused. The one fact that stands out clearly is that the problem is far from solved. Indeed, the problem has been scarcely defined sharply. This is, of course, due primarily to the inherent difficulty and complexity of the question, for each crop and each locality presents a peculiar forecasting problem. Moreover, the solution of the problem requires the co-operation of meteorologists, agronomists, physiologists, pathologists, and entomologists. No one person is capable of mastering all the specialties involved, and co-operation between experts in these diverse sciences is difficult to secure and hard to maintain. Hitherto the bulk of the investigations has been made by statisticians or meteorologists, and in consequence comparatively little attention has been paid to the plant as a reacting organism.

The purpose of the present paper is to bring together what is known concerning the forecasting of yields of wheat from the weather and to present as simple and as lucid a picture as possible of the status of existing knowledge of this problem. This demands in the first place consideration of weather as an environmental factor, consideration of the biology of the wheat plant as the basis of its reaction to the weather, consideration of the methods used in forecasting yields from the weather, and finally a discussion of how these methods have been applied to wheat. Incidentally, reference is made to other crop plants when data on any particular point are lacking for the wheat plant. Emphasis is laid upon disentangling the numerous elements of a complex problem of fundamental importance as yet unsolved. It is hoped that interest in the possibility of forecasting yields from the weather may be stimulated and that biologists in particular may be aroused to attack some of the fundamental problems of the laws of growth of crop plants upon the solution of which in the last analysis depends the solution of the problems of forecasting crop yields by *objective* rather than *subjective* methods.

II. WEATHER FACTORS IN PLANT GROWTH

For present purposes weather may be resolved into three factors: light, heat, and moisture.

The Light Factor

Green plants cannot mature without light because it is from light—ordinarily sunlight—that they supply themselves with energy. With the assistance of sunlight they compel carbon dioxide from the air to combine with water with the ultimate result that sugar is formed.[1] This process is known as photosynthesis. The sugar (carbonaceous material) thus formed is then used as food by the tissues and organs of the plant. Plants may therefore be said to manufacture a large part of their own food. Upon the amount of carbonaceous material formed by photosynthesis depends, therefore, the rate at which the plant can grow. The formation of sugar by photosynthesis goes on predominantly in the leaves, and is, ordinarily, a function of the extent of the leaf surface that is exposed to light. Hence the extent of the leaf area is a limiting factor[2] determining how much carbo-

[1] The different steps in the process are not known with certainty, nor is the nature of the process fully understood. Cf. H. A. Spoehr, *Photosynthesis* (New York, 1926); and C. L. Alsberg, "Progress in Chemistry and the Theory of Population," *Industrial and Engineering Chemistry*, 1924, XVI, 524.

[2] There are other factors besides leaf surface, such as leaf thickness, chlorophyll content, etc.; but these need not be considered here.

naceous food shall be available to the green plant for maintenance and growth.

The amounts of carbon and energy that are assimilated depend theoretically also upon the intensity and character of the light falling upon the leaves; as a practical matter deficiency of light is rarely a limiting factor in determining growth of crops in open, unshaded fields. Brown has shown that the intensity of illumination is commonly much greater than the optimum.[1] It may be reduced to nearly one-quarter that of ordinary English sunlight before the rate of photosynthesis is changed materially. Under ordinary conditions of cultivation, therefore, sunshine is in all probability not an important factor in directly determining yields in a given locality. If, nevertheless, agricultural meteorologists and statisticians have found relationships between light intensity and yields in a given locality, this is probably due to the fact that there is a high correlation between sunshine and temperature. In other words, when it is sunny it is usually warm, and warmth, as we shall see, has important effects upon the growth rates of plants.[2] Some crops, indeed, produce best when the intensity of sunlight is below average; to some plants intense sunlight is injurious.

While in all probability the intensity of sunlight is not fundamentally important in a given locality except for its heat effects, the length of the day is most important. This changes in each latitude in a quite constant way, but it is different in different latitudes. The hours of sunlight per day of the growing season increase with the latitude. At higher latitudes the growing season is shortened, with spring coming later and autumn earlier; but the hours of sunshine are not proportionately diminished because the days are longer in summer. This is an important factor in making it possible to grow crops at high latitudes. There are of course other factors, the most important of which is perhaps that the varieties selected for cultivation at high latitudes have usually shorter growing periods than those grown nearer the equator.

The total number of hours of sunshine to which a plant is exposed during the growing season does not always determine the effect of light upon it. The ratio of length of the day to the length of the night is important—at least for certain plants—as shown by Garner and Allard.[3] Apparently in some cases plants may be brought to flower and fruit earlier or later by adjusting this ratio. Probably this phenomenon is also a factor in determining yields at different latitudes. The wheat plant, however, is not much influenced by light periodicity, for at the Food Research Institute spring wheat has been brought to maturity under continuous illumination.

The Heat Factor

A plant's temperature changes with that of its environment. Only to a limited degree can it protect itself from freezing, as by making its sap more concentrated.[4] Only by evaporating water from the surface of its leaves—a process which botanists call transpiration—can it resist heat. Transpiration is effective because as water evaporates it absorbs heat and so cools the plant. As the surface of the leaves from which evaporation takes place is comparatively great, quite large quantities of water may be evaporated by a plant and transpiration be correspondingly effective as a cooling measure.

The activity of all living substance, whether animal or plant, so far as known, is greatly influenced by temperature. Cold retards all vital processes till at given temperatures they practically cease, whereas warmth speeds them up till at certain degrees of heat life ends. The limiting temperatures, and the effects of temperature within these limits, are different for different species and varieties. So far as the effects of temperature are concerned, vital processes resemble chemical processes.

[1] H. T. Brown, "The Reception and Utilization of Energy by a Green Leaf," *Nature*, 1905, XCII, 525.

[2] Cf. also F. M. Hildebrandt, "A Physiological Study of the Climatic Conditions of Maryland, as Measured by Plant Growth," *Physiological Researches* (Johns Hopkins University), 1921, II, No. 8.

[3] W. W. Garner and H. A. Allard, "Effect of the Relative Length of Day and Night and Other Factors of the Environment on Growth and Reproduction in Plants," *Journal of Agricultural Research*, 1920, XVIII, 553 ff.

[4] R. Newton, "Colloidal Properties of Winter Wheat Plants in Relation to Frost Resistance," *Journal of Agricultural Science*, 1924, XIV, 178 ff.

Many chemical reactions approximately double their rate for each 10°C. (18°F.) rise in temperature. This is known as Van't Hoff's Law. Living things react to changes in temperature in somewhat similar proportions, and many experiments have been performed to prove that they obey Van't Hoff's Law, though without conclusive results. The point to be noted in this connection is that the activity of living things does not increase directly in proportion to rise in temperature.

Since the plant, in comparison with the animal, has no power to change its location and but limited power of control over its own temperature, the rate at which its life processes go on changes with the temperature of its environment. It must cease to grow when the temperature drops to a certain point.[1] This point varies for different kinds of plants, but for most field and garden crops it is close to 6°C. (42.8°F.).[2] On the other hand, the plant must grow more rapidly when the temperature becomes elevated up to a certain point. At temperatures much elevated above those to which it is adapted, the plant is in a state analogous to fever. Beyond a certain point excessive heat means death. A crop growing in the open fields subject to all the vicissitudes of the elements grows very irregularly—faster on warm days, more slowly or not at all on cold ones.

One must distinguish the manner in which light is useful to plants from the manner in which heat is useful. Light serves as a direct source of energy, without which the green plant can neither live for long nor grow. Heat is not a form of energy that plants can use directly. It is necessary to plants not for itself but because it creates conditions that make chemically possible the various life processes. It is not changed by the plant into some other form of energy as is light in photosynthesis. In fact, heat is formed by plants when they transform food materials in their life processes. Warmth is to be regarded then as a condition for growth, not as taking part in the growth processes like light and plant foods. Indirectly, of course, heat shares in the vital processes, as when it is absorbed in the evaporation of water in transpiration and so serves to cool the plant. When agricultural meteorologists write, as they often do, of the total degrees of temperature a plant requires to reach maturity, they do not mean what plant physiologists mean when they speak of the amount of potash or nitrogen required by a plant. These are actually used by the plant; indeed, they are incorporated in it. What the agricultural meteorologist means is that the temperature must reach a certain level for a certain length of time for the maintenance of the chemical processes necessary to enable the plant to mature.

These temperatures vary for different species of plants and even for different varieties of the same species. For most plants there is a considerable range of temperature over which they will grow and mature, but since the life processes go on at different rates at different temperatures the lengths of the different growing periods are modified by the prevailing temperatures. They may be shortened or lengthened. The plant may bloom earlier or later.[3] The phenomenon is complex. There are other factors besides temperature, but this is not the place for a full discussion of the subject.

Hence most plants grow only when the temperature remains within certain limits. When it rises too high or falls too low they may become dormant or die. Low temperatures may hinder germination, stop or retard growth, or actually injure and kill. High temperatures, among other effects, tend to produce dessication, as we shall see. Most crops of temperate regions grow when the mean daily temperature ranges from 9.4° to 22.2°C. (49° to 72°F.).

Warmth acts not merely upon that part of the plant that is above ground but also upon the subterranean parts. Soil temperature is a most important factor in the plant's environment. The heat of the soil is derived from the sun, but a trifling

[1] The application of this idea to growth is apparently due to De Candolle. Cf. E. J. Salisbury, "Phenology and Habitat with Special Reference to the Phenology of Woodlands," *Quarterly Journal of the Royal Meteorological Society*, 1921, XLVII, 231.

[2] The British Meteorological Office adopted 42°F. as the critical point. Cf. E. Mawley, "Weather Influences on Farm and Garden Crops," *Quarterly Journal of the Royal Meteorological Society*, 1898, XXIV, 63.

[3] Cf. A. J. Connor, "Relation of the Weather to the Yield of Wheat in Manitoba," *Monthly Bulletin of Agricultural Statistics* (Canada), April 1918, 115 ff.

amount also comes from the interior of the earth. In summer, heat is lost in the strata below the surface. The temperature of the surface soil is influenced by many factors such as physical state, water content, covering with vegetation or snow, and the like. Soil temperature affects both the germination of seeds and the growth of plants.

The Moisture Factor

As plants require a certain amount of light and heat to live and grow, so they require a certain amount of moisture. This they derive by absorption from the soil through the roots. At the same time that plants are absorbing moisture from the soil they are losing moisture by evaporation (transpiration), principally from the surface of the leaves. In order that the plant may always have in its body enough water to carry on its life processes it must, obviously, absorb as much through its roots as it loses through its leaves. The two must approximately balance. Disturbance of this balance may be brought about by either of two sets of conditions or by both combined. First, there may be so little moisture in the soil that the roots are powerless to furnish it to the plant as rapidly as moisture is lost by evaporation from the leaves. Secondly, the plant may evaporate moisture at so rapid a rate that the roots cannot keep up the supply even though there be enough available moisture present for them to meet the demands of a less rapid transpiration. Not at all infrequently too scanty soil moisture and very rapid transpiration occur at the same time.

The quantity of moisture entering unirrigated soil depends primarily upon the amount of precipitation, principally rain and snow; the actual precipitation, however, is less important for the plant than the amount that remains in the soil for the plant to use. This depends upon many other factors, the most important of which are the run-off and the time when the precipitation occurs.

The run-off is the amount of water that runs off into brooks and streams without sinking into the soil. It depends upon many conditions. More moisture will run off a hillside than off a plain. Obviously, if a given amount of rain falls in a short time, more will run off than if the same amount is spread over a longer time. Obviously, too, rain will sink more quickly into sand than into clay. On the other hand, more water will be held by clay than by sand because less will be lost by subsoil drainage. In any given locality underground drainage conditions will be important in determining how much of the precipitation will remain as soil moisture.

If the soil is bare of vegetation and hard baked, more will run off than if the soil is covered with grass, shrubbery, or forest. On the other hand, vegetation growing upon the soil tends to reduce soil moisture because the growing plants use it up. The cultivation of fields lying fallow has for one of its purposes the destruction of weeds in order to prevent their exhausting soil moisture. Another purpose is to break up the hard surface layer so that rain may sink into the soil more readily and not run off. This cultivation has another effect: moisture evaporates from the surface of the soil; as the surface dries out, fresh moisture is drawn up to it by capillary action through the pores of the soil. Cultivation breaks the continuity of the capillary pore spaces and so lessens the rate at which water reaches the surface and is evaporated.

If moisture falls in the form of snow, anything that causes the snow to melt slowly must reduce the run-off and give time for more of the snow water to seep into the ground. This will be favored if the spring is late or if the land is covered with forest trees that intercept the sun's rays.

The amount of soil moisture available to the plant is not, however, indicated by the percentage of moisture in the soil. The availability depends in large measure upon the character of the soil. Not all the moisture of the soil is free; some of it is so tightly held by the constituents of the soil that it is not available to the plant. The degree to which this occurs varies in different soils; it is least in sand which holds but little of the water firmly; it is greatest in certain types of heavy clays which hold considerable water so tightly that plants cannot absorb it.

The time when precipitation occurs is also of great importance to the plant. Some of the soil moisture used by crop plants, especially in semi-arid regions, may have entered the soil and been stored there before the crop was planted. In analyzing the effects of precipitation upon crop yields, it is, therefore, necessary sometimes to go back to a consideration of the weather before the crop is even planted. Plants require different amounts of moisture at different periods of their growth. Rain that falls at a time when the plant requires little of it may be of no use to the plant, because by the time it is needed it may have largely disappeared from the soil. In considering the suitability of any climate for a given crop it is necessary to know not merely the annual rainfall of the region but also how it is distributed week by week through the year. In the life of each plant, some days are crucial. Similarly in attempting to estimate the effect of rainfall upon the probable yield, it is necessary to know at what stage of the plant's growth it fell and what the plant's requirements are at that time. The first is easily obtained from meteorological data. Concerning the second we are as yet largely ignorant because so little is known concerning growth rates of crop plants and concerning their requirements at different growth stages. So far as anything is known about these requirements it has been inferred from the results of statistical studies of correlations between rainfall data and crop yields in previous years. From such correlations, indeed, in the absence of exact physiological experiments, attempts have been made to reason concerning the requirements of plants at different stages.

Humidity and temperature are also important factors in determining soil moisture. When the air is very humid, evaporation from the soil's surface is less, other things being equal, than when the air is dry. High temperatures, as every one knows, increase evaporation. As important as humidity and temperature are air currents, and especially high winds. Wind is of importance in all countries, but in some regions it is of outstanding significance. The winds from one direction may be warm or cold, moist or dry, gentle or strong. Thus the monsoon of India and the Chinook of western Canada exercise a determinative influence on the crops of a particular year. Many regions have definite prevailing winds, persistence in or variation from which greatly modifies the other climatic relations. Winds may do damage not merely by beating down the crop or by causing grain to shatter, but also by greatly increasing evaporation. Hot dry winds are especially injurious not merely by depleting the store of water in the soil, but also by increasing greatly the plant's transpiration and making the maintenance of the plant's water balance difficult. As we shall see, when hot, dry winds come at the time of flowering of the wheat plant, they are especially injurious and favor the formation of sterile heads. Hence, when there is a combination of low humidity, high temperature, and strong wind, the soil loses much water by evaporation. Unfortunately, but little attention has been paid to evaporation. Chilcott seems to be the only man who investigated the question adequately.[1] He reached the conclusion that in the Great Plains area of the United States, a semi-arid region, evaporation is at least as important as precipitation.

It is clear then that while precipitation determines by and large the amount of available soil moisture, a given amount of rain or snow does not everywhere and at all times raise the total soil moisture to the same degree. Still less does it necessarily increase the moisture available to the plant to the same degree, for the fraction that is available depends in larger measure upon the amount of moisture left in the soil at the time the plant needs it than upon the amount of precipitation.[2] The actual moisture available in the soil is by far the more significant fact. Yet most investigators, as we shall see, have dealt with the total precipitation rather than available soil mois-

[1] E. C. Chilcott, *The Relations between Crop Yields and Precipitation in the Great Plains Area* (U.S. Department of Agriculture Miscellaneous Circular No. 81), 1927.

[2] "Because of differences in time and manner of distribution, amount of run-off, which in turn is influenced by soil structure, rapidity of evaporation, etc., rainfall alone, indeed, yields data of little value in a study of the water relations of crop production." —J. E. Weaver, F. C. Jean, and J. W. Crist, *Development and Activities of Roots of Crop Plants; A Study in Crop Ecology* (Carnegie Institution of Washington, Publication 316), May 1922, p. 33.

ture.[1] The reason is not that they have been unaware of the greater significance of available soil moisture, but rather that rain- and snowfall data are easily obtainable whereas soil moisture data are not generally available. These can be obtained exactly only by appropriate analysis. If moisture determinations were substituted for precipitation data in making forecasts, it is extremely probable that these would gain materially in accuracy; indeed, this procedure has actually been practiced by Broonoff.[2]

Some of the very factors that reduce soil moisture, notably low humidity, high temperature, and wind, greatly raise the moisture requirements of plants. They increase evaporation from the leaves and therefore increase transpiration. So it comes that a luxuriant vegetation is possible as one approaches the poles of the earth with a rainfall that in warmer regions is quite incapable of supporting any vegetation at all. In high latitudes, 250 millimeters (9.8 inches) of precipitation per annum are ample to grow a crop of grain. In the Sahara there are considerable areas with 800 to 900 millimeters (31.5 to 35.4 inches) of rain yet quite incapable of supporting agriculture.[3]

If soil moisture conditions, temperature, humidity, and air currents are such that the balance between moisture loss by transpiration and moisture absorption through the roots is disturbed, the plant dries out, dessicates, and must ultimately die if the disturbance of balance continues. Certain plants, including some of the sorghums and millets, have various means of protecting themselves more or less perfectly against dessication so that they seem to stop growing for a time till rain comes. Some, like the sugar beet and alfalfa, protect themselves to some extent by developing a tap root system that follows the ground water to considerable depths as the water table sinks. Other plants with but a shallow root system depend principally upon water near the surface and are soon damaged by continued lack of rain. Hence the effect of a small amount of precipitation may be very different on different plants. It is believed that small rainfalls during a drought may actually do more harm than good, because by merely wetting the surface of the ground an effective dust mulch may be destroyed and thus more water lost to the crop by evaporation than has been gained by the shower. Or numerous light showers during early growth, by merely wetting the surface, may cause certain crop plants to root near the surface where the soil will quickly dry out in later dry spells.[4] In any event, if the water balance is seriously disturbed the plant is injured, if it is not killed, and this injury tends to reduce yields. Hence the conditions disturbing the water balance of plants are fundamental in forecasting yields and for this reason they have been considered in some detail in this section.

Excessive rainfall as well as deficient rainfall may hurt crops. Opinions differ in regard to how excessive rain does injury. Lawes and Gilbert suggested that too much rain hampered root development and washed out nitrates from the soil.[5] Fisher, from a study of the effect of rain on different wheat plots more or less heavily fertilized, has brought forward strong evidence in support of the suggestion that a large part of the ill effects of too much rain is due to the leaching out of nitrates. He also pointed out that, since much rainy weather at the time of fall plowing and sowing of winter wheat tends to reduce acreage because the soil is not in condition to be worked, there is likely to be a selective restriction of acreage. Some kinds of land are more easily made unworkable by rain than others, and, therefore, conceivably, heavy autumn rains may change the average character of the land that is actually sown to wheat and thus indirectly affect

[1] Cf. J. B. Kincer, "Forecasting Crops from Weather Conditions," in *The Problems of Business Forecasting; Papers Presented at the Eighty-fifth Annual Meeting of the American Statistical Association, Washington, D.C., December 27–29, 1923,* edited by W. M. Persons, W. T. Foster, and A. J. Hettinger, Jr. (New York, 1924), p. 265.

[2] P. Broounoff, "Crops and the Weather. Monograph on the Adaptation of Farmers to Climatic Conditions," *Bulletin of Foreign Agricultural Intelligence* (Canada), 1916, VI, 372.

[3] F. Aeroboe, *Allgemeine Landwirthschaftliche Betriebslehre* (Berlin, 1923), p. 450.

[4] J. Warren Smith, *Agricultural Meteorology, The Effect of Weather on Crops* (New York, 1920), p. 166.

[5] J. B. Lawes and J. H. Gilbert, "Our Climate and Our Wheat Crops," *Journal of the Royal Agricultural Society,* Second Series, 1880, XVI, 173 ff.

the average yield of the region.[1] In this connection, it is significant to note that Gericke found that the quantity of nitrogen available to the plant greatly influences the lengths of the different growth periods and that the application of nitrogenous fertilizers has very different effects at different stages.[2] Moreover, Gericke has also shown that the amount of nitrogen available has very great influence on root development.[3] No doubt these factors contribute to the varying effects of rainfall. Finally, rainfall has three other effects of possible significance in the present connection: one is that rain carries air into the soil; another is that rain greatly influences the temperature of the soil; the third is that heavy rains may favor the growth of weeds. Fisher has brought forward evidence to indicate that the evil effects of a succession of wet years may be due in part to excessive growth of weeds.[4]

III. PLANT REACTIONS TO WEATHER FACTORS

How plants react to their environment has been studied by direct observation of crops growing in the field, by observation of plants growing under carefully controlled experimental conditions, and by the statistical analysis of past crops and past weather records. We shall have more to say about these methods of study later. For the moment it is sufficient to note some of the more important known reactions without troubling to ascertain how they were discovered.

Some Pertinent Distinctions

The reaction of plants to their environment has been treated to some extent in the preceding section. It is different at different stages of their development. It is different for different species. One must distinguish especially between annuals, biennials, and perennials. It is obvious that injury done to an annual plant has, ordinarily, more profound effects upon its subsequent life than a similar injury to a perennial, for the annual has but the remainder of the growing season to recover, whereas a perennial, if it survives the injury, may ultimately repair itself in subsequent years. In this study we are concerned solely with annuals.

Furthermore, we must distinguish between vegetative and reproductive growth. Reproductive growth is the production of flowers, fruit, and seed; vegetative growth, the production of all other organs. The laws that govern the two, so far as they are known, are in certain respects quite different. The external conditions that favor vegetative growth do not necessarily favor reproductive growth, and vice versa. It is well known that the rankest-growing wheat field does not necessarily yield the most seed, though it does furnish the most straw. Indeed, for certain plants there is good evidence of the existence of a sort of antagonism between vegetative and reproductive growth.[5] Alfalfa presents a good example. When there is plenty of moisture, a rank vegetative growth is produced; the crop goes for hay. When droughty conditions threaten the life of the plant there is a prolific production of seed.[6] Therefore, in assessing the influence of weather upon crop plants, one must distinguish between those which are cultivated chiefly for their vegetative parts and those which are grown

[1] R. A. Fisher, "The Influence of Rainfall on the Yield of Wheat at Rothamsted," *Philosophical Transactions of the Royal Society of London*, Series B., 1925, CCXIII, 89 ff.

[2] W. F. Gericke, "Certain Relations between the Protein Content of Wheat and the Length of the Growing Period of the Head-bearing Stalks," *Soil Science*, 1922, XIII, 135 ff.; "Differences Effected in the Protein Content of Grain by Applications of Nitrogen Made at Different Growing Periods of the Plants," *ibid.*, 1922, XIV, 103 ff.

[3] W. F. Gericke, "Certain Relations between Root Development and Tillering in Wheat: Significance in the Production of High-Protein Wheat," *American Journal of Botany*, 1922, IX, 366 ff.

[4] R. A. Fisher, "Studies in Crop Variation. I. An Examination of the Yield of Dressed Grain from Broadbalk," *Journal of Agricultural Science*, 1921, XI, 107 ff.

[5] Cf. also discussion on R. H. Hooker's paper ("Forecasting the Crops from the Weather") in *Quarterly Journal of the Royal Meteorological Society*, 1921, XLVII, 249.

[6] J. C. Alter, *Alfalfa Seed Growing and the Weather with Particular Reference to Conditions in Utah* (Utah Agricultural College Experiment Station Bulletin No. 171), 1920, p. 8.

mainly for their seed. The weather that favors one not infrequently is disadvantageous to the other. Crops in the first class are the various sorts of hay, root crops, sugar cane, and tobacco. Crops in the second class include all the grains, flax when grown for seed and not for fiber, the pulses, cotton, nuts, and fruits.

The phenomenon just described is perhaps nothing but a special case of Darwin's law that fecundity is related to the chances of survival; or, in the language of the psychiatrist, the stimulation of reproductive growth by unfavorable conditions may be looked upon as a sort of defense reaction. So long as the parent plant finds living conditions easy, it is under no special urge to reproduce abundantly; the production of small numbers of offspring suffices to insure survival of the species. When, however, living conditions are hard, the chance of survival of offspring is small, and the plant reacts by producing a large number of offspring. On the other hand, all seed crops are very sensitive to injury during the short period of flowering and seed formation, for injury at this period leads to more or less complete loss of the whole crop. Vegetative crops, especially root crops, on the contrary may during drought become more or less dormant; so long as they are not killed, subsequent precipitation can start them growing again so that they yield something and not infrequently considerable quantities if the subsequent weather is very favorable. Hence a seed crop as a rule is more exacting in its meteorological requirements than a vegetative crop.

Stages of Plant Growth

It would take us too far afield to consider in detail the general subject of the physiology of plant growth. So far as that is necessary for present purposes we need consider only certain aspects of some of the stages of growth of the wheat plant. The growth cycle of wheat has been divided into different stages by different investigators. J. Warren Smith recognizes the following "important periods of growth" of wheat:[1] germination, tillering, jointing, heading, blossoming, and ripening. Broonoff gives the following phases for winter cereals:[2] (1) from seeding to appearance above ground; (2) from appearance above ground to the day when the layer of snow becomes firmly established; (3) from the day when the layer of snow becomes firmly established to the period of the thawing of the snow; (4) from the period of the thawing of the snow to heading; (5) from heading to "waxy" maturity (apparently the dough stage of the seed). Azzi, since he made his studies at Bologna, Italy, where snow plays no rôle, reduced Broonoff's phases for spring cereals to three:[3] (1) from seeding time to appearance above ground; (2) from appearance above ground to heading; (3) from heading to maturity.

In the present paper we shall consider five periods, one of which precedes the time of sowing. These divisions are: (1) the formation of the seed to be sown; (2) germination and the formation of the first leaf; (3) growth after the formation of the first leaf to heading; (4) heading and flowering; (5) formation and maturing of the grain.

1. *Formation of the Seed*

It has long been known that the character of the seed has a considerable effect upon the character of the yield. "Spring-wheat seed obtained from farther north will ripen earlier and give a better yield and quality than seed from the same strain ripened farther south. Winter-wheat seed, on the other hand, from points farther south will give better yields than northern grown seed of the same variety."[4] This is true of a number of other crops. Hooker has shown that in England the weather during the maturing of peas and beans has a very great effect on the yield of the crop from this seed.[5] He has also shown that

[1] Smith, *op. cit.*, 1920, p. 186.

[2] P. I. Broonoff, "The Meteorological Bureau and Agricultural Meteorological Stations Directed by the Bureau in 1901," *Memoirs of Agricultural Meteorology* (Petrograd), 1901, No. 1.

[3] G. Azzi, "The Importance of Agricultural Meteorology from the International Point of View," *Bulletin of Foreign Agricultural Intelligence* (Canada), February 1916, VI, 138.

[4] Smith, *op. cit.*, 1920, p. 252.

[5] R. H. Hooker, *op. cit.*, 1921, and "The Weather and the Crops in Eastern England, 1885–1921," *Quarterly Journal of the Royal Meteorological Society*, 1922, XLVIII, 115 ff.

there is a distinct tendency, at least in England, for an above-average crop of winter wheat to be succeeded by one below average, a relation for which he can find no explanation other than some character inherent in the seed.[1]

It follows, then, that study of the reaction of the crop to weather must be extended back into the period of the preceding crop year when the seed was formed. This may be necessary also because, as pointed out above, conditions obtaining for some time before sowing may influence materially the soil moisture available. In England, however, where the rainfall is above the optimum for wheat, Fisher found no correlation between the weather in the months preceding sowing and wheat yields.[2] The study of perennial crops may sometimes have to be extended back even into the preceding year. Thus "a dry and warm June usually precedes a good apple crop the following year. As the fruit buds develop in the preceding year and as wet weather favors active extension growth which is produced at the expense of fruit-bud formation, it follows that a dry and warm June should be favorable for the formation of a good number of fruit buds for the next year's crop. A good rainfall in June produces a large amount of soil moisture when the buds are developing, thus making a preponderance of extension growth and thus a larger percentage of branch and leaf buds and a smaller percentage of fruit buds."[3] In other words, here, too, is an example of the antagonism between vegetative and reproductive growth discussed above.

It is not so easy to explain why the conditions under which the seed of an annual has been formed should influence the yield. Sometimes it is undoubtedly less an effect of weather conditions on the development of the seed than direct injury to the mature or maturing seed, as when there is wet weather after wheat is in the shock causing it to sprout or mold. Wet weather near harvest apparently acts unfavorably in this manner upon peas and beans in England.[4]

In other instances the explanation is unquestionably more subtle. Possibly in these we have to deal with another aspect of Darwin's law that fecundity is related to the chances of survival. Perhaps this aspect of Darwin's law might be formulated thus: When the chances of survival of a species are suddenly reduced, the generation first subject to the adverse conditions responds with the production of offspring with greater vigor or fecundity than their parents, or both. Hooker found for wheat[5] that in England a warm June and July result in the production of good quality of seed but not a great yield.[6] But this law is merely a general statement of observed facts; it is not an explanation.

When we seek for the mechanism involved, it is hard to discover. A number of possibilities suggest themselves. A poor wheat crop is apt to be one in which the individual kernels are light; those of a good crop heavy. If a farmer always plants the same volume or weight of seed to the acre, he will be apt therefore to sow more seeds to the acre when the seed is from a poor crop than when it is from a good one. The result may be that he has a denser stand of plants from the poor crop seed than from the good. This may possibly account for the difference in yield,[7] though it

[1] Hooker, *op. cit.*, 1922. [2] Fisher, *op. cit.*, 1925.

[3] Smith, *op. cit.*, 1920, p. 127.

[4] Hooker, *op. cit.*, 1922. [5] *Ibid.*

[6] Perhaps the quality of crops raised in different regions is an expression of the same phenomenon. The highest qualities of many crops are produced only where conditions are far from optimal (cf. Hooker, *op. cit.*, 1922). The best oranges are grown at the very limits of orange culture (cf. W. G. Reed, "Frost in the United States," *Proceedings of the Second Pan American Scientific Congress*. Section II, Astronomy, Meteorology, and Seismology, 1917, II, 593; also J. E. Corts, *Citrus Fruits* [New York, 1915], p. 25). The better classes of wheat are grown either so far north or at so high altitudes that there is grave danger of frosting, or in regions so arid that there is danger of crop failure. Of course, quality is a man-made concept. It may have nothing whatever to do with any defense reaction of the plant. However, the fact that high-quality agricultural products are produced so frequently only near the limits of possible cultivation is at least significant. It has certain important economic results. The product of high quality is greatly prized; in consequence it brings a relatively high price. The high price of the quality product tends to increase the acreage at or near the possible limits of cultivation. Production in such localities is more hazardous and the hazards color the whole picture of marginal production. These considerations affect also, as we shall see, the problem of forecasting, for where marginal conditions prevail the forecasting problem is not the same as in regions where conditions are at or near the optimum for the crop plant.

[7] *Hearings on H.R. 7401 before the House Committee on Agriculture*, June–July 1921 (preliminary print), p. 109.

is but fair to say that, while agricultural scientists have performed many experiments to determine whether dense or thin sowings and whether light or heavy seed give the best yields, agreement on these points has not yet been reached. Probably there is no one answer, and different results are obtained with different wheat varieties, different soils, and different climates.

Perhaps the explanation is to be sought rather in the fact that most crops are not composed of pure lines, and are therefore aggregations of individuals of varying character. The different individuals even of a pure line show not a little variability. One of the variable characters is undoubtedly ability to resist adverse conditions. Greater resisting powers are no doubt sometimes associated with greater ability to produce seed under adverse circumstances. Consequently, the offspring of the more resistant individuals will be represented in greater numbers in the harvest when conditions are adverse then when they are favorable; and this may have its effects upon the following crop.

Another possibility is suggested by an observation, as yet not published in detail, of H. L. van de Sande-Bakhuyzen in his study of the growth of the spring-habit wheat, Hard Federation, under constant illumination, humidity, and temperature, made at the Food Research Institute.[1] The observations seem to indicate that the extent to which a seedling exhausts the endosperm determines the size of the first leaf. The endosperm, it will be recalled, is the flour-containing part of the seed and constitutes its major portion. In germination the embryo or germ as it develops into the seedling feeds upon the endosperm until the seedling has acquired a root system capable of drawing its material sustenance from the soil. Until the roots begin to function the first leaf is formed at the expense of the reserve food material in the endosperm. It is obvious, then, why there should be a correlation between the degree to which the seedling exhausts the endosperm and the size of the first leaf. But the size of the first leaf profoundly affects the future growth rate of the plant, for reasons which will be made clear below.

We do not yet know what determines whether a given seedling consumes its endosperm more or less completely. It may be that it depends upon purely fortuitous circumstances, such as slight variations in the depth of the seed beneath the soil surface and the like. But it may well be that the power to exhaust the food supply of the endosperm is really inherently different in different individual seeds. It is probably not very closely correlated with size of the seed, for in his experiments van de Sande-Bakhuyzen used seeds of very nearly the same weight. But the ratio of endosperm to total weight may not have been constant. Perhaps it is correlated with the weather conditions prevailing while the seed was formed; but this is merely a speculation to be tested by future research.

2. *Germination and Formation of the First Leaf*

The conditions for germination are a sufficiently high soil temperature and adequate moisture. According to Sachs wheat can germinate at +5°C. (41.0°F.).[2] The maximum is 36° to 38°C. (96.8° to 100.4°F.) and the optimum 20° to 25°C. (68° to 77°F.). If wheat is sown too early in the fall, while the ground is warm, plants may start well but will soon decay. In India it is considered safe to seed when the temperature of the soil has fallen to about 25°C. (77°F.) but not when it is as high as about 30°C. (86°F.).[3] On the other hand, if the seeding is done so late that the soil temperature is so low that germination is slow or does not take place at all, the plant cannot get a proper start before winter sets in. And so a very late summer in the warmer regions of wheat culture or a very early winter in the cooler regions of wheat growing may greatly diminish the yield of winter wheat. A very late spring may delay seeding of spring wheat and so injuriously shorten the

[1] H. L. van de Sande-Bakhuyzen, "Studies upon Wheat Grown under Constant Conditions, I," *Plant Physiology*, 1928, III, 1 ff. Cf. also C. L. Alsberg and E. P. Griffing, "The Objectives of Wheat Breeding," WHEAT STUDIES, 1928, IV, 280.

[2] J. Sachs, "Zur Keimungsgeschichte der Gräse," *Botanische Zeitung*, 1862.

[3] Smith, *op. cit.*, 1920, p. 183.

growing period that the plants become frosted in the fall before the seed is mature. Or, if after seeding the weather turns cold for any extended period, the evil results may be the same.

It seems fairly certain that wheat needs only sufficient moisture during the first six weeks of its life to keep it growing vigorously.[1] Too much moisture may under some circumstances be unfavorable.[2] On the other hand, so is too little. If the fall is very dry, the wheat may be so delayed in germinating that cold weather overtakes it before the plants have established themselves.

The time that elapses between seeding and the emergence of the plant varies with the variety and with the environmental conditions of which soil temperature and moisture seem to be the most important. In northwestern Ohio it averages nine days.[3]

Furthermore, as indicated in the preceding section, the manner of germination of spring wheat is very important, since it determines the size of the first leaf. But the size of the first leaf determines the size of the second leaf, and the first and second leaves together determine the size of the third, and so on, till in the end the size of the first leaf determines the size of the plant itself. These close interrelations are the consequence of the manner in which green plants supply themselves with energy by photosynthesis. As has already been pointed out, the extent of the leaf area is the principal factor determining how much carbonaceous food is available to the plant for synthesis and growth. Now we see why the size of the first leaf of spring wheat, which has a short growing period and produces only a small number of leaves, determines the rate of subsequent growth. If the first leaf is small, it can make only a small amount of sugar and furnish, therefore, only a small amount of food for the growth of the second leaf; the second leaf will also be small. If on the contrary, the first leaf is large, it will make much food available for the formation of the second leaf and this also will be large. As the second leaf begins to function, it too synthesizes sugar and contributes to the supply of food available for the formation of the third leaf. If both the first and second leaves are large, the third leaf will, therefore, be large, and this cumulative process will go on with the formation of each new leaf affecting in the end the size and vigor of the fully grown plant.

Whether the same phenomena occur in winter wheat has not yet been investigated. It is to be anticipated, however, that, in all probability, if the same relations between exhaustion of the endosperm and size of the first leaf hold also for winter wheat, the final effect upon the plant as a whole is likely to be much less than is apparently true for the spring-habit wheat, Hard Federation. Winter wheat has a much longer growing period. Differences in assimilation rates, i.e., in photosynthesis, should produce less pronounced effects. Moreover, it tillers[4] much more vigorously than spring wheat, so that finally a single seed forms a clump. Whether such a clump is an individual or a colony, is by no means certain.[5] In either case, the clump is almost sure to reflect the condition of the seedling six or eight months previous much less than does the spring-wheat plant with only a few tillers and a very much shorter growing period. The fact that winter wheat may sometimes be pastured during the winter without ruining the crop is evidence in support of this view.

3. *From the Formation of the First Leaf until Heading*

During this period, the longest in its life, the wheat plant (spring or winter) is apparently far less sensitive to weather conditions than during the period of germination. In the earlier stages of the period immediately following germination and emergence of the plant it seems more susceptible to adverse influences generally

[1] Smith, *op. cit.*, 1920.

[2] R. H. Hooker, "Correlation of the Weather and Crops," *Journal of the Royal Statistical Society*, 1907, LXX, 1 ff; Fisher, *op. cit.*, 1921.

[3] Smith, *op. cit.*, 1920.

[4] By tillering is meant the habit that wheat shares with many other grasses of dropping some of its branches to the ground and so growing roots at the nodes or joints of the branches.

[5] F. L. Engledow and S. M. Wadham, "Investigations on Yield in the Cereals," *Journal of Agricultural Science*, 1924, XIV, 71 ff.

than in the later ones. It is especially important that a good root system be developed early and that tillering be good—especially with winter wheat. Too little moisture and too low soil temperatures are unfavorable, although, as we shall see, moisture requirements vary. In some regions there is rarely too little, and often too much; in others there is rarely too much, but often too little. A strong root system is obtained with only a moderate amount of moisture, but strong tillering seems to require somewhat more. Early tillering is important so that the plant may soon cover the ground and thus fight weeds more successfully. Too early sowing, however, if October is warm, increases the danger from the Hessian fly in many sections of the United States.

Growth of winter wheat through the winter is subject to certain unfavorable environmental conditions. In very humid climates too much moisture is unfavorable.[1] In other dryer climates there is danger of winterkilling, which will be discussed at greater length later. A dry April seems to be unfavorable to Hessian fly damage.[2] In regions with mild winters, warm weather seems favorable,[3] for in such climates considerable growth may be made, when warm days occur. Haberlandt gives 4.5° C. (40°F.) as the minimum temperature for the growth of wheat, and Azzi in studying the effect of winter weather upon wheat assumed that there is suspension of growth when the average temperature in the daytime is less than 4° C. (39.2° F.).[4]

For spring wheat the principal things to note are that moisture and temperature conditions apparently, so far as they exert an influence, act by lengthening or shortening the period under discussion. Connor believes the longer the interval between emergence and heading,[5] the greater the yield, and finds a positive correlation between the yield of straw and the length of the period from appearance to heading. There should, therefore, be a positive correlation between the yield of straw and the yield of grain, yet this seems to be true only for small and large yields of grain, intermediate yields of grain varying independently of the yield of straw.

On the whole, however, most investigators have found that the wheat plant shows relatively little response to variations in weather conditions in the period under discussion provided these variations are not extreme. It should be noted, however, that some have regarded the period immediately before heading, as we shall see, as one in which the wheat plant is quite susceptible to the weather.

4. *Heading and Flowering*

It is now very generally agreed that cool weather and plenty of moisture at the time of heading or flowering are favorable to good crop yields, at least in climates that are not too humid. Opinions differ in regard to the exact stage at which these conditions should prevail. Some think they should prevail just as the plants are beginning to head, others between the boot and bloom periods, and still others between the bloom and milk stages.[6] It seems quite well established that high temperature and lack of moisture at the time of blooming tend to produce sterile heads. This tendency is aggravated if at the same time there are high winds which increase the already high transpiration.

Broonoff found the ten days before heading most important, rain being needed at that time.[7] He studied wheat by five-day periods which he called "pentads." Azzi also examined short periods[8] and reached the same conclusion for Italy that Broonoff did for Russia. Azzi found that rain within ten days before and during heading and flowering is very favorable. Unfortunately, his series of observations covered a very short period—only five years. He found further that lack of rain during the above period may be compensated for, if

[1] Hooker, *op. cit.*, 1907.

[2] W. R. Walton, *The Hessian Fly and How to Prevent Losses from It* (U.S. Department of Agriculture Farmers' Bulletin 1083), March 1920.

[3] Hooker, *op. cit.*, 1907.

[4] G. Azzi, "The Influence of Meteorological Factors on the Yield of Wheat in the Province of Bologna, Italy," *Bulletin of Foreign Agricultural Intelligence* (Canada), March 1916, VI, 227.

[5] Connor, *op. cit.*

[6] Cf. Smith, *op. cit.*, 1920, p. 191.

[7] P. I. Broounoff, *Les Cultures Agricoles et le Temps* (Petrograd, 1912).

[8] Azzi, *op. cit.*, February 1916, p. 141.

there is enough rain in the preceding ten days to carry over.[1] Most other investigators have studied the effect of weather during intervals longer than five or ten days. Since the flowering period is brief these investigations have not been able to settle the question whether the critical time is before, during, or after flowering. They have merely determined the general time when plenty of moisture and cool weather are important. Broonoff is quite right in believing that most can be learned by studying successive five- or at most ten-day periods of growth.

The situation is further complicated by the fact that wheat does not each year head and flower at the same calendar date. Connor, writing of Canadian conditions, puts it thus: "Now the time of heading of wheat is a moving point, the motion inverse to the minimum temperature, and therefore any selected periods in days before heading, if expressed in terms of age of plant, is itself a variable depending on the weather since appearance."[2] Most investigators have lacked data on the exact time of heading and flowering; they have usually had data merely on the temperature day by day, the rainfall day by day, and the yields. They have rarely had data on the exact time of heading and flowering. Therefore, their conclusions have had to deal with the general rather than with the precise stage of growth of the plant.

A further consequence of the fact that so long a period is commonly studied is that no satisfactory answer has been given to the question why the heading and flowering period demands cool temperatures and moisture. Of course, it is assumed that in general there is some relation with increased transpiration but most investigators make no attempt at an explanation. Connor, however, offers one.[3] He is of the opinion that if in the earlier stages of the wheat's growth there be cool and rainy weather, the heading will be delayed and the subsequent yield will be heavy, but if the weather be warm and dry, heading will be hastened and the subsequent yield light. This he explains by the assumption that at any instant the height of the straw is a measure of the total nutriment received. But since a portion of this nutriment is expended in producing the straw, and a part expended in the energy of the life processes, the total will not be directly proportional to the yield in grain. Connor suggests tentatively that the amount of starch stored varies with the water transpired, a hypothesis that would explain the findings of Thatcher[4] that less starch is formed in shade-grown plants. Furthermore, Connor, perhaps, gave more importance to growth conditions in the earlier stages than do most other investigators because he studied growth by thirty-day periods, which are much too long to make possible the recognition of special conditions at the time of heading and flowering.

Connor is right, however, in his endeavor to put the phenomena upon an underlying physiological basis, as has been shown recently at the Food Research Institute by van de Sande-Bakhuyzen,[5] who was able to show that at the time of flowering there is a great increase in transpiration without any change in the environment whatever. This definitely fixes flowering as the most exacting period of those now under consideration—at least for the wheat van de Sande-Bakhuyzen studied, Hard Federation. These experiments explain why this period is so critical. If transpiration increases greatly there is a tendency to disturb the water balance of the plant. The demand upon the roots for moisture is increased. The roots have difficulty in meeting it. Anything that diminishes transpiration, such as cool, overcast, humid weather, diminishes the demand upon the roots; and, conversely anything that increases transpiration, such as hot, dry, windy weather, increases the demand upon the roots. If transpiration becomes too great, the roots are overtaxed; they supply the plant with less water than it loses by transpiration; the plant dries out, and is injured. Van de Sande-Bakhuyzen was

[1] Azzi, *op. cit.*, March 1916, p. 227.

[2] Connor, *op. cit.*

[3] *Idem.*

[4] R. W. Thatcher, *A Report of the Investigations Concerning the Chemical Composition of Wheat, 1906 to 1912 Inclusive* (State College of Washington Agricultural Experiment Station Bulletin No. 111), 1913.

[5] H. L. van de Sande-Bakhuyzen, "Studies upon Wheat Grown under Constant Conditions, II," *Plant Physiology*, 1928, III, 7 ff.

able to show that under environmental conditions that may be considered normal and under which the roots are quite up to the task of supplying the plant with all the water it needs, the water balance is disturbed when the plant flowers. Indeed, he was able to show that under these apparently normal conditions the percentage of solids in the plant increases; in other words, the plant undergoes some degree of dessication, to its undoubted injury. The significance of this injury will be discussed below.

5. *Formation and Maturing of Grain*

As has been stated in the preceding paragraphs, it is probable that at the time of flowering there is more or less dessication of the wheat plant and a corresponding injury. From this dessication the plant apparently is unable to recover completely, for the ratio of solids (dry weight) in the plant to water continues to increase, ultimately leading to the death of the plant. Other things being equal, the moment of death depends, therefore, first, upon the degree to which the plant has been injured at the time of flowering and, second, upon the environmental conditions prevailing in the period following flowering. If these are such as to favor an abnormally high transpiration rate, then the progressive dessication of the plant will be comparatively rapid and the survival period correspondingly short. Very hot, very dry, and very windy weather must, therefore, tend to shorten the survival period. If on the contrary, environmental conditions are such as to favor the restoration of the water balance, then dessication will be slower and the survival period correspondingly longer. Rainy, cool, humid weather, therefore, must tend to lengthen the survival period.

The length of the survival period after flowering must be an important factor in determining yields. It is obvious that if the period is long there is more time for the deposition of material in the seed than if it is short; the kernels must be larger, better filled, and plumper, with correspondingly favorable effects upon yield. Cool, humid weather during the earlier stages of ripening must be favorable for good yields, though apparently far less important than during flowering. Indeed, too much moisture toward the end of the ripening period, especially at harvest, may be unfavorable.[1]

Furthermore, the length of the survival period after flowering seems to influence the chemical composition of the grain. There is good reason to believe that the protein percentage of the wheat berry depends for a given variety, in part at least, upon the length of the ripening period.[2] It is further generally believed that in the formation of the wheat berry the nitrogenous material, or protein, is laid down in greater proportion than the starch in the earlier portion of the period in which the berry is formed. In the later portion relatively more starch is laid down.[3] Indeed, for a given wheat variety, the total amount of starch so stored seems to be far more a function of the length of the survival period than is the total amount of protein. Grain that is hastened toward maturity or stopped from reaching maturity, as by an early frost, is liable to contain a relatively high percentage of protein and a relatively small proportion of starch. Such grain is liable to be small-kerneled, shrunken, or shriveled. On the other hand, if the survival period is long, there is ample time for the maximum of starch to be deposited in the grain. The kernels, while containing very nearly the same absolute amount of protein, show a lesser percentage because there is so much more starch in them. They are liable to be relatively large, plump, and well filled. Naturally, such grain is heavy and the yields are correspondingly large.

We have seen, then, that the character of the grain and the weight of it produced are, among other things, a function of the length of the survival period. We have also seen that the length of this survival

[1] Cf. Hooker, *op. cit.*, 1907; also under "Formation of the Seed," above, p. 13.

[2] F. W. McGinnis and G. S. Taylor, "The Effect of Respiration upon the Protein Percentage of Wheat, Oats, and Barley," *Journal of Agricultural Research*, 1923, XXIV, 1041; also Thatcher, *op. cit.*

[3] However, W. E. Brenchley and A. D. Hall believe there is a continuous flow of nitrogen into the berry to maturity ("The Development of the Grain of Wheat," *Journal of Agricultural Science*, 1909, III, 195 ff.), and suggest that the nitrogen percentage depends upon the amount of carbohydrate lost by respiration. However, McGinnis and Taylor (*op. cit.*) have shown that such losses are too small to be determining.

period is in large measure a function of the injury done the plant at the time of flowering and in lesser degree a function of conditions afterward. Hence the period of flowering is a very critical one for the plant; and the length of time a given variety is able to survive after flowering in any given locality is a most important characteristic since it affects yields.

Critical Periods

There is, then, perfectly definite evidence established by physiological experiments to show that there are at least two important critical periods when the weather should be more important than at other times. One is the period of germination and formation of the first leaf; the other is the period of flowering. Statistical studies of various sorts and of varying degrees of excellence, that have aimed at the investigations of the relation of weather and crops, either indicate that in fact at these times weather influences are especially pronounced or else are not inconsistent with the expectations one would entertain on physiological grounds. Much of the statistical evidence as such would hardly justify this conclusion because of the limited value of the methods used, but the statistical evidence, supporting, as nearly all of it does, the experimental evidence, indicates that we have to deal with real phenomena of practical importance.

That two critical periods have been recognized for wheat does not signify that there are no others and least of all that the weather is a matter of indifference except at the critical periods, but merely that deviations from the optimum must be much greater at other than these two critical periods to affect yields greatly.[1] Thus in Ohio neither the precipitation throughout the season nor the temperature in the fall or summer seems to be a determining factor for winter-wheat yields; whereas a warm March has a most decisive, favorable influence,[2] and a late snowfall is injurious.[3] No similar correlation has been obtained in other states. Indeed, the reputed favorable effect of a snow covering during the winter months seems to be much less important than is commonly believed, at least in many sections of the United States.

Which of the two known critical periods of the wheat plant is the more important possibly depends on local conditions. Where the summer is usually cool and humid and the fall often too wet or too dry or too cold or too warm, the germination period seems to be the more critical. Where the summer is often hot and dry the plant seems to be exposed to the greater hazards at the flowering period. In some regions there is little to choose in regard to the hazards of either period. Where seeding and flowering time present nearly optimal conditions neither period may seem critical. Rather will some other period seem more important.

The term "critical period" needs now to be considered critically. The concept seems to be due to Russian investigators who first gave it precise form, though the general idea is of course an old one.[4] Broonoff, Gauer, and Parlman seem to have been responsible for introducing the concept in a practical way. Unfortunately the term is used loosely in two rather different ways: sometimes it refers to a definite stage of the plant's development; sometimes to a definite calendar date. The term should really be used only to designate the critical period of the plant's development and not a calendar period, for a calendar period is fixed, whereas the date on which a plant reaches a critical period of its development is not.[5] The confusion that arises from lack of realization of the difference between these two concepts has been a serious handicap to the scientific development of forecasting. It would be desirable to

[1] Cf. R. H. Hooker, "The Weather and the Crops in Eastern England, 1885–1921," *Quarterly Journal of the Royal Meteorological Society*, 1922, XLVIII, 134 ff.: "Sometimes a very big excess or deficiency at a somewhat less important period can overweigh a small deviation at the normally critical period."

[2] T. A. Blair, "A Statistical Study of Weather Factors Affecting the Yield of Winter Wheat in Ohio," *Monthly Weather Review*, 1919, XLVII, 841 ff.

[3] Smith, *op. cit.*, 1920, p. 262; also "Effect of Snow on Winter Wheat in Ohio," *Monthly Weather Review*, 1919, XLVII, 701 ff.

[4] Mawley, (*op. cit.*, p. 74), for example, writes, "There are two critical periods when fine weather is of the greatest importance [to wheat]; the first when it is coming into flower, and the other at harvest time."

[5] Cf. Connor, *op. cit.*

have two different terms for the two concepts, say "critical stage" and "critical time" (pentad, decad, or month). Hereafter, the term "critical stage" will be used.

Weather Factors at Non-critical Stages

Except where weather factors are near the optimum at critical stages, as in the case of winter wheat in Ohio cited above, the weather conditions must be rather severe at non-critical stages to exert anything like the influence that is exerted by much less severe weather at the critical stages.

Under some circumstances extreme weather may act indirectly either by favoring disease or insect attack or by some form of mechanical injury, rather than by direct action upon the vital processes of the plant. Thus in some sections abnormally wet weather before heading may be injurious by favoring rust attack—whether by creating favorable conditions for the fungus or lowering resistance of the plant physiologically is not yet quite certain.

Furthermore, in some regions the character of the winter weather is important to winter wheat, but this may be due in large measure rather to physical conditions that lead to winterkilling than to a physiological reaction of the plants.

Winterkilling may be caused by any one of four factors: heaving, smothering, freezing, and physiological drought. *Heaving,* which is common in the eastern United States, is due to alternate thawing and freezing; the soil expands, lifting the plants so that the roots become exposed. *Smothering* occurs when the ground is covered with an ice sheet. *Freezing* is most apt to occur when a mild spell is followed by a sharp, severe drop in temperature. *Physiological drought* occurs sometimes in winter because plants are unable to preserve their water balance. In cold weather the humidity is low and the air is very dry. At the same time the ground may be frozen, so that the moisture is not readily available.[1]

It is not proposed in this study to enumerate and analyze all the weather factors that may affect yields at non-critical stages —many of them are not understood. A few of them have been set forth largely as examples.

IV. SOME INTERRELATIONS OF GROWTH FACTORS

Liebig's Law of the Minimum

The occurrence, at least in theory, of optimum growing conditions raises certain interesting questions in regard to the nature of optima and of limiting factors. Liebig many years ago propounded his law of the minimum for those constituents of the soil that the plant uses. This law runs to the effect that the growth of plants is limited by that mineral ingredient of the soil necessary for growth which is present in least amounts. If a single mineral ingredient is available in inadequate amount it is this ingredient that determines growth even though all other ingredients be present in surplus.[2] Liebig's law of the minimum no longer commands quite the respect it formerly did, now that more is known concerning soil flora and fauna and concerning the occurrence in soils of substances toxic to plants. Indeed in certain respects its validity has been challenged.[3] Whatever the justification for the questioning to which Liebig's law has been subjected in recent years, the law does express a general truth, viz., that there are individual limiting factors for crop development. This is probably merely a special case of the universal biologic law of the threshold: an organism does not react to an environmental factor until that factor reaches a certain dimension, whether in intensity, in quantity, or what not.

[1] J. Warren Smith, *Agricultural Meteorology, The Effect of Weather on Crops* (New York, 1920), p. 209.

[2] Justus von Liebig, *Die Chemie in ihrer Anwendung auf Agricultur und Physiologie. Zweiter Theil, Die Naturgesetze des Feldbaues.* Achte Auflage (Braunsschweig, 1865), p. 223, "Ein jedes Feld enthält ein Maximum von einem oder mehreren und ein Minimum von einem oder mehreren anderen Nährstoffen, mit diesem Minimum, sei es Kalk, Kali, Stickstoff, Phosphorsäure, Bittererde, oder ein anderer Nährstoff, stehen die Erträge im Verhältnisz, es regelt und bestimmt die Höhe, oder Dauer der Erträge."

[3] E. A. Mitscherlich, "Das Wirkungsgesetz der Wachstumsfaktoren," *Landwirthschaftliche Versuchstationen,* 1921, XCIX, 133.

Limiting Factors of the Weather

Liebig propounded his law for the mineral plant foodstuffs in the soil. Undoubtedly, it holds as much for other environmental factors as well, the factors that in their totality make up the climate and the weather. And so agricultural meteorologists are fully justified in writing of limiting weather factors. It is obvious that there must be a lower limit of soil moisture below which seeds will not germinate. There must be a lower limit of rainfall below which a zero yield is obtained. These considerations of limiting factors are important in the statistical treatment of crop and weather data, as is pointed out in a subsequent section.

Liebig recognized that growth is the resultant of many factors. Increasing the minimum factor is effective in increasing yield only up to the point at which this factor is now present in correct proportion to the other necessary factors. If increased above that level, then these added increments are without favorable effect. Some other factor has now become the minimum.[1] Conversely, decreasing a given factor has a similar effect, for it may change the factor that is minimum. A striking example of an indirect effect of this kind has been demonstrated by Fisher[2] who found that excessive rainfall acts upon wheat in England principally by removing nitrates from the soil and somewhat by favoring the growth of weeds. The effect of rainfall there is dependent, in consequence, upon the amount of nitrate in the soil, i.e., upon the state of fertilization.

It follows further from these considerations that it is altogether unlikely that yields are directly proportional to increase in any single factor. The effect of each factor is modified by the character of the rest. It is questionable, therefore, whether, as a practical matter, one is ever justified in speaking of an optimum condition for crop production as a fixed and absolute constant. If the effect of each environmental factor is in part a function of all the other factors that make up the environment, then the optimum for that factor must be a variable. One is, therefore, not justified in saying that the optimum rainfall for wheat is so many inches; one is justified only in saying that for the average conditions prevailing in a given region the optimum rainfall is thus and so.

That there can be strict proportionality only over a very narrow range of variation of a single factor has also important implications for the statistical analyses of crop yield and weather data, as we shall see. There is abundant evidence in the literature that strict proportionality between variations in weather factors and variations in crop yields is not necessarily found. The fact that relatively large changes about the optimum have relatively small effects is such evidence. Hooker has pointed it out for weather conditions in England as they affect wheat.[3] Another case in point is the statement of J. Warren Smith[4] that in the corn belt there is a critical July rainfall value of about 3 inches. If the rainfall is much less than 3 inches a small increase does not increase the yield of corn (maize) nearly as much as the same increase when the rainfall is already 3 inches or more.

A further complication that arises from the lack of direct proportionality in the response of plants to quantitative changes in individual environmental factors is that the response to deviations from the average of local weather conditions is different according as this average is close to or far removed from the optimum. The extreme case is, of course, the locality where there is always danger of crop failure. The Great Plains area of the United States and Canada is a region of this kind. Chilcott has shown definitely that in this area crop yields are not directly proportional to rainfall.[5] Barkley has reported a similar lack of proportionality for Victoria.[6]

[1] Liebig, *op. cit.*, p. 227, "Um diese Thatsachen richtig zu verstehen, musz man sich daran erinnern, dasz das Gesetz des Minimums nicht für einen Nährstoff allein, sondern für alle gilt; wenn in einem gegebenen Falle die Ernten an irgend einer Frucht, begrenzt sind durch ein Minimum von Phosphorsäure im Felde, so werden die Ernten steigen durch Vermehrung der Phosphorsäuremenge bis zu dem Punkt, wo die zugeführte Phosphorsäure im richtigen Verhältnisse steht zu dem jetzt vorhandenen Minimum an einem anderen Nährstoffe."

[2] Fisher, *op. cit.*, 1921. [3] Hooker, *op. cit.*, 1922.

[4] J. Warren Smith, "Agricultural Meteorology," *Proceedings of the Second Pan American Scientific Congress.* Section II, Astronomy, Meteorology, and Seismology, 1917, II, 75 ff.; *Agricultural Meteorology, The Effect of Weather on Crops* (New York, 1920), p. 153.

[5] Chilcott, *op. cit.*

[6] H. Barkley, "Climatic Controls and World Prices," *Wheat and Grain Review* (Melbourne), 1927, VII, 8 ff.

The varying response of the wheat crop to changes in weather factors in different climates is illustrated by the results obtained in a preliminary study of the correlation of yields and rainfall in the state of Kansas, which, while not definite enough to justify positive conclusions, is suggestive.[1] In eastern Kansas the annual rainfall ranges, roughly, from 30 to 40 inches; in central Kansas from 20 to 30 inches; in western Kansas from 15 to 20 inches. Statistical analysis of weather and yield data for eastern Kansas indicates a tendency to excessive rainfall with detrimental effect on the yield especially when the May and June precipitation is increased. In central Kansas, on the contrary, increased rainfall tends to be favorable, except in June.[2] In western Kansas when suggestive results were obtained they tended to show that increased rainfall was at no time unfavorable and that it was usually positively favorable. This is in harmony with the conclusions of others from field experiments. Call and Hallsted find moisture the limiting factor in the production of wheat in western Kansas.[3] The most important single factor is the amount of available soil moisture at seeding time, though this does not alone insure a good crop because of the not infrequent occurrence of drought and hot, dry winds in spring and summer.

Importance of Phenological Records

As has been pointed out above, plants pay but little attention to the calendar; they germinate, blossom, ripen their seeds according to the season, not according to the calendar. The progress of the seasons is different from year to year and from locality to locality, so that seeds germinate, flowers bloom, and fruits ripen on different dates in different places and in different years at the same place. To be sure, there is an average date in each locality for each phenomenon, but in a given region in a given season the deviation from the average date may be considerable. That branch of agricultural meteorology concerning itself with the determination of data of this kind is known as phenology. The importance of keeping phenological records can hardly be overestimated and the necessity for the expansion of this sort of work by the United States Department of Agriculture and the several colleges of agriculture cannot be urged too strongly.[4]

Unfortunately, comparatively little is known of the average dates when crop plants enter upon their different stages of growth in the different regions of the United States or of the deviations from the average dates from year to year. Agricultural meteorologists in studying the relation between crop records and weather records are compelled to compare the weather at certain dates rather than at certain stages of a crop's development. Often these comparisons are made by months or weeks, but these are wholly arbitrary divisions which need not necessarily correspond to any physiologically circumscribed period of plant growth. As we have seen, critical stages may be of quite short duration. In such cases, much more numerous data are necessary for the recognition of effects, if the weather is analyzed month by month, than if short periods are taken. Even ten-day periods or weeks may prove too long intervals for clear results if the critical stage happens to begin at the end of one period and to last into the beginning of the next.

When phenological data are not available, it is sometimes possible to compensate for their lack on the assumption that if in a given year the season is late, plants will bloom and ripen seed at a later date than the average, and that, conversely, if the season is early, plants will bloom and ripen seed earlier than the average. If one knows from weather records how much earlier or later, as the case may be, the seasons have been in the different years, one can apply appropriate corrections to the dates at which the weather factors are correlated with yields. An index of earliness or lateness of the season that may be employed for this purpose is the last killing frost in spring. If one also knows the average daily

[1] This unpublished study was made at the Food Research Institute by Susan Burr.

[2] H. B. Laming, as stated by J. Warren Smith (*op. cit.*, 1920, p. 206), however, obtained results in correlating rainfall and wheat yields in central Kansas that are less easily understood.

[3] L. E. Call and A. L. Halsted, *The Relation of Moisture to Yield of Winter Wheat in Western Kansas* (Kansas State Agricultural College Agricultural Experiment Station Bulletin No. 206), May 1915.

[4] More attention is now being paid to the keeping of such records in the U.S. Department of Agriculture. Cf. Callender, *op. cit.*

temperature rise in the spring months, one is in a position to apply a correction for earliness or lateness of the season. Thus, in Utah the average temperature rise is about one degree every four days in March and April and one degree in three and one-half days in May. On this basis, starting from the date of the last spring frost, the earliness or lateness of the season might be calculated and appropriate corrections applied to the dates through the growing season.[1] Another method of correction might be developed from a consideration of whether the accumulated temperatures (see p. 28) are above or below the average. However, such corrections are rarely made in published scientific studies on the relation of weather to crop yields. In view of this, and, among other things, of the fact that the correlations are made with calendar dates rather than with stages of plant growth, it is difficult to harmonize all the findings of investigators concerning the effects of weather on a given crop.

Reasons for Conflicting Results

The considerations presented in this section give the key to the puzzle presented by the conflicting statements of competent scientists that their findings indicate that this or that set of weather conditions in this or that month are favorable or unfavorable to high yields in this or that region. These conflicts arise from the facts that calendar dates do not correspond to the same stages of growth from year to year; that optima are probably variable from year to year; that optima are different in different climates; that the responses to environmental variations are not necessarily quantitatively proportional; that responses vary according as conditions of growth are close to or far removed from the optimum. One is not justified, therefore, in saying that wheat demands a specified climate; rather one is justified in saying that wheat thrives in a certain rather wide range of climates. To bring together all the statements that have been made concerning the climatic requirements of the wheat plant is, therefore, of little value and will not be attempted in this study. To do so would lengthen this paper needlessly and would contribute comparatively little to the reader's understanding of the subject, if indeed it did not confuse him.

V. METHODS OF FORECASTING YIELDS FROM THE WEATHER

There are two different types of data that may be used to forecast yields from the weather: data obtained by experiment and data obtained by experience. The former are derived from exact scientific experiments upon the reaction of plants to weather factors. The latter are the weather and crop data of the past, and the yield to be expected in a given year with given weather is deduced by statistical methods from the experience of the past. One might be called the experimental method; the other the statistical method. The two methods are at once corrective of and supplementary to one another. Naturally, the distinction between them is not sharp. Every experiment is an experience, and data obtained by experimental methods often require statistical analysis in order that valid conclusions may be drawn from them.

Experimental Methods

The experimental methods endeavor to establish the laws that govern the growth of plants, for if these be known, the reaction of the plant to any environment is known. If the laws were known that govern the growth of the crop plant—the optimum supply of foodstuffs, of light, of moisture, of warmth; the reactions to deviations from the optima at each stage of development; etc., etc.—it would only be necesary to ascertain what the environment has been up to the time at which the forecast is made and the prophecy becomes a simple matter of computation.[2] The principal uncertainty in such a prophecy would be the possibility that during the remainder of the growing season the weather might not be optimal. The prophecy would thus be subject to a probable error ascertainable with considerable exactness from the weather records over a series of years past. The nearer the date of prophecy to the date of harvest, the smaller would this probable error be.

[1] Alter, *op. cit.*, p. 17.

[2] It must, however, be borne in mind that the optimum environment for the plant is not necessarily best for farm operations.

There are two methods that may be used to discover the laws of growth of plants. One is to grow the plant in the same locality for many years, recording carefully at the same time in detail when it passes through its different stages of development and finally recording the yield. Coincident with these observations, careful, detailed records are made of the environment, such as rainfall, temperature, hours of sunshine, wind velocity, humidity of the atmosphere, soil temperature, soil moisture. After such records have been kept for many years, yields are compared with the environmental conditions prevailing at different stages of growth and conclusions drawn concerning the kind of conditions that accompany large or small yields. These conclusions may be made the basis of forecasting. This method might be called the method of field experimentation.

The second method might be called the method of laboratory experimentation. The plants are grown under perfectly standard, controlled conditions so that the environment is known in all its factors from germination to seed formation. Throughout, observations and measurements are made upon the plants and the yield determined. If conditions are kept constant and optimal during the entire period, one is enabled to discover the normal rate of growth and one is able to plot that rate as the growth curve. If conditions are kept optimal and constant except for one factor, say soil moisture, which is made to vary, one is able to determine how soil moisture affects rate of growth and yield and one is able to fix the lower and upper limits of soil moisture below or above which, respectively, the plant is injured. And this may be done similarly for every other known growth factor.

The laboratory method has the advantage that it does not take decades to learn many of the fundamental laws that govern the growth of plants. It has the advantage that it enables one to determine what influence each of the many factors, the totality of which is the environment, has upon the plant. It has the disadvantage that it is doubtful if it is possible to reproduce in the laboratory exactly the conditions in the field, such as, for instance, crowding, the soil flora and fauna, insect, worm, and fungus attacks.

The field experiment method has the advantage that the plants are grown very nearly under the same condition as in large-scale crop production. It has the disadvantage that it is decades before one can have confidence in the results. It has further the disadvantage that since the range of variability of environmental factors in any one locality is restricted, field experiments must be carried on in many localities over a wide expanse of territory. Again, it has the disadvantage that since there is so large a number of variables in the environment it is extremely difficult to tell which of the many factors was responsible for the result.

Unfortunately, to discuss the method of forecasting yield from a thorough knowledge of the plant's reaction to its environment is as yet largely academic, since there is hardly a crop plant, the life history of which, so far as its laws of growth are concerned, is thoroughly known. The method is discussed here, nevertheless, in the hope of stimulating plant physiologists to concentrate more than they are now doing upon the study of the laws of growth of the more important crop plants; for this method, of all those that have been proposed, furnishes the most logical and the most accurate basis for forecasting. Probably thoroughly reliable methods of crop forecasting will not be achieved until research upon the physiology of crop plants has given us fairly complete information concerning their life history.[1] It may seem a long way 'round to achieve success by this route, but perhaps it will be found to be the shortest road in the end. This is not to be taken to mean that we know next to nothing about the effects of weather upon crops. The meteorological requirements of a number of crops are more or less well known but this in itself does not furnish a deep insight into their laws of growth. If growth laws were known the reasons for certain meteorological requirements would be known both qualitatively and quantitatively.

Though the laboratory method gives the more basic information it has been em-

[1] Engledow and Wadham (*op. cit.*, p. 287), in discussing breeding for high yields, express the opinion that a successful analysis of growth would afford an analysis of yield and that it is quite patent that yield must continue to be imperfectly understood so long as growth remains unanalyzed.

ployed much less frequently than the field method. The reason is simple: it requires highly trained scientists and quite elaborate equipment. Field experiments on the contrary may be conducted without the help of a highly trained personnel. Highly trained scientists are needed only for general supervision and for the analysis of the data. Moreover, field experiments serve certain immediate practical purposes and it is for such purposes rather than for forecasting that they have commonly been performed.[1] It is not astonishing, therefore, that the normal growth curves of crop plants are but imperfectly known. For the Hard Federation variety of spring wheat it has recently been determined at the Food Research Institute.[2] The extension of work of this kind is of extreme importance as certain to furnish in the end a scientific basis for forecasting. It should be undertaken by governmental agencies.

Despite the many practical uses, other than forecasting, to which the results obtained by the field experiment method may be put, there are but few countries in which this method has been exploited adequately. It is true that in very nearly every agricultural experiment station in the world small plots of crop plants are grown and carefully observed while at the same time weather records are kept. Mostly, however, the experiments have other purposes than to contribute to the improvement of methods of forecasting. The data have rarely been used for this purpose, although at times they have been published in sufficient detail to be inherently useful for this end. To be useful for the development of methods of forecasting, field experiments should be continued under the same experimental conditions for many decades. There are very few places in the world where this has been done; possibly Rothamsted is the only place, and even there the primary purpose was to determine the effects of continuous cropping and of fertilizers. The collection of meteorological data, at any rate during the earlier years, seems to have been limited to the more simple measurements.[3] Even so the experiments yielded interesting results suggestive for forecasting purposes;[4] but it was not until 1925 that the data were subjected to adequate analysis[5] that showed brilliantly not merely the results that may be achieved by statistical methods but also the fundamental value of long-continued field experiments.

Fundamentally important as the English investigations have turned out to be, it was in Russia, apparently, that field experiments designed to furnish information useful in forecasting were first deliberately inaugurated with the authorization of the Russian Bureau of Agricultural Meteorology in 1894 under the directorship of P. Broonoff.[6] This Bureau began operations in 1896 and by 1912 had 81 different stations where meteorological records were being kept near to test plots of growing crops. R. W. Mills began investigations of a similar character in Canada in 1915.[7] Our own Department of Agriculture planned to establish a similar program of research in 1914, but first the war and later the administration's policy of economy prevented the appropriation of adequate funds to make such a vitally important national program possible.[8] Very recently some phenological investigation has been begun,[9] but the work of the Department, though of very great value, hitherto has had to be limited very largely to the use of the statistical method (see below). The situation should be remedied speedily, since results from field experiments are obtainable only after observations have been made over a long period of years. The Rothamsted series has extended over more than 60 years and is by

[1] One of these practical purposes of interest in the present connection is that the experimental plot may be regarded as a sample of the entire crop area and used in estimating the yield for a considerable area. Lawes for many years estimated the wheat yield for England with considerable success from the produce of the standard experimental plots at Rothamsted; as the produce here was over or under the average, so it was assumed would be the general produce of the country (A. D. Hall, *The Book of the Rothamsted Experiments* [London, 1917]).

[2] Van de Sande-Bakhuyzen, *op. cit.*, 1928 (II); H. L. van de Sande-Bakhuyzen and C. L. Alsberg, "The Growth Curve in Annual Plants," *Physiological Reviews*, 1927, VII, 151 ff.

[3] Mawley, *op. cit.*, p. 82.

[4] Lawes and Gilbert, *op. cit.*

[5] Fisher, *op. cit.*, 1921.

[6] P. Broonoff, "The Meteorological Bureau and Agricultural Meteorological Stations Directed by the Bureau in 1901," *Memoirs of Agricultural Meterology* (Petrograd), 1901, No. 1.

[7] R. F. Stupart and R. W. Mills, "Meteorology in Canada in Relation to Agriculture," *Bulletin of Foreign Agricultural Intelligence* (Canada), 1916, VI, 307.

[8] Cf. Kincer, *op. cit.*, 1924.

[9] Callander, *op. cit.*

no means as long as statisticians deem desirable. Therefore, every year's delay in making a beginning means a delay in obtaining results because the data for that year are lost and can never be used.

Statistical Methods

The statistical approaches to the forecasting of crop yields have been of two sorts. One approach to the problem is to forecast the weather for longer or shorter periods in advance under the assumption that the probable character of the crop depends at least in a general way upon the future weather. The other approach is to compare weather conditions of past years with crop yields of those years and from these data to develop mathematical formulae by which the most probable yield may be forecast for any given set of weather conditions in a given locality.

1. *Long-Range Weather Forecasting*

The first approach has been made by statisticians, economists, and meteorologists in endeavoring to establish weather cycles. H. L. Moore has proposed an eight- and eleven-year cycle,[1] Sir Napier Shaw, an eleven-year cycle,[2] and Sir William Beveridge, a sixteen-year cycle.[3] Earlier authors have proposed still other cycles. Some cycles were derived from meteorological or related data, others from crop yields, and still others from economic data, such as series of prices. The mathematical technique most frequently used for the treatment of the data is known as harmonic analysis and the graphic presentation of the results of this kind of analysis is known as a periodogram. The method implies the possibility of long-range weather forecasting, in which numerous competent meteorologists at present have little confidence. The method is, nevertheless, alluring because the "establishment of cycles or periods whereby an indication could be given of probable yield far in advance, even within rather wide limits of accuracy, either in a given area or for the world at large, would be an achievement of the very highest importance."[4] No other method holds out hope that crop yields may be predicted far in advance of the planting of the crop. It is discouraging, therefore, to find that a considerable number of cycles have been announced. Until general agreement has been reached in regard to which of them is significant, it is obviously hopeless to expect that this method can be used in a practical way in forecasting.

The forecasting of the weather even for shorter periods, say a year, would be tremendously helpful, especially to farmers. If it were possible to know in the fall what type of weather was likely to prevail in the following summer, farmers would be able to contract or expand their fall-sown acreage accordingly. If it were possible to foretell in the spring the probable general character of the coming summer, farmers would be able to shift their crops to those most suitable to that type of summer. It is interesting to note that a good deal of research has been carried on with this end in view, and although it has not yet led to very tangible results, the outlook is far from hopeless. Okada, for example, has endeavored to establish a relation between the temperature in the winter and spring in the Aleutian Islands and the summer weather in northern Japan, August being the critical month in that country for the rice crop.[5] Several other studies are based on the assumption that ocean temperatures must profoundly influence climates and weather—an assumption by no means unreasonable. It is not impossible that progress in this sort of weather forecasting may result ultimately from progress in the science of oceanography. It is not illogical to imagine that better knowledge of ocean temperatures, ocean currents, and the like, and of the factors that control them, may lead to better forecasts of the weather. However, even if weather forecasts of this type should become possible or if definite weather cycles should ultimately be established, the crop forecasts that might be based upon them

[1] H. L. Moore, *Economic Cycles: Their Law and Cause* (New York, 1914); *Generating Economic Cycles* (New York, 1923).

[2] W. N. Shaw, "The Law of Sequence in the Yield of Wheat for Eastern England, 1885–1905," *Journal of Agricultural Science*, 1907–8, II, 17.

[3] W. H. Beveridge, "Wheat Prices and Rainfall in Western Europe," *Journal of the Royal Statistical Society*, 1922, LXXXV, 412 ff.

[4] Kincer, *op. cit.*, 1924.

[5] J. B. Kincer, "Does the Formation of Abnormally Heavy Ice in the Bering Sea Cause Famine in Northern Japan. A Review," *Monthly Weather Review*, 1922, L, 582 f.

would hardly be more than general in character. They cannot be expected to be as exact as those that can be made from the weather at a critical stage especially when the critical stage is of only a few days' duration. It may become possible to forecast that a year may be bad on the average, but this does not necessarily mean that the few critical days must be bad.

2. *Short-Range Forecasting*

The second approach to our problem is the one that seems most promising, and it is the one upon which the greatest amount of attention is being focused. It is the method of statistical analysis of the crop and weather records. Any statistical method is admittedly a makeshift, used because exact experimental data or accurate field observations are not as yet available in sufficient numbers or extending over long enough periods of time. Were such data at hand, the method would be unnecessary. In other words, if there were available reasonably perfect experiments on the effects of environmental factors upon yield, the statistical method of forecasting yields from the weather would be superfluous. Statistical methods in general are unnecessary where the results of exact experiments are available. This has been put very clearly by Yule, thus: "The more perfect the experiment—the more nearly the experimental ideal is attained—the less is the influence of disturbing causes, and the less necessary the use of statistical methods. The more imperfect the experiment—the greater the failure to attain the experimental ideal—the greater is the need for statistical methods."[1]

The use of weather data to forecast yields is nothing new, but the use of mathematical procedures in this connection is modern. Before the method of correlation (see below) was introduced in meteorology the procedure employed was to count the number of cases in which the values of the two series simultaneously exceeded or fell below the respective means of the series. This gave one a general idea of the effect of variation of one variable upon the other. This method, however, is not precise since it leaves out of account the magnitudes of the deviations from the means. The method was improved by charting the variables, say yields, against rainfall or temperature at a given time, and fitting a straight line or a curve to the data if inspection of the chart indicated a relationship between the variables. From the curve or from the equation expressing it could be determined the probable values of one variable for all possible values of the other.

In the meanwhile a new method, the method of correlation, had been developed by mathematicians and biometricians, notably Karl Pearson. This method has for its purpose to express by means of a number, called the correlation coefficient, designated by the symbol r, the degree of interdependence that exists between two phenomena; and also to develop a formula, called the equation of regression, to enable one to determine with a high degree of probability one phenomenon from the other. This method was first applied to crop-yield forecasting by Hooker[2] in 1907. Jacob, working isolated in India,[3] used the same method in 1910 without knowledge of Hooker's paper. Since that time it has become the method most generally employed for studying the interrelation of crop yields and the weather.

It is not necessary to explain in this paper the mathematical technique of the method, since it is fully treated in standard textbooks on statistics.[4] It is necessary, however, to point out what are the weather phenomena that are most frequently compared with yields over a series of years in

[1] G. U. Yule, *The Function of Statistical Method in Scientific Investigation* (H. M. Stationery Office, London, 1924), p. 3. Jacob (*op. cit.*, 1916, p. 132) expresses the same thought: "the yield of each crop per acre . . . . is a statistical problem only because of its complexity; and the more physical and biological laws can be applied to it, the smaller will be the unexplained residual effects to which it will be necessary to apply statistical methods.

[2] R. H. Hooker, "Correlation of the Weather and Crops," *Journal of the Royal Statistical Society*, 1907, LXX, 1 ff.

[3] S. M. Jacob, "On the Correlation of Areas of Matured Crops and Rainfall and Certain Allied Problems in Agriculture and Meteorology. (A preliminary enquiry)," *Memoirs of the Asiatic Society of Bengal*, 1907–10, XI, 347.

[4] G. U. Yule, *An Introduction to the Theory of Statistics* (London, 1911). For readers who require more complete explanation of the mathematical methods than is given by Yule, numerous more elementary texts are available. Among these, F. C. Mills' *Statistical Methods Applied to Economics and Business* (New York, 1924) may be mentioned as containing sections on abbreviated methods of computation and on curvilinear correlations, not included by Yule.

calculating correlation coefficients and in developing equations of regression. The most frequently employed weather factors are rainfall and temperature. The reasons for selecting these are not merely their obvious influence upon crops, which in some of its aspects have been discussed in a preceding section, but also the ease with which they are measured. Sometimes sunlight is also used, but its measurement is not easy, and long series of sunlight measurements are available for but few localities. Investigators have had to content themselves as a rule with counting the number of hours of sunshine on the days in question.

Selection and Adjustment of Data

Crop yields and weather data are rarely used as such in calculating correlation coefficients or developing regression equations. Most commonly deviations from the normal are employed, as, for example, deviations of yield from the normal for the region, as compared with deviations of the mean temperature or of the rainfall from the normal.

Various devices are used to take account not merely of total rainfall, but also of its distribution. Weighting is applied according to the number of days rain fell, or according to the number of days with given amounts of rainfall.

Rain may be measured; from the number of inches recorded by a rain gauge, the number of tons of water falling upon an acre may be calculated. Heat can less easily be measured in this way; thermometer readings cannot be converted into a value corresponding to inches of rain or tons of water. Yet a value for temperature corresponding to the rainfall of a period is required for purposes of correlating temperature with yields. Such a value is obtained by computing the accumulated temperatures for the period, i.e., the sum of the excesses of the mean daily temperatures for the period over the minimum temperature permitting growth. For wheat this minimum temperature may be taken as about 6.1°C. (43°F.). For sugar cane Walter took the temperature as about 21.1°C. (70°F.).[1] Of course, for purposes of calculating the correlation coefficient from deviations from the normal, it is immaterial what base line is taken. Indeed, there may be some advantages in taking a higher temperature than 6.1°C. (43°F.) for a crop like wheat, say 15.6°C. (60°F.), since smaller numbers are obtained for the deviations that facilitate computations. Kincer[2] has suggested that for spring-seeded crops the mean daily temperature at the average date of beginning planting be taken as the base. This temperature is very nearly the same everywhere for a given crop, though the day in the spring when this temperature is reached is different in different latitudes and at different altitudes. The use of daily mean temperatures introduces errors where the length of day and night are very unequal, as was long ago pointed out by Buchan.[3]

It has also been proposed to weight the temperature data in some manner to take account of Van't Hoff's Law (see p. 7) under the assumption that it holds for the growth of plants. It has, further, been proposed to weight the temperature data in some manner to take account of certain physiological effects of warmth determined by experiment.[4] Since, in sunshine, the leaf temperature is higher than the air temperature, it has been proposed to deduce the leaf temperature from the air temperature and to use the value so obtained instead of the air temperature.[5] This suggestion brings into the correlation the sunshine factor.

The list of procedures, either used or suggested, to be applied to the data before the actual calculation of the correlations or equations is undertaken might be greatly enlarged; but it is sufficient to point out in this place that the results obtained showing the average effect of a single factor, for example, rainfall, upon the final yield shows also the effect of the average weather as-

[1] A. H. Walter, *The Sugar Industry of Mauritius. A Study in Correlation, Including a Scheme of Insurance of the Cane Crop against Damage Caused by Cyclones* (London, 1910), p. 62.

[2] Cf. Smith, *op. cit.*, 1920, p. 67.

[3] *Quarterly Report of the Meteorological Society of Scotland*, June 30, 1862, p. 2, cited by H. Mellish, "Some Relations of Meteorology with Agriculture," *Quarterly Journal of the Royal Meteorological Society*, 1910, XXXVI, 77 ff.

[4] B. E. Livingston, "Single Index to Represent both Moisture and Temperature Conditions as Related to Plants," *Physiological Researches* (Johns Hopkins University), 1916, I, 421 ff.

[5] D. A. Seeley, "Relation between Temperature and Crops," *Monthly Weather Review*, 1917, XLV, 354.

sociated with the rainfall and includes all contributory causes so associated. In view of the complexity of crop growing, it is practically impossible completely to segregate a single factor, nor indeed would this be of practical importance. It would seem advisable, therefore, to select for correlation studies and crop forecasting purposes that environmental factor which is the resultant of or associated with the greatest number of other environmental factors. In semi-arid regions it may be better to use evaporation from a free-water surface than precipitation, for evaporation is the integration of several other important factors, such as temperature, wind velocity, and relative humidity.[1] Still better, of course, would be the multiple correlation (see below) with evaporation and precipitation. Better still should be the correlation with soil moisture, for this is the resultant of the character of the soil, the precipitation, and the evaporation both from the surface of the soil and the surface of the crop's leaves. It is not impossible that better forecasts could be based on soil moisture than upon precipitation; but, so far as the writer is aware, this does not seem as yet to have been attempted.

Significance of the Correlation Coefficient

The finding of a statistically significant correlation coefficient does not in itself justify the conclusion that the two phenomena for which the coefficient has been found are therefore directly causally related. Yule has the following pertinent remarks to make on reasoning of this type:[2]

> "You can prove anything by statistics" is a common gibe. Its contrary is more nearly true—you can never prove anything by statistics. The statistician is dealing with most complex cases of multiple causation. He may show that the facts are in accordance with this hypothesis or that. But it is quite another thing to show that all other possible hypotheses are excluded, and that the facts do not admit of any other interpretation than the particular one he may have in mind.

It follows, necessarily, that the converse is true, i.e., that the failure to find a significant correlation coefficient does not prove that there is no relation between two variables. The finding of a significant value indicates a very high probability of a causal relationship; whereas failure to find a significant value may merely mean that an existing relationship has been masked by factors which have not been taken into consideration.

The correlation coefficient, together with its probable error, presents a quantitative expression of the probability that two variables are interdependent. If there is an exact correspondence, the correlation coefficient will be either +1 or −1. For example, if an increase in rainfall always increases wheat yields by an exactly proportional amount, the correlation coefficient would be +1; conversely, if it always decreases yields by an exactly proportional amount, the correlation coefficient would be −1. A high value with a small probable error indicates that there is great probability of some direct or indirect relationship between the two variables. The reliability of the relationship depends both upon its uniformity and upon the number of times it has been observed to occur. If the correlation coefficient is not very high a considerable series of data is required to establish its significance. If, as in forecasting yields from the weather, we are dealing with time series, we will have greater confidence in the coefficients calculated, the farther back into the past the data extend. The results obtained with series as short as twenty years may be regarded as of significant value only if the correlation coefficient is above .40. For a very short period, moreover, a small probable error does not necessarily indicate that the coefficient of correlation is significant.[3] The difficulties of dealing with short series have been set forth in detail by Fisher.[4]

If the two series of variables be charted as described in a preceding paragraph, a line may be fitted to the points. The line that best fits the points is known as the *line of best fit;* it describes the average relationship between the two variables and is known as the *line of regression.* Its equation is known as the *equation of regression,*

[1] Chilcott, *op. cit.*, p. 83.
[2] Yule, *op. cit.*, 1911, p. 4.
[3] Cf. March, *op. cit.*
[4] Fisher, *op. cit.*, 1921.

and the quantity which gives the slope of the line is called a *coefficient of regression.* By these means it is possible to calculate the value of one variable corresponding to a given value of the other.

Significant Correlation Coefficients

And this raises the question: How large must a correlation coefficient be before one is warranted in regarding it as significant for crop forecasting purposes? J. Warren Smith believes "it probably is safest to assume that there may be some relation if the correlation coefficient is three times the probable error and the relation is established beyond question if it is more than six times the probable error."[1] Kincer, on the other hand, believes that "for forecasting purposes one of less than .80 determined from a reasonably large number of observations with a corresponding small probable error has a limited value."[2] Wallén thinks that even small coefficients may express truly real relationships if one obtains several analogous coefficients for geographically adjacent regions or for regions of the same character.[3] Jacob is of the same opinion.[4] It should be pointed out, moreover, that several investigators have had fair success in forecasting with coefficients of less than .80.

VI. PITFALLS OF CORRELATION ANALYSES

Trends of Yields

There are a number of pitfalls into which an investigator may fall in using the correlation method. One of these is that the data on yields may in themselves show a very definite trend. Crop yields in a given locality may be growing steadily smaller or larger. If the system of agriculture practiced is not rational and the soil is being exhausted, the yield trend may be going downward. If a new plant disease or insect pest is introduced or if new land is brought into cultivation, the trend of yield may be changed. This has happened in the United States for cotton with the introduction of the boll weevil and the westward extension of cotton culture. Or the system of agriculture may be improving so that yields may be rising. Or improved varieties may have been introduced with higher yield characters than the older varieties that they supplant. Or low prices may be driving the crop off marginal land, leaving only the better land yielding heavily under cultivation. Or a competing crop may be introduced which gradually drives the crop under investigation off all but the land peculiarly adapted to it. Changes in yield due to causes like the last are especially likely to occur in regions new to agriculture in which experience has not yet determined what is the best agricultural practice. However, even in long-settled countries it has been found necessary to correct the data for secular trend of yields before calculating correlation coefficients. Wallén found this necessary for Sweden, chiefly because of the introduction of improved varieties of cereals.[5] Hooker surmounted this difficulty by correlating the difference between successive values rather than the values themselves.[6] This method, known as the variate difference correlation method, is regarded by Persons as particularly unreliable for short series.[7] Wallén preferred a method based upon a proposal of Charlier's.[8] Moore eliminated cyclical

[1] Smith, *op. cit.*, 1920, p. 57.

[2] Kincer, *op. cit.*, 1924, p. 268.

[3] A. Wallén, "Sur la corrélation entre les récoltes et les variations de la température et de l'eau tombée en Suède," *Kungl. Svenska Vetenskapsakademiens Handlingar,* 1917, LVII, No. 8.

[4] S. M. Jacob, "Correlation of Rainfall and the Succeeding Crops with Special Reference to the Punjab," *Memoirs of the Indian Meteorological Department,* 1916, XXI, Part XIV, p. 133.

[5] Wallén, *op. cit.*

[6] R. H. Hooker, "On the Correlation of Successive Observations; Illustrated by Corn Prices," *Journal of the Royal Statistical Society,* 1905, LXVIII, 696 ff. Cf. "Student," "The Elimination of Spurious Correlation Due to Position in Time or Space," *Biometrika,* 1914, X, 179 f., and O. Anderson, "Nochmals über 'The Elimination of Spurious Correlation Due to Position in Time or Space,'" *ibid.*, 269 ff. Also A. Ritchie-Scott, "Note on the Probable Error of the Coefficient of Correlation in the Variate Difference Correlation Method," *ibid.*, 1915, XI, 136 ff.

[7] W. M. Persons, "Review of *Forecasting the Yield and Price of Cotton,* by H. L. Moore," *American Economic Review,* 1918, VIII, 405 ff.

[8] C. V. L. Charlier, "Contributions to the Mathematical Theory of Statistics," *Archiv för matematik, astronomi och fysik,* VIII, No. 4.

and secular influences by converting the data into percentages of the averages for the previous three years and correlating these percentages.[1] Others have correlated not the data themselves but their deviations from the average. They have corrected for secular trend by breaking up the period into several portions and using the deviations from the average of each portion. R. A. Fisher has removed secular trend by fitting fifth-degree polynomials to the yield data and using the residuals in the correlation.[2]

Some investigators have also tested for secular trend not merely yield but also weather data, such as rainfall or temperature, with varying results. For the most part they have not found trends of the weather sufficiently pronounced to demand special provision in the calculations. It will be noted, however, that the method of Moore applies such a correction, for he correlated the relatives both of yield and of rainfall.

Interrelation of Weather Factors

In studying the effect of a single weather factor, such as rainfall, on a crop at different times, one may run into spurious results because the weather in one period is correlated with the weather in other periods. For example, if a high correlation is found between rainfall in August and yield, this value may be spurious because the yield is in fact primarily dependent on September rainfall, which is itself correlated with August rainfall. Further, if the rainfalls in August, September, and October are positively correlated *inter se*, then this fact will give a spuriously high value to all correlations of yield and rainfall for any one of the months; but if, on the other hand, the monthly rainfalls are negatively correlated among themselves, the true magnitude of the crop correlations will be masked. In such cases, the partial correlation coefficients must be calculated.

The hypothetical case of the preceding paragraph is not far-fetched; indeed, meteorological phenomena are very frequently correlated. Hence, before conclusions are warranted, it is often essential to calculate partial correlation coefficients, i.e., coefficients that are corrected for the effects of other correlated variables.

If the critical periods for the crop and locality are not known and are probably short, as is usually the case, the weather data must be obtained for successive short periods. Since the data for each period constitute a separate variable, the number of independent variables becomes large. The computation of partial correlation coefficients or even of partial regression coefficients only, to measure the effect of the weather factor in each period, becomes a laborious task.[3] More important, with such a large number of variables the partial correlation and regression coefficients must usually be small and their probable error large, so that in the end nothing whatever may be really proved.

Furthermore, the method of multiple correlation may yield entirely spurious results. Quoting Fisher:[4]

> The biometrical investigations for which the method of multiple correlation was developed, differ from such agricultural studies as the present in two main particulars. In the first place the number of individuals measured was taken to be large, of the order of 1,000, or at least of some hundreds, and the special problems of distribution which arise in small samples have only recently begun to receive attention. In the second place the number of measurements taken of each individual, or the number of *variates*, was generally small, and in all cases far smaller than the number of meteorological elements which may plausibly be regarded as affecting the crop. The sequence of weather to which crop variations may be ascribed extends over a year, or even more, and consists in this country [England] of abrupt, relatively violent and transient spells, each of which has its influence on the crop. If we wished to analyze the sequence no more closely than by monthly averages, we should still have 12 values for rainfall, and 12 more for maximum and minimum temperature, dew-point, grass minimum, solar maximum and soil temperatures, nor would it be unreasonable to include some such measure of insolation as is given by "Hours of Bright Sunshine," and averages of the direction and force of the wind.

[1] H. L. Moore, *Forecasting the Yield and the Price of Cotton* (New York, 1917), chapter iv.

[2] Fisher, *op. cit.*, 1925.

[3] J. B. Kincer and W. A. Mattice have proposed a substitute for the method of multiple correlation which is less laborious and apparently gives very nearly the same results ("Statistical Correlation of Weather Influences on Crop Yields," *Monthly Weather Review*, 1928, LVI, 53 ff.).

[4] Fisher, *op. cit.*, 1925.

The number of meteorological elements might be made to exceed even the longest series of crop records available, for the Rothamsted wheat records provide, after necessary deductions, only 60 yields. Consequently, if the computer were provided not with yield data at all, but with an equal number of values composed at random, he would still be able to express them with perfect accuracy in terms of the weather records, for the number of unknowns available would exceed the number of equations for them to satisfy.

It is of more practical importance that even when we have selected a number of meteorological variables which is less than the number of crops recorded, a strong semblance of dependence may be produced, even if fictitious data, unrelated to the weather, are substituted for the true crops.

Recognizing these facts, Fisher limited his investigation of the effect of weather on Rothamsted wheat yields to a study of the relation of rainfall to yield. Even with this restriction of scope, a very large number of independent variables would be required to determine the critical periods with precision by the usual method. Fisher surmounted this difficulty by the ingenious plan of expressing the distribution of rainfall in each year in terms of the six coefficients of a fifth-degree polynomial. He thus obtained six coefficients for each year, which he used as independent variables in place of the actual rainfall data by periods. He then calculated the partial regression coefficients. From the resulting regression coefficients, he obtained an equation in the form of a fifth-degree polynomial, showing the effect of one additional inch of rainfall at any time during the year. He holds that by this method more accurate results are obtained than by the usual method and the dates of the critical periods are located more precisely.

Even with this degree of refinement in the statistical analysis, it is most necessary for investigators who may undertake the interpretation of the results to bear in mind the fact that any given weather factor is usually very highly correlated with one or more other weather factors. Effects attributed by the statistical analysis to rainfall during a particular period may actually be due to temperature, amount of sunshine, wind velocity, or some other weather factor which is correlated with rainfall during that period.

Multiple Correlations

As has been pointed out repeatedly in the course of this study, the yield of crops is the resultant of many forces, and it would be desirable to determine the combined effects of as many environmental factors as possible. Obviously the more of such factors that may be brought into the calculation, the greater the certainty of the forecast. The method usually employed for this purpose is the method of multiple correlation, which, unfortunately, is laborious and correspondingly little employed.

Relations Not Necessarily Linear

Just as the environment is complex so is growth a complicated phenomenon. It is not a single homogeneous function but consists of many components. These are probably not all affected alike by a given environmental factor and they are probably all correlated *inter se*. For lack of knowledge, it is not possible to dissect the phenomenon of growth into its component factors and study the effect of environment upon each. Undoubtedly, were this possible, as it will be some day, it would make forecasting by statistical procedures vastly more certain. If the matter is mentioned in this connection at all, it is because it has certain bearings on the interpretation of correlation coefficients. If there is any basis for the law of the minimum (see p. 20), it follows that a favorable change in an environmental factor may be ineffective if some other factor is the limiting one. If the limiting factor is favorably changed, then the ultimate effect upon the plant must depend upon whether or not some other factor now becomes limiting.

This is no theoretical reasoning. Laboratory experiment and field observation may be brought to its support. For example, Brown has shown that the rate of assimilation in plants may be increased by increasing the partial pressure of the carbon dioxide in the air surrounding the leaves.[1] However, if this is done the result is abnormal since other factors in the plant are not, apparently, capable of adjusting themselves to the higher level of assimilation.

[1] Brown, *op. cit.*

Equally significant are the statistical deductions of J. Warren Smith[1] on the critical July rainfall value for corn to which reference has already been made. Other examples have been given in previous sections and they might be multiplied greatly.

These considerations are important because they indicate that the relations between environmental factors and yield are not necessarily linear.[2] Smith in the paper cited above gives a table (p. 79) showing the increase of yield of corn with increase of rainfall, which does not indicate a linear relation. Indeed, nothing that is known of the laws of growth gives reason to assume that a given quantum of a factor essential to the continuance of life calls forth always the same quantitative response. For animals we know that there is a level of food intake that permits only maintenance but not growth. This level must be exceeded before growth is possible. For plants we know that for each increment in leaf area there is an increment in assimilation[3] which affects necessarily the rate of growth of the whole plant. Indeed, Blackman has suggested that the vegetative growth of plants obeys the compound interest law,[4] although it has since been shown that this law does not in fact exactly express the phenomena.[5] At any rate no one has ever suggested that the curve expressing vegetative plant growth is a straight line, and it is, therefore, unlikely that the relations between growth rates and the environmental factors that condition growth are directly proportional. Concerning the laws of reproductive growth, we are much less well informed. There is, therefore, no reason to assume that the relation between environment and the plant—at least where vegetative organs furnish the harvest—is a linear function. This has been recognized by some students of forecasting.[6] A crop may fail because of too much as well as too little rain. If excessive rainfall occurs as frequently as deficient rainfall and is equally influential in reducing the yield, the correlation coefficient between rainfall and yield, calculated on the assumption of a linear relationship, will be zero. When the true form of the relationship is recognized, the relation may appear quite close. The coefficient of correlation must also be zero, theoretically, for all values of a limiting factor below the threshold. If it takes five inches of rain to produce a crop, then every rainfall less than five inches produces the same yield, viz., zero. This is, of course, an impossible case, yet there are regions enough where crop failures are not unusual, and the weight to be given such years is an important question, as will appear later in this study.

Now the correlation coefficients are commonly calculated on the assumption that the relationships are linear. The coefficient of correlation, *r*, is a measure of the degree to which two variables approach a linear relationship and it is significant only when a straight line gives a good fit to the points representing the paired values of the two variables. Hence, if the relationships between weather factors and crop yields are not linear, there may still be a high degree of correlation, even though the correlation coefficient, *r*, that is found be low. In such cases other methods of determining correlation must be used. Mills gives an example of such a case in the effect of different amounts of irrigation water upon the yield of alfalfa.[7] It is not impossible that cases of non-linear correlation may be found more often in the field of crop forecasting than linear ones.[8] If, nevertheless, some good results have been obtained with the methods of linear correlation, it is perhaps because the data analyzed may have been concentrated on so small an arc of the curve that it did not differ too much from a straight line. Furthermore, the methods for curvilinear correlation are laborious and since crop data are commonly

1 J. Warren Smith, "Agricultural Meteorology," *Proceedings of the Second Pan-American Scientific Congress.* Section II, Astronomy, Meteorology, and Seismology, 1917, II, 79.

2 A relationship is said to be linear when the line of best fit is a straight line.

3 Cf. Van de Sande-Bakhuyzen and Alsberg, *op. cit.*

4 V. H. Blackman, "The Compound Interest Law of Plant Growth," *Annals of Botany,* 1919, XXXIII, 353.

5 See Van de Sande-Bakhuyzen and Alsberg, *op. cit.*

6 R. H. Hooker, "Forecasting the Crops from the Weather," *Quarterly Journal of the Royal Meteorological Society,* 1921, XLVII, 82.

7 Mills, *op. cit.,* p. 433.

8 Cf. Mordecai Ezekiel, "A Method of Handling Curvilinear Correlation for Any Number of Variables," *Journal of the American Statistical Association,* 1924, XIX, 431 ff.

subject to a wide margin of error, it is often open to question whether it is worth while applying refined methods of analysis to a given case.

Kincer has recognized that the case in which conditions vary about the optimum requires special treatment.[1] He assumes that the most favorable conditions for cotton may be taken as a base and that any departures from these, whether above or below, whether of rainfall or temperature, are harmful. How far this assumption may be justified for all crops in all sections remains to be determined. Kincer, then, adopts certain numerical values for the harm done by rain or heat or cold, according as a plus deviation follows a plus deviation, a minus one a minus one, and so on. Thus a sequence of months with the same departure from normal is weighted as the most harmful. In addition he introduces certain slight modifications of the values to be introduced, when during several months the same conditions prevail. The values are stated "to have been fixed empirically from a general knowledge of the effect on plant development of certain combinations of weather," but what constitutes a plus, zero, or minus departure is not made clear except that 0.3 inches of rain below the normal for April or May is regarded as a minus. In this manner, Kincer works out a formula with which he obtained good results in forecasting the yield of cotton. Jacob had similarly good results for wheat in the Punjab.[2]

J. Warren Smith employed a similar principal. He regards all weather as favorable that is not plainly unfavorable. "An estimate is made of the unfavorable effects of features of the weather which are considered detrimental, and the sum is obtained of these harmful effects, which becomes the weather index of the year. . . . . From the weather index and yield value a regression equation is calculated."[3]

Treatment of Crop Failures

There is still another question that must be considered in this connection. It arises from the fact that not merely are relationships of environment and crop yield often not linear but that there are also limits beyond which no crop is possible. In other words, there is a sort of necessary threshold value for the environment. The wheat crop, for example, must fail if at certain stages of its growth there is not a certain minimum of soil moisture available. There is a threshold value for moisture which must be attained to make any growth at all possible, and there is another threshold value to make the formation of seed possible. This is perhaps only a special case of the general biological law of the threshold that living organisms do not react until the stimulus to which they are subjected reaches the threshold.[4] Every change in environment that so acts upon living substance as to call forth some change in the operation of its life processes is to be regarded as a stimulus.[5] Growth and seed production are to be regarded as affected by the stimuli furnished by the environment and, therefore, subject to the law of the threshold.

If this be true, it follows that a given increment in a necessary environmental factor must produce quite a different response according as the quantity to which the increment is added is below, at, or above the threshold value. If below the threshold value, this increment can have an effect only if it is large enough to raise the total above the threshold value; even a large increment may, therefore, have no effect at all. If the factor in question is close to the threshold value, it is obvious that even a small increment may have some effect. With increasing increments the effects become larger and then decrease until near the optimum they have little effect. These considerations present another rea-

[1] J. B. Kincer, "A Correlation of Weather Conditions and Production of Cotton in Texas," *Monthly Weather Review*, 1915, XLIII, 61 ff.

[2] S. M. Jacob, "Correlation of Rainfall and the Succeeding Crops with Special Reference to the Punjab," *Memoirs of the Indian Meteorological Department*, 1916, XXI, Part XIV, p. 133.

[3] J. Warren Smith, "Influence of Weather on the Yield of Crops," *Monthly Weather Review*, 1922, L, 567 ff.

[4] However, in certain cases, if the stimulus is close to the threshold value and is repeated there may be summation of stimuli with resulting reaction.

[5] E. Mangold, "Reiz und Erregung, Reizleitung und Erregungsleitung," *Ergebnisse der Physiologie*, 1923, XXI, 370.

son for believing that the relations between environmental factors and yields are not universally linear.

But they raise also another question concerning the treatment of data in analyzing relationships between crops and the weather in years of complete or nearly complete crop failures. Are such years to be given the same weight as the far more numerous years when the crop was either good or poor, but by no means a failure? Suppose, for example, that in a given region we have a series of 30 years of crops in which the crop was a complete failure three times because the rainfall at the appropriate season did not reach the threshold value of 7 inches. Let us assume that in one of these three years of crop failures the rainfall was 2 inches, in another, 4 inches, and in the third, 6.5 inches. Are we to treat all three years in the same way? Regarded by themselves they show no correlation of crop yield with rainfall. To include them with the years in which the rainfall exceeded the threshold value results in obscuring the real correlations that exist. To use correlation coefficients and equations of regression so obtained to forecast crops has the result of making forecasts for the years when the rainfall exceeded the threshold value much less certain than they might be if the three years were left out of the calculation or if some form of adjustment were introduced which would give to a precipitation of 2, 4, and 6.5 inches, respectively, the same significance, since they are equally effective in causing crop failure. This, however, does not seem to be the practice of statisticians, and so we encounter instances of low or not significant correlation coefficients which would become high or significant if a single year or only one or two years were omitted. Shaw proposed that such years be eliminated.[1] To this Hooker objects.[2] On the other hand, there is much to be said in favor of Shaw's suggestion. It is not a case on all fours with that of a biased chemist who suppresses the results of analyses which do not fall in line with some hypothesis he is supporting. It is more like the case of a chemist who, in determining carbon and hydrogen, finds that his combustion tube has cracked, so that he knows his result not to be valid and, therefore, rejects it.

In the hypothetical case under consideration, we know definitely from biological laws that we introduce an error by including in the series on which calculations are based the widely differing rainfall values for the years of crop failure. It seems patent that some method of adjusting the data for these years must be used to avoid error, or else that they should be left out and the resulting regression equation used only within the limits from which it was calculated. One needs no regression equation or refined mathematics to forecast a complete crop failure whenever the threshold value of rainfall is not reached. All one needs to know is what this value is. Moreover, in effect, some statisticians have been rejecting certain data because they have found, or assumed, no correlations to exist. Thus, it is the custom to take into the calculations only temperatures above 5.6°C. (42°F.) because crop plants grow little if at all at lower temperatures. Hooker, for example, could find no specially significant correlations for temperatures below 5.6°C. (42°F.); therefore he does not discuss them.[3] Walter, in correlating rainfall with the yield of sugar on Mauritius,[4] writes that "it has been considered that during excessively wet periods rainfall which increases the temperature of the soil at a depth of five feet raises the moisture-content of the soil to such an extent that a further fall, in excess of the evaporation from a free-water surface, is non-effective and has therefore been rejected." In principle, there is no difference between these procedures and the rejection of years that are

[1] "But there was one year, 1879, when there was really not enough warmth to grow a wheat crop at all in this country [England]. Practically the experiment failed, and to bring a failure of this kind, when the accumulated temperature was only numerically low, into association with other data where there was more or less proportionality, seemed to require a certain amount of justification. Is it therefore justifiable to leave out some of the specially exceptional cases? . . . . A very high coefficient obtained for all years with one or two exceptions might have a very different meaning."—Discussion of Hooker's paper, "Correlation of the Weather and Crops," *Journal of the Royal Statistical Society*, 1907, LXX, 1 ff.

[2] *Idem.*

[3] *Idem.*

[4] Walter, *op. cit.*, p. 62.

subliminal with regard to some essential meteorological weather factor.

If no assumption is made that the correlation is linear and if the correlation coefficient, *r*, is not calculated, the question what to do with the years of crop failure because some factor, say rainfall, is subliminal does not arise. In that event, some method of determining curvilinear correlation is to be employed. The appropriate curve would be one that reaches zero and becomes horizontal at the point representing the threshold rainfall value.

Hail and Hurricanes

A related question is what to do in the series one is studying with years in which there is crop failure or very great reduction of the yield because of some catastrophe like hail or hurricane, and not in any way because of the particular weather factor one is correlating with the yield. In a region where catastrophes of this kind occur, the forecast made with the aid of a regression equation thus calculated might be qualified with a statement of the probability of the occurrence of such a catastrophe as determined from past weather records. Fortunately, hail is a local phenomenon and perhaps need not often be considered when one is dealing with a large area. However, it would seem from Chilcott's observations[1] that there are regions where it is an important factor in the aggregate.

Hurricanes, on the other hand, may cover a wide expanse of territory and do not necessarily completely destroy the crop. The question then arises how to correct the yield of the hurricane years — in other words, to determine what the yield would have been if no cyclone or other catastrophe, damaging but not completely destroying the crop, had occurred. Walter, dealing with the effects of cyclones on sugar cane,[2] has developed a method for the purpose.

The justification for special treatment of the data for years in which hail, hurricane, or other catastrophe not under investigation has affected the crop is not so clear as the justification for special treatment of data for years in which the weather factor under investigation falls below the threshold. In all years there are some such special factors at work. The selection of certain cases for special treatment may readily introduce a bias into the results. Such selection is undoubtedly justified in certain cases, but care must be exercised.

The biological laws that we have been considering, the law of the minimum, the law of the threshold, the laws of growth generally, make it extremely improbable that crop growth and crop yield data have necessarily a normal dispersion,[3] that is, a chance distribution. There is every reason to believe that it cannot be normal in a climate such that there are occasional failures due to, say, subliminal rainfalls, while failures practically never occur from excess of rainfall. In such climates the average crop for a definite period that includes years of subliminal rainfall is not produced in the years of average rainfall. Indeed, the correlation coefficient, *r*, is designed to be applicable to normal distributions. Its interpretation in other cases must be made with some caution. Perhaps in the difficulties that arise from "skew" (i.e., not normal) distributions is to be sought a part of the explanation for the greater uncertainty of forecasts where fluctuations of climate are violent and extreme[4] and for the fact that a crop failure seems easier to forecast than a bumper crop.[5]

The methods developed by Fisher, to which reference has been made repeatedly, obviate many of the difficulties encountered in applying the well-known methods of total, partial, or multiple correlation to the problems of crop forecasting. They are cer-

[1] Chilcott, *op. cit.*

[2] Walter, *op cit.*

[3] If a curve be plotted of which the abscissae represent the value of the series "and the ordinates the number of times each value occurs, a 'frequency curve' is obtained. If this is of the 'cocked-hat' shape, showing a maximum at the center and tailing off symmetrically at either end, with an equation of the form

$$y = ae^{-\frac{x^2}{2\sigma^2}},$$

the frequency distribution is called normal."—R. H. Hooker, "An Elementary Explanation of Correlation: Illustrated by Rainfall and Depth of Water in a Well," *Quarterly Journal of the Royal Meteorological Society*, 1908, XXXIV, 277 ff.

[4] R. H. Hooker, "Forecasting the Crops from the Weather," *Quarterly Journal of the Royal Meteorological Society*, 1921, XLVII, 90; G. Taylor, Agricultural Climatology of Australia," *Quarterly Journal of the Royal Meteorological Society*, 1920, XLVI, 331.

[5] Hooker, *op. cit.*, 1921, p. 91.

tain to inaugurate a new era in crop forecasting by statistical procedures.

It may be objected that in the discussion here presented of forecasting wheat yields from the weather insufficient account has been taken of damage through fungus and insect attack. It is true that these are important hazards of which little account is taken in most of the statistical studies of crop forecasting. These are just a few of the many factors that for one reason or another must be left out of account until much greater progress has been made in the subject. However, the omission is not in all cases as serious as might be supposed, because the incidence of a good many of the more important fungus and insect attacks is greatly dependent upon the weather. The damage done to wheat, for example, by the Hessian fly in certain regions varies greatly with the weather.[1] The number of broods of coddling moths in a year, and therefore the damage they do to fruit trees, is a function of weather.[2] The damage done to wheat by rust is closely correlated with the weather.

VII. PRESENT RESULTS AND LINES OF IMPROVEMENT

From the perusal of the preceding sections the reader may have received the impression that the problem of forecasting wheat yields from the weather is so complicated and so beset with pitfalls as to be hopeless. Certainly the results already achieved are limited. No government as yet undertakes to forecast the yields of its own crops on the basis of weather data. Nevertheless, we may confidently look forward to improvement in methods and to increasing partial application of them. In spite of all the complexities involved, there is reason to believe that if competent investigators continue to address themselves to the problem as assiduously during the next twenty years as they have during the past twenty, the forecasting of crops from the weather—or at any rate from environmental factors—may be made at least as satisfactory as by the present subjective methods and probably much more so. At the very least, it can be made an invaluable check upon current practice. At best it should be more accurate and the forecasts more timely than with the present methods. There is reason to believe that ultimately the statistical method may displace very largely the subjective method. Certainly, it is a much less expensive procedure. Moreover, it has especial value in forecasting crops in foreign countries, either countries from which reports are received so tardily as to be of little value, or countries which do not make forecasts, or countries in which bias may be suspected.

Fisher has shown what may be done with adequate mathematical technique even though the data be limited. The yields he calculated from the rainfall data alone agreed very well with the actual yields as determined by weighing on certain fields at Rothamsted for 60 years. He found[3] that in one plot 11 per cent, and in others 40 per cent of the variance is expressible in terms of the sequence of rain records. As he puts it: "It is remarkable that so much of the variance as 40 per cent should be expressible in terms of a single meteorological element such as rainfall, especially when it is remembered that all the causes of variation without exception, including casual errors, and the quadratic terms of the rainfall effect, are included in the remaining 60 per cent. This leads us to think that a record of rainfall, in spite of the many disabilities which have been urged against it, is of more value than any other single element, in characterizing the season." Hooker is of the same opinion. He believes that "such portion of the effect of sunshine, humidity, the electrical state of the atmosphere, and probably even insect and fungoid attacks, etc., as has not been accounted for owing to their correlation with rainfall, is of minor importance."[4] On the other hand, Chilcott is convinced that in the Great Plains area of the United States it is not the most important determinant of yields.[5]

[1] Cf. Smith, *op. cit.*, 1920, p. 247.

[2] A. L. Quaintance and W. M. Scott, *The More Important Insect and Fungous Diseases of the Fruit and Foliage of the Apple* (U.S. Department of Agriculture Farmers' Bulletin 492), 1912.

[3] Fisher, *op. cit.*, 1921, p. 133.

[4] Hooker, *op. cit.*, 1921, p. 80.

[5] Chilcott, *op. cit.*

Even with less perfect methods and less reliable data than those of Fisher, useful results have been obtained. Moore has had much success in forecasting the yields of cotton.[1] Using methods analogous to those he had developed for cotton, he was able to forecast the yield for wheat, barley, and oats in the Dakotas more accurately than the United States Department of Agriculture in 8 cases out of 9. In the single case in which the Department of Agriculture was more accurate, its forecast was made within a fortnight of the harvest.[2] Hooker was able to get very good results for wheat in eastern England.[3] Wallén obtained satisfactory agreement with official estimates of yield for the different provinces of Sweden, even though his basic data left much to be desired.[4]

Besides the study of Moore, a number of studies on wheat have been made in the United States with, for the most part, fairly good results considering the general character of the data. Among the more interesting of these studies are those by Blair[5] and J. Warren Smith.[6] Not all of these are pushed to the point of attempting forecasts, but they bear directly on the question. In India very fair results have been attained by S. M. Jacob.[7] In Australia significant studies have been made by Barkley.[8] For Argentina, Hessling has demonstrated a negative correlation between temperature and wheat yields.[9] Rainfall he found not to be a matter of indifference, but correlations were much less definite than with temperature. Hessling was able to forecast the yields from the August to November temperature alone some time in advance of the harvest.

Moreover, by taking other weather factors into consideration in addition to temperature, the forecasts could no doubt be improved. The United States Department of Agriculture has been using the method of correlation in forecasting the yield in Argentina,[10] and also in India and Victoria.[11] The specific manner in which the method is being applied to the data for these countries has not yet been made public, only brief preliminary accounts of the work having appeared. The usefulness of drawing more than one weather factor into the computations is also made clear by the work of Kincer and Mattice.[12]

It is not easy to form a judgment concerning the practical usefulness of these forecasts at the present time because most investigators have compared their forecasts with official estimates of yields made after the harvest, sometimes several months later, instead of with forecasts made at corresponding dates before harvest as did Moore. Those who have compared forecasts based on weather with official crop estimates after harvest have not done justice to the method. It is true that in some years such forecasts diverge considerably from final yield estimates after harvest, but it is probable, as Moore found, that official forecasts not based on weather diverge still more from the final estimates.

A further difficulty in assaying the practical value of yield forecasts based on weather is the lack of a reliable standard of comparison. One can but assume that the official final estimates after the harvest are trustworthy. Yet errors in official estimates of wheat crops of 10 per cent are probably not unusual. The official estimate

[1] Moore, *op. cit.*, 1917.

[2] H. L. Moore, "Forecasting the Crops of the Dakotas," *Political Science Quarterly*, 1920, XXXV, 204 ff.

[3] R. H. Hooker, "The Weather and the Crops in Eastern England, 1885–1921," *Journal of the Royal Meteorological Society*, 1922, XLVIII, 115 ff.

[4] Wallén, *op. cit.*, 1917.

[5] T. A. Blair, "Partial Correlation Applied to Dakota Data on Weather and Wheat Yield," *Monthly Weather Review*, 1918, XLVI, 71 ff.; "Rainfall and Spring Wheat," *ibid.*, 1913, XLI, 1515 f.; "Temperature and Spring Wheat in the Dakotas," *ibid.*, 1915, XLIII, 24 ff.; "A Statistical Study of Weather Factors Affecting the Yield of Winter Wheat in Ohio," *ibid.*, 1919, XLVII, 841 ff.

[6] J. Warren Smith, "Effect of Snow on Winter Wheat in Ohio," *ibid.*, 1919, XLVII, 701 f.

[7] S. M. Jacob, "On the Correlation of Areas of Matured Crops and the Rainfall and Certain Allied Problems in Agriculture and Meteorology. (A preliminary enquiry)," *Memoirs of the Asiatic Society of Bengal*, 1907–10, XI, 347; "The Correlation of Rainfall and the Succeeding Crops with Special Reference to the Punjab," *Agricultural Journal of India, Indian Scientific Congress Number*, 1916, 86 ff.

[8] Barkley, *op. cit.*

[9] N. A. Hessling, "Relations between the Weather and the Yield of Wheat in the Argentine Republic," *Monthly Weather Review*, 1922, L, 302 ff.

[10] "The Agricultural Situation in Argentina," *Foreign Crops and Markets*, 1928, XVI, No. 16.

[11] "Relation between Wheat Yield and Rainfall in India and Australia," *ibid.*, 1927, XIV, No. 11.

[12] Kincer and Mattice, *op. cit.*

of the Argentine wheat crop of 1927–28 was certainly underestimated by about 10 per cent,[1] though whether due to an error in estimating yield or acreage it is not possible to say. It is probable that the differences between official estimates of yield and those based on the weather factors are in appreciable measure due to error in the official estimates. Similarly the Canadian crop has been apparently underestimated in each of the four crop years preceding the current year, twice by as much as about 10 per cent.[2]

Lines of Improvement

The directions in which the forecasting of crop yields from the weather may be improved are: improvement of the statistical methods; improvement of the meteorological data; improvement of the agricultural data.

To improve the statistical methods is a task for mathematicians. Great progress has been made in this direction, especially by Fisher, and while further improvements and refinements of methods will no doubt be forthcoming, it is probable that the methods now available are sufficiently good for the not very accurate data to which they must be applied. The greatest immediate need is for methods that will reduce the heavy labor at present required in making the computations. Another need is for better grouping of the data presented to the statistician. In a large country like the United States, climates and soils vary greatly. Political units are not necessarily climatically homogeneous. At present, data are grouped rather by political units, such as states, than by climatic or agronomic units. Most states are not homogeneous in regard to climate, soil, or types of agriculture. Many of them include several types of climate and of agriculture. A climatically and agriculturally homogeneous area may include portions of several states. When the data for such a state are lumped together, it is difficult and indeed frequently impossible for the statistical analyst to unravel relationships. These may differ in different parts of a state and so in the total for the state may be quite unrecognizable. It is, therefore, highly important that for forecasting purposes the country be redistricted, ignoring political units and dividing the country into a larger number of districts that are as far as possible homogeneous in climate and soil. Forecasts, if made for such districts and subsequently combined appropriately to represent political units, would be more accurate. To some extent, this plan is practiced in the United States Department of Agriculture, but it should be pushed much farther. Even with the meteorological data now being gathered, if taken from stations properly located and correlated with yield data from the same region, it is possible that statisticians would be able to furnish forecasts as good as or better than are made at present.

The meteorological data on the whole are as accurate as can be expected. Their principal defect is that in many regions the series do not extend as yet over a sufficiently long number of years. That is a defect that will remedy itself in time. Another defect is that the data are often too much limited in scope, being usually confined to daily rainfall and maxima and minima of temperature. More complete records for more stations are needed. It will probably also prove profitable to add to or to substitute for the meteorological observations records of soil conditions. It is not unlikely that the moisture content of the soil at different depths may prove to be a better index of probable yield than rainfall. Similarly, records of soil temperature at different depths may prove a better index during the germination period than air temperatures. At the very least, studies should be made to compare the value for forecasting purposes of these data with the meteorological data commonly used. The reading of soil thermometers is not difficult. With recording thermometers, even reading is unnecessary; the records may be sent in to the central station from time to time. The taking of a soil sample is not difficult; it may be shipped in a sealed container to a central station for the moisture determination.

By and large, it is the agricultural data that are the least perfect and most readily

[1] Cf. a forthcoming Wheat Study, viz., "Review of the Crop year, 1927–28," Wheat Studies, 1928, V, No. 2.

[2] *Idem.*

capable of improvement. In the main, statisticians and meteorologists are waiting for progress by agricultural scientists. This can hardly be made until much further research has been carried on concerning the reaction of crops to various weather factors. The quickest and most effective way to get much of this information is through carefully controlled laboratory experiments. It is important, if this work is to be done with reasonable despatch, that it be assisted and supported by governments, for, if special inducements are not offered, plant physiologists in sufficient numbers will not attack the problems. There are so many problems of greater biological interest, though not of greater economic importance, that may be undertaken with modest resources and solved with less labor that these will continue to engross the attention of physiologists, unless some sort of subsidy is offered.

At the same time, a series of field experiments should be undertaken of the type described in a previous section. The stations should be scattered widely at points strategically located as regards climate and soil. The stations need not be elaborate or expensive to operate. While the results to be anticipated cannot be obtained until after a long period of years, the stations may well serve as samples for the regions in which they are located. It is not impossible that a thousand or even fewer stations appropriately located in the United States might give data permitting far more accurate crop forecasts than many thousands of condition reports from crop correspondents. The operating costs might not be very much greater after the expenses of installation have been met than for the methods now in use. Moreover, at the same time, the stations would furnish priceless phenological and other data. The United States Department of Agriculture and the experiment stations of the several states already maintain a goodly number of stations that with certain simple adjustments would serve the purpose for their respective regions.

In the meanwhile, it would be well worth while to try the experiment of asking a carefully chosen, small list of crop correspondents to send soil for moisture determinations to a central laboratory. It would not be necessary to collect samples throughout the growing season of wheat. A few samples from each locality collected at the critical stages—say the time of sowing, the time of emergence, the beginning of flowering, and the end of flowering—should be sufficient. It is highly probable that a statistician with a good series of soil-moisture data before him would forecast yields more accurately and at less expense than by current methods.

In short, the conclusion is warranted that the time is ripe to use the weather to a greater extent than has been the practice in the past as a basis of forecasting the wheat crop. If the lines of investigation that have been suggested by numerous competent scientists are prosecuted vigorously, it is well within the range of possibilities that within a few decades this type of forecasting may supersede, or at the very least, supplement in important ways, present subjective methods. Moreover — and this is a very important consideration in any question which has political aspects, as nearly every economic question has—the forecasts would be more objective than those made by present methods. They could be checked by any one who cares to take the trouble; the government's forecast would be more defensible against the charge, very frequently made, that there is bias, deliberate or unconscious, in its published figures. Governments will undoubtedly proceed cautiously, and, while the statistical methods are being tested, will use them for many years merely as checks upon present methods.

The forecasting of crop yields must, in all probability, always depend in part upon statistical analysis. Experimental work will, as far as one can at present foresee, make its greatest contributions toward the problems of forecasting by furnishing improved bases for statistical analysis. It is capable of determining critical periods that may be recognized through statistical analysis alone with difficulty, and, above all, it is capable of determining rather precisely those factors that exert the greatest influence upon crops. It can discover, as statistical analysis by itself never can, how and why certain environmental influences affect crop yields; it is clear that such knowledge is of the greatest importance in statistical analysis, which is never a mere mechanical, mathematical process like the operation of a calculating machine. Statistical analysis demands the exercise of judgment, and the broader the basis of knowledge upon which such judgment is based, the better and more rational the results.

Experiments may serve in other ways also to facilitate and render more precise the work of the statistician. They should be of great value in making clear the form of the relationships between environmental factors and yields, whether the relationship is linear or not, and, if curvilinear, experiments may well give indications regarding the type of curve that would best express the relationship. When the experiments are conducted under conditions closely approximating those in the field, as regards soil character, fertilizer applied, method of cultivation, weed infestation, and susceptibility to disease, they may form the basis for a complete formulation of the forecasting equation, subject only to adjustment from the statistics to assure the mean of the forecasts remaining close to the mean of the actual yields.

Even when the experiments have been conducted under conditions believed to be considerably different from those in the field, the indicated effects of the minor weather factors may frequently be more trustworthy than the effects of such factors as measured statistically. It will undoubtedly prove desirable on occasion to build up forecasting equations by combining coefficients for the major factors derived statistically with coefficients for minor factors derived experimentally.

Special study will also have to be made of trends of yield through collection of data on factors affecting the trends. The effects of such factors as the introduction of new varieties, better seed or certified seed, new methods of culture, changes in fertilizer practice, soil exhaustion, geographic shifts in the areas under cultivation, will always require close watching since they may cause a change in trend of yields. Unfortunately, such changes in trend will affect the computed line of trend only after they have been in force for a period of years. It is well known that a line of trend may become subject to an increasing error at its extremes. Unless the forecaster is on the lookout for new factors possibly affecting trends of yields and is ready to make allowances for them, he may be seriously misled. The forecaster must also take into consideration in each year special conditions that may arise to change the critical stages of the plants' growth from the normal, as, for example, dates of sowing.

In short, the forecasting of yields from the weather cannot safely be left wholly in the hands of the agricultural meteorologist, or of the statistician, or of the agronomist. The successful solution requires the co-operation of all these, together with that of the physiologist. Such co-operation will have to be maintained for many years to come in order that the forecasting may not leave out of consideration new factors resulting from changes in agricultural practice or fail to apply new discoveries in the several sciences. For some time to come, the best results may be obtained by basing estimates of the effect of minor factors on experimental results, estimates of the effect of major factors on statistical results.

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