THE PLANT DISEASE REPORTER

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THE PLANT DISEASE SURVEY

Division of Mycology and Disease Survey
BUREAU OF PLANT INDUSTRY, SOILS, AND AGRICULTURAL ENGINEERING
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PLANT DISEASE LOSSES: THEIR APPRAISAL AND INTERPRETATION

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DIVISION OF MYCOLOGY AND DISEASE SURVEY

Plant Industry Station Beltsville, Maryland

PLANT DISEASE LOSSES: THEIR APPRAISAL AND INTERPRETATION

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FOREWORD

Paul R. Miller

The Plant Disease Survey is glad to publish Dr. Chester's fundamental analysis of importance, principles, problems, and techniques of plant disease appraisal. This sort of contribution to plant pathology is a special interest of the Survey since it is of such immediate concern to our objectives. We should like to have been responsible for the preparation of this work ourselves; however, Dr. Chester has probably achieved greater objectivity than we could have and thus has been more effective in his presentation.

Our expression of interest in this work does not mean necessarily that we are in agreement with all its viewpoints. In spite of minor differences of opinion, however, we are fully convinced that such a handbook of disease appraisal, its significance and applications, has long been needed, and will be of great use to plant pathologists.

Most of this manuscript was completed while Dr. Chester was head of the Department of Botany and Plant Pathology at Oklahoma Agricultural and Mechanical College, Stillwater, Oklahoma. Inasmuch as Dr. Chester was then a collaborator of the Plant Disease Survey, and since our collaborators are considered an official and essential part of the Survey organization, we feel that its publication as a Supplement to the Plant Disease Reporter is especially appropriate.

PROLOGUE

"It will be necessary for agriculture to become better informed on the extent and nature of all of its losses before much progress can be made toward reducing them."
--R. C. NEWTON, 1945.

"Apart from its purely scientific interest, accurate determination of the loss caused by a given disease offers the only safe guide in a rational policy of control."
--E. P. MEINECKE, 1928.

"How can we expect practical men to be properly impressed with the importance of our work and to vote large sums of money for its support when in place of facts we have only vague guesses to give them and when we do not take the trouble to make careful estimates? Determination of loss is a difficult and complicated matter, but I believe that we should seriously attempt it. We should develop quantitative methods, and make careful counts in restricted areas. I believe the accumulation of reasonably accurate data on losses will ensure us the attention of the public as will no other argument. . . . . . . The preparation of reliable and comprehensive estimates for even a few of the more serious plant diseases would be of immense educational value to the public and would tend to increase the support given all plant disease work."
--G. R. LYMAN, 1918.

"It is too bad that so many have contributed so little to this very important subject."
--W. D. MOORE, 1945.

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THE VALUE OF ACCURATE INFORMATION ON PLANT DISEASE LOSSES

INTRODUCTION: -- Because plant diseases cause economic loss and consequent hardship to society the science of plant pathology exists with the objective of preventing such loss. The funds upon which the science depends, whether public, industrial, or private, are almost invariably assigned with the understanding that they shall be used in research, education, and regulation designed to reduce the economic burden which plant diseases impose on the producers and users of agricultural commodities. Rare indeed is the plant pathologist who can say with Aristaeus: "From studying what are called maladies, I have come to consider them as necessary forms of life. I take more pleasure in studying them than in combating them."

Organized plant pathology may be compared with organized detection and prevention of crime. Imagine, for a moment, a crime-regulatory organization in which little is known of the comparative importance of different violations, in which the efforts of the police in detection and the judgments of the court are hampered by a lack of knowledge of which crimes are felonies and which are misdemeanors. The most glaring and odious crimes would be detected and appropriately punished, but there might be many cases when a spectacular crime of light import would detract the attention of police from more serious but less obvious crimes. On apprehension, the forcefully crude but petty thief might be judged with great severity, while the more subtle and more dangerous embezzler or large-scale swindler might escape with little effort at prevention of his future operations.

Unthinkable as such a situation would be in modern society, we have its counterpart in modern agriculture. We have little exact information on the relative destructiveness of diseases of crop plants or livestock, or of numerous other agricultural hazards, on which we might base the most effective and economical program of loss prevention. In plant pathology in particular, apart from the exceptional case of forest decay appraisal, our information on absolute and relative losses from plant disease is fragmentary and often demonstrably in error. As a result, our efforts in crop disease control have frequently been directed against diseases of lesser economic significance while others of greater destructiveness have received little attention. The case of potato latent mosaic is a striking illustration of this misplaced emphasis.

Potato latent mosaic, discovered and called "healthy potato virus" in 1925, is present in practically every potato plant grown in America, except new seedlings. Not for 20 years was its damage measured and found to average 13% of the crop, a figure confirmed by independent loss measurements in America, Australia, Scotland, and England. This measured amount of loss from latent mosaic is twice as great as the average annual loss from potato late blight (Phytophthora infestans), Rhizoctonia, and scab (Streptomyces scabies) combined, and four times the annual average loss from late blight, according to estimates of losses from these other diseases in the Plant Disease Reporter from 1919-1939.

Applying this figure, 13% loss, to American potato production during those 20 years, latent mosaic has caused a total loss of 1.1 billion bushels of potatoes. The bases for control of this disease by seed certification and varietal resistance have been available for many years. If the damage from latent mosaic had been measured and recognized when the disease was first discovered, if research on its control had been immediately undertaken, and if no more than one-tenth of this loss had been averted as a result, the gain would have amounted to 110 million bushels of potatoes with a value dwarfing to insignificance the cost of the research involved.

A similar situation has prevailed in the related sciences of human and veterinary medicine. In the former case, mortality statistics have, at last, effectively revealed the relative destructiveness of human ailments. Overpublicized minor diseases, such as leprosy, have been relegated to the background, while previously neglected major diseases, such as heart and kidney affections, are beginning to receive attention commensurate with their importance. In veterinary medicine, a start has been made toward determining, on a national scale, the relative destructiveness of livestock diseases.

A comprehensive study of the comparative losses from plant diseases is long overdue. Such a study has three aspects: (a) standardized, reasonably accurate appraisal of disease intensity; (b) translation of disease intensity into crop loss in terms of production units; and (c) interpretation of the impact of this crop loss on human welfare.

This book is primarily concerned with the first two of these aspects of the problem; the third, which is in the domain of economics and sociology, is considered only briefly.

PLANT DISEASE APPRAISAL AS A SERVICE: -- The determination of the occurrence, intensity, and destructiveness of plant diseases, though essential, is not an end in itself. It may be compared with the intelligence service of a modern army. Through extensive observations and probings, it uncovers the position, strength, and potentialities for destruction of the enemy, -- in this case, the agents of crop disease. Guided by this intelligence, and only so, the strength of the army can be applied at the most strategic points; in our case, research, education, and regulatory efforts can be applied mainly to those plant disease problems where the limited personnel and facilities can accomplish the most economic good.

There are three stages in the development of an adequate understanding of the extent and effects of crop losses: first, the development, by research, of standardized methods of loss appraisal and conversion factors which translate a given intensity of disease into loss percentage; second, well-planned surveys to apply these methods on a sufficiently broad scale to give a reliable picture of disease loss over a broad area; and third, summation, analysis, and interpretation of the survey data to determine the economic significance of plant disease losses.

The plant disease survey is an essential part of the activity, but it must be based on appraisal research, and its results must be subjected to economic interpretation if the survey is to attain the full measure of its usefulness as a service to other agricultural activities. Surveys in the past have frequently been deficient, first, in lacking an accurate experimental basis for disease appraisal and, second, as a result of this, in yielding data that are incomplete, non-uniform, and difficult to interpret in terms of economics. This may be a chief reason for the lack of interest in the support of surveys that has characterized the policies of some agricultural agencies.

Surveys are justified and valuable insofar as their results are of service to agricultural "action programs". If surveys rest on a sound scientific basis developed through appraisal research, and if their findings give a reliable, concrete, comparative picture of relative and absolute losses, the survey findings can be of immeasurable value in a wide variety of agricultural activities, as seen in the following examples.

THE USES OF ACCURATE DATA ON PLANT DISEASE LOSSES: -- Each of the major phases of agricultural science, research, education, regulation, various "action programs", and agricultural economics, can benefit in an important degree from the availability of accurate data on plant disease losses.

Some plant diseases are spectacular, but with relatively little economic significance; others subtly destroy unsuspected and important fractions of crops. The percentage of loss from disease which may be disregarded, economically, varies widely from one crop to another, and, in a single crop, from one disease to another, depending on the nature of the loss and the existence or lack of economical control measures. NEIL STEVENS (1938), in dealing with growers, advises: "If your loss is less than X%, forget it!" But, we must know the value of X in each case. Knowing it, and the significance of values greater than X, we can proceed intelligently and economically in each of the several agricultural activities that contribute to the reduction of wastage and unnecessary loss in crop production and utilization.

PLANNING AND DIRECTION OF AGRICULTURAL RESEARCH: -- The curtailment of scientific graduate training during World War II and the absorption of an increasing number of plant pathologists and mycologists into industrial and military research, make it mandatory that the work of the depleted and inadequate ranks of these scientists be directed at the most strategic points in the war against plant disease. As a nation with a moral and practical obligation to provide large sections of the world with agricultural necessities, we cannot afford to waste our limited scientific manpower by expenditure of research effort on problems of less economic and social singificance while more critical problems are being neglected. Accurate comparative information on plant disease losses and their effects is the necessary guide to the most efficient use of our resource of research ability.

How do agricultural research projects originate? Why is one problem selected in preference to others? Many factors are involved: personal preferences; availability of men with specialized interests or training; physical facilities; pressures from grower-groups or others; and restricted permissible uses of research funds; but, most frequent is the apparent importance of the problem. Rarely is this apparent importance verified by comparative study of the many lines of possible research; indeed, it is frequently impossible to make such a study, -- the data on which to base it do not exist.

The apparent importance of a problem may be far from its true relative importance. Problems appear to be important when they are well publicized; when, by chance, they come frequently to the attention of the research worker or administrator; when they catch, momentarily, the fleeting attention of the capricious public eye; when examples of the problem exist close to the research headquarters. Sometimes problems that appear to be outstanding are truly so; but, in too many cases, they are outweighed in importance by other, less apparent ones.

As NEIL STEVENS (1945) has emphasized, field observations, surveys, are of critical importance in determining how a worthwhile research program shall be chosen. As we will see later, the value of these surveys in orienting research increases with increase of the definiteness of the survey data and of their interpretation in terms of crop loss and the economic consequences of this loss.

"Life is far too short to carry out experiments to decide whether a given disease is, or is not, worth studying," writes STEVENS. This is true if the researcher is alone in his efforts, but he need not be. There is a small but growing body of comparative data to which he may turn in his attempt to evaluate the importance of the problem at hand. With the combined efforts of many pathologists over a period of years, it may not be too visionary to suppose that there will gradually be evolved a picture of comparative agricultural hazards which will be of very material aid in selecting the most productive areas for research.

Even such inadequate comparative data as are now available may be of some limited help in selecting problems. An example of this, for facilitating research on new fungicides, has been given by M^cCALLAN (1946), who derived an "index of disease importance" to indicate the most pressing problems in fungicide research (p. 288). Approaches such as this will have greater and greater value in the planning of research as we develop a more reliable basis of knowledge on the extent and relative importance of the losses from the various diseases of crops.

DISEASE APPRAISAL AS A RESEARCH TOOL: -- Besides its value in initiating research, the determination of the distribution, intensity, and destructiveness of plant disease frequently may be an important element in the research itself. Studies on the ecology or epiphytology of disease, as STEVENS (1945) has pointed out, depend largely or almost entirely on estimates of disease losses determined by survey methods. The most precise and detailed laboratory, greenhouse, and field plot experiments on the survival and spread of disease and its relation to the environment, must be validated by analysis of disease development under natural conditions over a wide area. This analysis, if it is to be of value, must be made by methods of determining disease intensity and loss which are reasonably accurate and reliable. Excellent examples of the contribution which disease appraisal makes to research are found in the 8-year ecological study of fruit tree diseases in Illinois, made by TEHON and STOUT (1930). Using objective methods of scaling disease intensity, they arrived at numerous conclusions on the ecology of various fruit diseases through a study of the variation in disease intensity in different years, crops, and diseases of the same crop.

Standardized and reasonably accurate methods of measuring disease intensity and loss again are helpful or indispensable in disease control experiments. Whether attempted control is through the use of fungicides, the development of disease-resistant varieties, or some modification of cultural practices, in all cases, the experimenter must find a means of comparing and expressing, in quantitative terms, the differences in disease intensity between treated and check plantings. He needs, further, to correlate these differences in disease intensity with yield differences. To him, a standardized, objective, quantitative system of appraising disease intensity and loss is the yardstick by which he measures the progress of his research and by which he demonstrates to others the success of his accomplishments and their value in practical agriculture.

PLANNING EFFECTIVE TEACHING AND EXTENSION ACTIVITIES: -- As in research, so in educational work, -- the need is great, the workers are few, their efforts must be directed at the problems that are actually, not only apparently, of greatest importance. The extension plant pathologist selecting the limited number of projects that will constitute his program, the teacher of plant pathology, the writers of textbooks, bulletins, and popular accounts of plant diseases, those whose work is agricultural education in any manner, all have the same need of concentrating their limited efforts on those pathological problems of greatest real significance. The most useful direction of these efforts depends on a comparative knowledge of the losses caused by the various diseases, based on tested methods of disease appraisal, extended to cover significant areas by disease surveys, with the findings interpreted in terms of agricultural and general welfare.

In educational work, facts, not guesses, must support efforts to encourage laymen to follow and support plant disease control practices. These facts on the seriousness of diseases and the need for their prevention can only be obtained by systematic, scientific disease loss appraisal.

Examples of the value of plant disease surveys to the agricultural extension worker have been given by CHUPP (1945) and the usefulness of sampling in extension work has been discussed by SABROSKY (1946). Mrs. SABROSKY'S paper deals with personal polls as an aid to extension work, but the principles apply equally well to samplings of crops. At several points in the extension worker's program, such samplings are helpful in determining the needs for extension activity and program planning; in ascertaining the extent to which recommended practices are being carried out and are proving effective; and in assembling data required for periodic reports.

DETERMINATION OF THE ECONOMICS AND VALUE OF PLANT DISEASE CONTROL MEASURES: -- The expense of disease control is justified only when it can be demonstrated that the cost of control is materially less than the loss suffered when the disease is uncontrolled. The cost of control can be easily calculated; the cost of disease, on the other hand, can be determined only by experiment, measurement of loss, and economic analysis of the loss factor. This is more difficult, yet it must be done before the expense of control practices can be recommended with assurance.

The comparison of these two costs, that of disease loss and that of disease control, must be made under the practical conditions of growing and handling crops. The efforts of both research scientist and extension or survey worker are required, the former to provide dependable methods of disease intensity and loss appraisal, the latter to use these methods under conditions of commercial crop production, storage, and marketing, on a sufficiently broad scale to assure that the economics in favor of control practices are generally applicable. The end result, to expand NEIL STEVENS' (1938) phrase, is the advice to the practical men of agriculture: "If your loss is less than X%, forget it. If it is as high as Y%, you will profit by spending Z dollars to prevent it." Y cannot be guessed at; it must be measured.

There are, doubtless, many cases of plant diseases against which no efforts at control have been directed because, although the loss is considerable, it has never been conclusively demonstrated. In such cases, we can expect that the measurement of loss may be followed by the economically sound, widespread use of more or less costly control measures. There are many crops which are never sprayed or dusted, on which the cost of fungicide applications might be a profitable investment. Important forage legumes are in this category. The measurement of losses caused by soil-borne root diseases may reasonably be expected to be followed by an important extension of the practice of soil disinfestation, once the cash value of this has been shown. Plant pathology may learn a lesson from recent findings in entomology, where, as pointed out by PEPPER (1947), "the remarkable yield increases from new insecticides indicate that it may be profitable to use insecticides on low income crops such as hay and pasture." He cites, as an example, a 50% increase in alfalfa yields from one application of an insecticide, indicating formerly unsuspected insect damage to this crop.

A knowledge of the amount of crop loss from a disease may be helpful, not only in determining whether or not to apply control measures, but also in deciding which of two control measures, one costly but highly efficient, the other less expensive and less efficacious, to use. The cost of the disease, if known, would determine, for example, whether to combat tomato leaf diseases by the partially efficient, inexpensive methods of sanitation, tillage, and crop rotation, or whether to resort to the more costly but more efficient use of fungicides.

In developing, through research, a new method of plant disease control, every plant pathologist has the hope that it will become widely used. He can stimulate its use if his announcement contains experimental data demonstrating that the cost of the control measure is substantially less than the loss which it prevents.

In the recurrent periods of fungicide scarcity, as in both world wars, it is a matter of national security that the limited supply of chemicals be applied against those diseases which would occasion the most serious losses if uncontrolled. Choice of the diseases to be controlled, under these conditions, depends on the value of the crop in the national economy, which is known, and the loss in that crop if certain diseases are uncontrolled, which must be measured. From this point of view, a reliable body of data on comparative crop losses from diseases is a national resource.

APPRAISAL OF THE PRESENT AND POTENTIAL SALES VALUE OF THE CROP: -- Foreshadowing what might be done in applying knowledge of crop losses to agricultural planning and action programs, we have, as a solitary but outstanding example of what has been done, the case of forest appraisal. In determining the value of timber in the forest now or at some specified future date, the appraisal of loss due to decay has become an exact science, and a needed one, because erroneous appraisals discourage contracts and sales.

By use of suitable techniques which have been developed, tested, and approved, it is possible for a well-trained timber cruiser to determine the amount and value of cull which must be deducted from the apparent volume of timber in a forest, in order to calculate the net merchantable timber with sufficient accuracy to permit intelligent financial operations in marketing of the crop. Since decay is the leading cull factor and cause of timber loss, its accurate appraisal goes far in determining the value of the timber.

By means of correlations which have been established between present cull amount or present cull indices and the amount of cull at any specified future date, it has become possible to calculate, with a practically sufficient degree of accuracy, not only the present sales value of the crop, but its future sales value, and from this, to determine the increments of increasing or decreasing value of the forest investment in future years.

Detailed discussions of the appraisal of sales value of standing timber are commonly given in books on forest mensuration and forest pathology. Particularly recommended to those who wish to study further, this aspect of crop loss measurement is the chapter, "Loss and Appraisal of Damage", in D. V. BAXTER'S book, "Pathology in Forest Practice", (1943).

There appear to be few, if any, cases, other than that of forests, in which appraisal of loss from disease, present or potential, is commonly used in determination of the sales value of the crop, other than in a very general and inexact manner. The estimation of hail damage for crop insurance purposes is considered below in another connection. Yet, one can think of many instances in agriculture in which the development of proven methods for determining the influence of the disease factor might be extremely helpful in connection with the sale or rental of farm properties.

This would apply particularly to perennial herbaceous crops such as alfalfa, to nursery stock, to fruit and nut orchards, and to shade trees. In the cases of the tree crops, some of the methods of forest disease appraisal might be applied, with modifications, supplemented by others. As one of many possible examples, the value of alfalfa stands often depends largely on the rate at which they deteriorate from bacterial wilt (Corynebacterium insidiosum). The studies of SALMON (1930), GRABER and JONES (1935), and WEIHING, et al., (1938), on the annual tempo of wilt increase and forecasting wilt losses in future years, if supplemented by data correlating alfalfa stands and yields, would provide a basis for fairly accurately determining the sales or rental value of an alfalfa field, insofar as this leading variable is concerned.

THE VALUE OF DISEASE LOSS DATA TO AGRICULTURAL ECONOMICS: -- There are many contact points between the various activities in the field of agricultural economics and the subscience of plant disease loss determination. Two of these, crop insurance, and land utilization, are discussed separately in later sections.

An important service is rendered to agriculture by the periodic crop news and yield forecasts issued by agricultural economists. The value of this service depends entirely upon its timeliness and accuracy. Some of the factors which have important bearing on crop yields and prices are unpredictable, which increases the necessity for full, balanced consideration of those factors that do have predictable effects on yields. There are numerous cases where plant diseases, acting over a wide area, produce important downward revisions of yield estimates by harvest time. In many of these cases, there exists, or could be obtained, the necessary information to enable the crop reporter to correct his yield estimates well in advance of harvest time. For every degree of greater accuracy and for every deductible day in the earliness of the estimate, its value to growers and marketers increases. The crop reporter needs to know the relative yield-depressing effects of the different diseases, and for each important disease, whenever this information can be secured, he needs to know that a given intensity of disease at a given stage in crop development is regularly followed by a given percentage reduction in crop yield at harvest time. Such information is already available for a few diseases, such as the smuts and rusts of wheat. If this could be extended to include the majority of important diseases of leading crops, properly supported by plant disease surveys to determine the acreages involved in disease, plant pathology could aid agricultural economics to strengthen materially its reporting and forecasting service.

Other points of contact between the two services occur in the compilation and analysis of production statistics and crop prices. Knowing the effect of given intensities of disease on yields and having available survey data of past years on disease intensity, it becomes possible to interpret the role of plant disease in the production totals, to determine the extent to which new disease-control measures may influence future production, and to gain some conception of the levels of production that are attainable with increased disease control. Since the damage from many plant diseases takes the form of lowering the quality of produce, this is reflected in the price received per unit of the crop. The analysis of price variations in the past would be materially aided by recognition of the extent, in any given case, to which disease loss is expressed as quality reduction. Even the forecasts of prices to be received for crops not yet harvested will frequently be improved by definite knowledge of the effect of a given disease situation on the quality of the crop to be harvested later. In a year of destructive rust, a large amount of wheat with low test weight can be expected, and in a potato late blight year, a high percentage of storage and market spoilage can be predicted, but these are more or less isolated cases. We need reliable data that tell us under what circumstances and to what extent, quality reduction from disease, such as to affect price levels, may be anticipated.

Much that has been said above, in reference to disease loss appraisal as it pertains to sales value of the crop, may be applied to the related problems of farm taxation and farm mortgaging and credit. Equitable taxation rates and financially sound farm mortgages and loans depend on a knowledge of many factors, among which the chief one is the value of crops which the farm can produce, Since plant disease is one of the major variables in farm crop production, the disease factor is an important element in the productive capacity of the farm. The same applies to other growing stock, as nurseries or shade trees, which are taxable or which have value for securing loans.

Appraisal of farm lands for tax assessment purposes should be based on the productive capacity of the land. If the yields of the land fall short of its ability to produce because of crop losses due to negligence of the farmer to follow well-established disease control practices, the farm is none the less capable of producing higher yields and its taxation should be on that basis. The differential between apparent value, as seen in actual yields, and real value can be known, insofar as potential yields are reduced by preventable disease, only if one knows the extent to which given diseases reduce yields. Here, crop disease loss information, coupled with appraisal of the disease situation on given farms in question, gives a needed basis for assessment of farm taxes. A similar situation obtains with respect to farm mortgages and credits. The losses suffered from disease affect the loan value of the farm as truly as losses from soil erosion, and a reasonably exact knowledge of these losses is fundamental to evaluation of the farm for assuring security of farm loans.

In the economics of agricultural marketing, there is also an unsatisfied need for more accurate information on the extent to which plant diseases produce deterioration of harvested crops. The absolute amount of market wastage is enormous and is commonly regarded by the marketer as necessary "shrinkage". Most of this loss is caused by diseases, which in many cases are preventable. If we had a comprehensive and reasonably accurate basis of data for evaluating market losses in their true light, it would become recognized that such losses are not inevitable, efforts at their prevention would be justified and facilitated, and market loss prevention would no longer be largely a matter of trial and error. The results would greatly benefit both marketer and consumer, and the agricultural economist who deals with marketing problems would be provided with a more rational, scientific basis for his evaluation and interpretation of market losses.

Finally, a reasonably complete and accurate picture of plant disease losses could make an important contribution to the planning of national agricultural economy, particularly in time of war, when such knowledge becomes a factor in national security. An understanding of the amount of loss of strategic agricultural products caused by plant diseases, present or potential, would make it possible to anticipate such losses and maintain production to meet necessary quotas by increased efforts at disease control or by the planting of additional acres to offset the losses.

A case in point is that of the new Victoria blight of oats (Helminthosporium victoriae). Discovered in Iowa in 1945, in 1946 it destroyed one-fourth of the great Iowa oats crop. In Kansas, it caused 1% loss in 1946 when it was discovered, and a loss of 20-30% in eastern Kansas in 1947. It is now widespread throughout the United States, and many farmers have been discouraged from planting oats or have shifted from the rust- and smut-resistant but blight-susceptible Victoria types of oats to blight-resistant but rust- and smut-susceptible older oat varieties, avoiding one risk by assuming another.

A disease of this magnitude has a profound effect on national production, the full degree of which we probably have not yet witnessed. It unquestionably was a major factor in the meat famine of 1945. It exemplifies strikingly the need for agricultural economists to be supplied, at the earliest possible opportunity, with reliable information on the extent of crop disease hazards, so that such losses as these, telling blows to the national economy, can be diminished by agricultural planning for offsetting the losses by increasing the planting of substitute crops, or by more extensive use of disease control practices.

One can conceive of cases of the opposite sort. If a crop is already being produced in sufficient abundance, despite regular losses from disease, and if new, efficient disease control measures that will greatly reduce these losses are in the process of widespread adoption, economic dislocations from overproduction could be avoided by planning a reduced acreage to compensate for increased acre yields, but this could only be intelligently done if the amount of loss suffered, and about to be prevented, is known.

To the plant pathologist, there appears to be an appalling lack of consideration of the destructiveness of plant diseases in the activities of agricultural economics. Cotton pathologists feel confident, for example, that diseases regularly destroy about one-fifth of the cotton crop. They are shocked to find, in official estimates of factors which reduce the cotton crop (e.g., Anon., Bur. Agr. Econ., U. S. Dept. Agr., 1944), that all cotton diseases are included in "all other" factors which combined are estimated to have an almost inconsequential effect in reducing cotton production as compared with insects and climatic factors.

It is true that the agricultural economist might make better use of what scattered information there is available on the amounts of plant disease losses, -- if he could find this information and could translate it into terms and on a scale similar to those in which other loss factors are expressed. But, so long as a reasonably complete and accurate body of information on plant disease losses is lacking, it is the plant pathologist and not the economist who must bear the brunt of the responsibility. Many ways in which economists could profit by this information have been suggested. Here is an undeveloped service to agriculture of great potential value. It rests with plant pathologists whether they will make the necessary effort to furnish the economist with the needed information on the amounts and kinds of loss caused by plant diseases.

THE VALUE OF PLANT DISEASE LOSS DATA TO COMMERCIAL AGRICULTURAL INTERESTS: -- Timely and accurate knowledge of crop losses is essential in making economical and profitable disposition of harvested crops. It has importance in such regards as allocation of suitable numbers of railroad cars or trucks to harvest points, the planning of canning and packing operations, management of crop storages to provide against shortages of supply, and determining financially sound price levels and commodity trading. Agricultural trade publications regularly publish news of crop disease outbreaks as a service to their industry. In these some attempt is made to weigh the effect of the disease on supply and marketing, but such attempts, at present, can be little more than speculation, in view of the lack of organized quantitative information on crop disease as a factor in reducing crop supply and quality.

Manufacturers and dealers in agricultural chemicals and equipment also have a stake in disease loss measurement. Such measurements may disclose new markets for their products. When it can be shown that a given disease causes a regular loss of a given amount, the manufacturer of fungicides, knowing the extent to which his chemicals can control the disease, is in a position to determine whether or not to undertake an extensive publicity and sales program. To him, the two most important points to be established are: (a) will his product control the disease; and (b) can the product be marketed at a price substantially below the benefit to be realized? The benefit, the crux of the matter, is that fraction of a healthy crop which may be destroyed by uncontrolled disease, the loss, and there can be no intelligent appraisal of the future markets for pesticides until the loss factor has been measured.

An example: Is there a market for fungicides to prevent defoliation in the huge national acreage of alfalfa? There is every reason to believe that available fungicides can control the leaf-dropping which is so common in this crop that one normally finds the ground about alfalfa plants carpeted with fallen leaves, the victims of fungus infection. As much as 50% of the foliage is commonly defoliated, lost from the hay and unavailable for aid to the plant in seed production. Are these leaves dropped after their usefulness to the plant is past or is photosynthesis somewhat or severely curtailed by their loss? In a word, what economic loss results from the defoliation? Is this loss sufficiently great to more than offset the cost of one, two, or more applications of fungicides? The loss has never been measured, evaluated, related to the cost of controlling defoliation. Yet, a major branch of the fungicide industry might develop on the basis of such measurements and analyses for alfalfa and a number of other field legumes.

Almost isolated in this field is the attempt by McCALLAN (1946) to find indications of the needs for fungicides by means of his index of disease importance, described on page 288. The attempt is praiseworthy. Its weakness, as McCALLAN recognized, lies in the imperfections of his initial data, the Plant Disease Reporter crop disease loss estimates. If plant pathologists could substitute measurements for the estimates, often little better than guesses, which these data represent, a very practical and profitable service would be rendered to commercial agricultural interests, one which they, to some degree, could underwrite with profit.

THE DETERMINATION OF HARVESTING CYCLES: -- In planning for the most profitable forest management, a comparison of timber growth increments and decay increments makes it possible to determine the most economical cutting cycle for each forest type. This use of plant disease loss measurement, which is exemplified in the pioneering work of MEINECKE (1929) on quaking aspen and has since been extensively studied, makes it possible to avoid losses by harvesting the timber just before the inroads of decay begin to reduce the net annual increase of wood volume to an unprofitable level. The methods of measuring gross and decay increments will be considered in another connection; here, it is only necessary to point this out as another valuable contribution made through a fairly exact knowledge of the amount and nature of loss caused by plant disease.

In general, this principle does not apply to other crops than forest trees, but there may be an occasional exceptional case. For example, in hay crops that are harvested more than once during the growing season, the maximum tonnage that can be obtained will be the difference between gross growth and the amount of growth which is lost through various causes, particularly leaf and stem diseases. The approach to this problem might parallel that in the forest. Increments of growth and of tissue loss could be measured, and from these measurements, it should be possible to determine both the most profitable intervals between mowing and the increase in hay expected to follow the development and use of direct disease control measures.

THE DETERMINATION OF THE PROBABLE SUCCESS OR FAILURE OF NEW AGRICULTURAL VENTURES: -- "The vindication of the obvious is sometimes more important than the elucidation of the obscure," wrote Chief Justice HOLMES. It is obvious that any new agricultural venture should be preceded by a careful analysis of the hazards involved; it is equally obvious that plant disease can frequently be a principal hazard in attempts at introducing crops into new areas. Yet, the list of agricultural failures due to neglect of this obvious hazard is a long and costly one. STEVENS (1934b) has listed more than 50 cases of agricultural projects that failed because of unforeseen or disregarded plant disease, a sad record of high hopes followed by disaster, crop abandonment, and farm failures.

In most such cases, the hazard could have been foreseen had there been appreciation of the destructiveness of the diseases in question and knowledge of their occurrence in the areas of the proposed projects. The trial- and -error method is a costly one, yet, in most cases, it has been the only means by which planners and growers have been dissuaded from their pathologically dangerous undertakings. In isolated cases, disease loss determinations, disease surveys, and disease hazard maps have made it possible to avoid certain disaster. One of these is the praiseworthy mapping of the Texas root rot (Phymatotrichum omnivorum) danger spots in Texas and Southwestern Oklahoma by the Division of Forest Pathology, U. S. Dept. of Agriculture, in cooperation with the Prairie States Forestry Project. The purpose was to delimit and define the disease hazard so that shelterbelts and nurseries of susceptible species could be located safely, while resistant species could be planted in infested soil.

An adequate basis for predicting the influence of pathology on contemplated agricultural ventures comprises several steps: measurement of the damage which diseases, at given intensities, are capable of producing; determination of past extensions of disease areas and of their present areas by survey methods; study of the ecology of diseases to determine the likelihood that a given disease could prosper in a new location and environment; and a summarizing of this information in the form of disease hazard maps to be used in agricultural planning, in the same manner and with the same advantages as land use maps or soil survey maps.

Part of the information needed for the construction of disease hazard maps is available. Disease loss measurement and disease surveying, two essentials, are treated throughout this book. Information on the ecology of plant diseases is commonly included in publications dealing comprehensively with the diseases. In many cases this information should be supplemented by trial plantings of the crop in the proposed new areas, preliminary to large-scale production undertakings. In the last essential, the summarizing of this information in the form of plant disease hazard maps, the data now in hand have not been fully utilized.

The geographic distributions of numerous plant diseases has been mapped, for example, in many instances in the volumes of the Plant Disease Reporter. The most extensive effort of this sort has been by the Imperial Mycological Institute at Kew, it series of "Distribution Maps of Plant Diseases" now including more than 100 maps. Because of their small proportions, their use as hazard maps is limited to crop planning on a major geographic scale. Yet, they are very helpful in showing at a glance the restricted areas of such crop-limiting diseases as Texas root rot, sugar beet curly top, peach yellows, and cotton leaf curl; the world-wide distribution of others such as the Fusarium wilts of banana, flax,, and crucifers, citrus psorosis, and flax rust; and the scattered but non-uniform distribution of still other destructive diseases, including onion yellow dwarf, tobacco downy mildew, and the Dutch elm disease.

Each map of this kind shows only the present distribution of one disease of a single crop. It has some use in agricultural planning, but there would be much greater aid if the needed data could be assembled in the form of maps, each showing the distributions of all major diseases of a given crop and, insofar as possible, the present non-infested areas in which these diseases are ecologically adopted and might be expected to flourish, if introduced. WEIR (1918) has called attention to the frequent use of pathological forestry maps in Germany, although they have not become commonly used in the United States, and NEIL STEVENS (1938) has mentioned having partial material for plant hazard maps; on two occasions, he attempted to interest the American Phytopathological Society in the development of such maps, but without success.

THE DETERMINATION OF THE LIMITS OF SAFE EXCHANGE OF AGRICULTURAL PRODUCTS AND OF DISEASE-REGULATORY ACTIVITIES: -- In many cases, the danger of introducing plant disease into a new area is so great that prudence demands prohibition or regulation of the movement of propagation materials or other crop products. Embargoes may have economic disadvantages and regulation is costly; these measures should therefore be based on a sound understanding of the potential destructiveness of the disease if it is introduced into a new area.

As with other disease-control measures, the necessity for and value of control by embargo or regulation are functions of the amount of loss the disease is capable of producing. The threshold loss amount, above which, regulation is justified and below which, the cost of regulation would not be warranted, should be the deciding factor in weighing the desirability of regulatory measures.

The threshold loss amount is a complex factor involving all economically important diseases of a given crop that might be introduced through commodity shipments and their combined potentiality for reducing yields in the new environment of the import territory. Despite its complexity, it would appear possible to determine the threshold loss amount with a sufficient degree of accuracy to serve the useful purpose of guiding the practice of disease control by regulation.

Several steps are involved: surveys to determine the incidence of diseases in the export region; measurements of the amounts of loss that they cause; testing, in the export region, of crop varieties that are grown in the import area to determine the degree to which they are subject to losses from the disease factors; determining the extent to which the diseases in question may survive transport and be able to establish themselves in the new area; and analysis of climatic and other environmental factors in export and import areas to ascertain their probable effects on establishment, persistence, and severity of the diseases in the new area. What has been said in the preceding section regarding disease hazard maps applies equally here; such maps are a good and needed means of summarizing the disease danger for the purposes of regulation.

Here, we are primarily concerned with one of these steps, the measurement of disease losses, in some respects, the least studied but most essential step of all. Suppose that a disease is transported, established, persistent, it still has little significance for the regulatory worker unless its capacity for causing crop loss can be demonstrated to be sufficiently great to outweigh the cost and economic dislocations of regulatory measures. Here, on an international scale, we again recall NEIL STEVENS' advice: "If your loss is less than X%, forget it!"; and again, we must know the value of X.

Some attention has been given to this problem in connection with seed-borne diseases, particularly, tuber-borne virus diseases of potatoes. In Bermuda, WORTLEY found by experiment that potato mosaic caused a loss of 50% and that the disease was introduced into Bermuda in imported seed stocks. As a result of his investigations, the importation of potato seed tubers was wisely brought under regulation. At the request of the Certification Committee of the Potato Association of America, LECLERG and others (1944, 1946) conducted tests in seven States during several years to determine the maximum percentage of virus-infected tubers that can be tolerated in seed potatoes without expectation of significant yield reduction. Their tests showed that the threshold value for loss was about 4% leafroll or spindle tuber; less than this amount of seed contamination did not constitute a serious meance to the grower; and this threshold value, once determined, could then be used to establish economical and safe certification standards.

What has been done in these two isolated cases can and should be done for many other diseases that are considered for regulation. Only with this type of information, can regulation be devised in such a way as to afford sufficient protection at the least cost in regulatory expense and economic hardship.

PLANNING BY FARMER-ASSISTANCE AGENCIES: -- A number of Federal agencies have been created for the purpose of assisting farmers in one way or another. The relation of plant disease losses to the work of certain of these, such as the Agricultural Extension Service and the Federal Crop Insurance Corporation, is discussed in other sections of this chapter. Here, we can consider plant disease losses in connection with the services of the Soil Conservation

Service, the Farm Security Administration, the Agricultural Adjustment Administration, the Commodity Credit Corporation, the Farm Credit Administration, and the agency which coordinates the work of some of these and other farmer-assistance organizations, the Office of Land Use Coordination.

All of these agencies are concerned with ameliorating and safeguarding the welfare of farmers, which depend chiefly on improving conditions of production and marketing of farm produce. Since plant disease is a major hazard in both crop production and marketing, it is to the interest of each of these agencies to know the extent of this hazard and give it due consideration in their action programs. When public money is spent to assist farmers in producing and marketing crops, and when these growing or harvested crops are destroyed by disease, the public money is wasted. This is excusable if the loss was inevitable despite careful planning; it is unpardonable if the loss was the result of negligence on the part of administrators who have failed to give attention to pathological hazards. Recklessness on the part of a driver who speeds his vehicle across hidden intersections may have its counterpart in reckless spending when foreseeable hazards are disregarded. Insofar as plant pathologists have failed to furnish such agencies with reliable data on the plant disease loss hazard, they must share the responsibility for this waste of public resources.

A major impediment to securing and using disease loss information in relation to farmer assistance agencies is the policy of "avoiding entangling alliances" which often isolates these agencies, despite their common interest in the welfare of the farmer, and which, in particular, prevents an advisory relationship with exchange of crop loss information between the action agencies and plant pathologists. The staffs of these Federal agencies are deplorably deficient in lacking the services of plant disease specialists, and their policies of isolation prevent their securing the aid of plant pathologists in other Federal or State agencies, despite the willingness of the latter to cooperate.

Among many examples, there is the case of a farmer who was resettled on a rich bottomland farm in southern Oklahoma. In the course of time, he was offered assistance to purchase the farm. Meanwhile, his cotton had been seriously damaged by Texas root rot. He refused to buy or remain on the farm because he knew the destructiveness of this disease and was inexperienced in growing root-rot-resistant substitute crops. The money spent in the attempt to resettle this farmer was wasted, although the invariable destructiveness of root rot in cotton is well known, and the occurrence of root rot on the farm (which would have been suspected from the location of the farm) could have been very easily determined.

After the costly experience of trial and error, some agencies have begun to include the disease hazard in their planning, in a limited way. The Soil Conservation Service issued orders that its nurseries be located outside the known root rot area and in locations not infested with root knot nematodes. The Forest Service approved only disease-resistant species for shelterbelts in the areas which it found by surveying to be infested with root rot. Soil Conservation County Committees in root rot areas have begun to recognize root rot infestation as a factor ranking with soil fertility and moisture supply in determining the type of local farming that will succeed.

Important though the disease hazard may be in long-established types of farming, it assumes even greater importance with changes in type of farming such as are frequent today. Introduction of irrigation, shifts in cropping practices, the culture of new types of crops, intensification and mechanization of farming, all may produce changes, some of them of critical importance, in the disease hazard. Plainly, we are faced with a twofold obligation: on the part of plant pathology, to furnish action agencies with as complete and reliable a body of information on the occurrence and destructiveness of plant diseases as is possible; and, on the part of the action agencies themselves, to make full use of this information in assisting in farm planning, advancing credit, marketing aid, and the other services for which these agencies are responsible.

THE BASIS FOR CROP INSURANCE AGAINST DISEASE LOSSES: -- Few professions are subject to such unpredictable and uncontrollable losses as that of farming. Insurance to protect the farmer against disastrous crop losses would appear to be one of the most valuable means for stabilizing agricultural income and improving the lot of the farmer. However, crop insurance is a most complex and difficult type of insurance to write on a sound financial basis for a number of reasons, including the variety and unpredictability of the risks, instability of the value of the insured property, and difficulty in appraising the amount and character of losses.

Because of these difficulties, many attempts at crop insurance, made by private insurance companies in the past 50 years, have all failed (Report of the Manager, Federal Crop Insurance Corporation, 1947). Since farmers did not have this aid from private enterprise, Congress passed the Federal Crop Insurance Act of 1938. Wheat was first insured in 1939, cotton in 1942, tobacco, corn, and flax in 1945, and the Act provided for experimental insurance of other crops. In 1947, after insurance of wheat, tobacco, and corn had resulted in credit balances, with a slight loss in flax and substantial losses in cotton, the entire program was placed on an experimental basis, since it was recognized that development of a sound crop insurance program is a long-time project, requiring many years of accumulated experience.

The Federal Crop Insurance program aims at protecting farmers from production risks over which they have no control, from seeding to harvest and threshing time. Indemnities for crop losses are paid on a basis of "average normal yield" for the insured farm or comparable farms in the area. They do not cover "avoidable losses such as those resulting from the use of defective or unadapted seed, failure to properly care for and harvest the crop, or failure to follow established good farming practices" (correspondence, F.C.I.C., 1947). These omissions are interpreted to include failure to prevent losses from plant diseases that might have been avoided by standard disease control practices such as the use of disease-free or disinfected seed, disease-resistant varieties, spraying or dusting, and other "reasonable and practicable disease control measures".

In practice most crop insurance indemnities are for losses caused by climatic factors such as droughts, floods, frost, or "poor growing conditions". At times, there have been substantial indemnities for insect damage, particularly from the cotton boll weevil and the corn borer. Indemnification for losses due to crop diseases are extremely low, entirely out of proportion to the damage caused by disease. In the case of wheat, for example, it has been authoritatively established that of all causes of crop loss, 80% are due to weather and miscellaneous factors, 12% to diseases, and 8% to insects. This figure for diseases, 12% of all losses, compares with actual indemnities for wheat diseases paid by the F.C.I.C. in 1940, 1941, 1942, and 1945, respectively, of 3.1%, 5.9%, 1.1%, and 0.76% of all indemnities paid on this crop. Diseases of wheat and estimation of the losses caused by them have been more thoroughly studied than is the case with cotton and other crops, where the disparity between the figures for indemnified disease losses and those for all losses in the crop is even greater. For 1945, the indemnities for all diseases in cotton, corn, and flax, in each case, were less than 1% of indemnities for all causes.

There are several reasons for the disproportionably low indemnities for disease losses. Some disease losses are preventable and therefore non-insurable. Others are not recognized as diseases by insurance adjusters and are classified under such captions as "excess moisture". Insurance covers only 50 to 75% of the average yield and disease losses of less than 50 or 25% of the average yield, in the two cases, might be disregarded or subordinated to more spectacular climatic loss causes.

But there is another, very important reason why plant disease losses have been given such trifling consideration in crop insurance, the fact that there is no comprehensive and useable body of information on the amount of damage caused by plant disease. Without this information, there is no sound basis for determining indemnities, therefore, plant diseases are almost disregarded as insurable loss factors.

The development of an objective basis for hail insurance illustrates what can be done and what needs to be done for crop diseases. With corn, (DUNGAN, ELDREDGE, KIESSELBACH and LYNESS), small grains (ELDREDGE), onions (HAWTHORN), flax (KLAGES), and soybeans (ELDREDGE and KALTON), in each case, experiments in which the crop was injured in imitation of hail injury have shown the amount of loss sustained by hail injury of different degrees of severity and at different growth stages. These experiments have provided a sound basis for hail insurance, the only type of crop insurance which has been scientifically based and the only one which is a proven success.

What has been done in providing a sound basis for successful hail insurance can and should be done for crop disease insurance. This need not be done for all diseases, but only for those that are significantly destructive and beyond the control of farmers. Since some diseases are highly destructive only in occasional or rare years, this type of insurance would need to be on an experimental basis for a sufficiently long time to permit calculation of reliable average losses. Attention must be given to the distinction between locally important diseases (which do not seriously affect average loss percentages, but which require more intensive appraisal) and diseases that occur more or less uniformly over wide territories. Because of the pathological characteristics of this risk, the development of successful crop disease insurance will require intimate collaboration of plant pathologists and crop insurance personnel.

Extended accounts of crop insurance are contained in the annual reports of the Federal Crop Insurance Corporation since 1943, and the papers of VALGREN (1922) and SCHLUMBERGER (1927).

THE VALUE OF DISEASE LOSS DATA IN OBTAINING SUPPORT FOR PHYTOPATHOLOGICAL RESEARCH, EDUCATIONAL, AND REGULATORY WORK: -- Last among the applications of information on crop losses from plant disease, but ranking high in importance to plant pathology, is the usefulness or indispensability of this information for securing financial support of pathological work. LYMAN pointed this out in 1918 (see quotation in Prologue), but, for the most part, his counsel was unheeded, and almost 30 years later, PAUL MILLER (1946) was impelled to remind pathologists that "if crop loss estimates are used to the extent of determining appropriation of public funds, we should either meet the challenge and improve their quality, thus putting ourselves in a position to defend their validity, or else admit their shortcomings."

Everyone who has dealt with administrators of funds will agree that the demonstration of the dollar and cents value of a proposed undertaking is the most persuasive of arguments. We know that plant diseases often cause enormous losses, that our modest requests for financial support represent but trifling fractions of those losses, and that our accomplishments in plant disease control repay manyfold the cost of our work. But, our own sincere convictions, unsupported by evidence, cannot be expected to persuade hardheaded men of finance of the value of our proposals.

Lately, there have been a few instances in which it has been possible to express the value of research in the concrete terms with which these men are familiar. REITZ (1947), in promoting an expansion of hard red winter wheat research, has demonstrated that a research investment of $200,000 per year has resulted in the production of 8 new wheat varieties which outyield the older varieties, because of disease resistance and other qualities, by 10 to 30%. These have produced a benefit of $50,000,000 per year or $250 of new wealth for every dollar invested in research. Similarly, CRAIGIE (1944) has shown that the introduction of rust-resistant wheat varieties in the Prairie Provinces of Canada has resulted in an annual yield increase of 41, 339,000 bushels valued at $27,242,000. The research which produced these varieties cost a total of $2,000,000. The profit in each single year is 13 times the total cost in all the years of the research that produced the new varieties.

The U. S. Department of Agriculture, keenly aware of the necessity of demonstrating the profits of research in competing for appropriations, has encouraged its personnel and their collaborators to supply data on the cost and profits of research, and the "Research Achievement Sheets" published from time to time by the Department contain reference data which include the cost and the value of each discovery.

The prosperity of plant pathology as a science depends most on the financial support which it receives. This support, in turn, depends to a major extent on the ability of plant pathologists to demonstrate the economic value of their work. The latter, finally, depends on the accumulation of reliable data showing in reasonably accurate terms the amounts of loss caused by the various diseases and, consequently, the gain from disease control that has been attained or is in prospect. From this point of view, the securing of these data, the measurement of plant disease losses on a broad and comprehensive scale, is not just another optional facet of pathological studies; it is vital to the prosperous future of the science.

THE ECONOMIC VALUE OF PLANT DISEASE FORECASTS: -- "Famine conditions in Europe and Asia have been aggravated sorely by a disastrous crop failure in the southern hemisphere. Not until December came, could the world's planners possibly know that the trans-equatorial fields had failed to yield their expected harvests, and by then, it was extremely late for the planners to design a new program of famine prevention."

This editorial from The Daily Oklahoman, April 29, 1946, strikingly illustrates the important service that can be rendered agriculture and society by developing the ability to forecast crop prospects reliably and predict crop losses or the escape of crops from loss factors. The crop hazards that vary from one season to another, the uncertain factors for which forecasts might be most useful, are weather, insect pests, and crop diseases. The situation with regard to each of these factors may be favorable, harmful, or ruinous. Progress toward the more accurate and more timely forecasting of losses or escape from any and all of these factors is progress toward sounder agricultural economy whether viewed from the standpoint of the farmer, individually or collectively, the handlers of agricultural commodities, or the national economy.

To the farmer, a reliable crop disease forecast appears to be most useful if it enables him to avert predicted disease outbreaks by timely intervention of disease control measures, such as crop spraying or dusting, or to save the expense of these control measures in those seasons in which the forecasts are for relative freedom from disease. This value of timely warnings has been repeatedly demonstrated in the forecasting and spray-warning services for preventing losses from the downy mildews of potatoes and grapes. The former were initiated in Italy in 1922, and the latter in Holland in 1926. These services soon became widely used in Europe and were the forerunners of the American potato and tomato late blight forecasts, evolved during

World War II, and since made the basis of a formal, nationwide plant disease forecasting system. (cf. pages 328 ff.). Blight forecasts and spray warnings have been issued in sufficient time to avert blight losses by spraying, and in years of minor blight, as in 1947, potato and tomato growers have been saved the considerable expense of unnecessary spraying.

Plant disease forecasting falls within the field of this discussion of plant disease appraisal from two points of view: first, because forecasting depends on the determination of disease intensity and its change in relation to weather, so that the reliability of forecasting depends on the accuracy of disease intensity appraisal; and, second, because the value of a plant disease forecast becomes greatly enhanced if the amount of loss that may be expected, and not merely intensity of disease outbreak, can be predicted. A disease forecast in terms of probable loss, for example, not only tells the potato grower that this is a season in which spraying will be warranted, but may also give him a basis for deciding how much spray expense is likely to be offset by the difference in yield between sprayed and unsprayed fields. Each advance toward more uniform appraisal of disease intensity, and toward correlation of a given disease intensity with the consequent loss factor, will thus contribute toward more reliable and useful forecasting.

Plant disease forecasts may also be useful to the farmer and others even though the nature of the crop and disease are such that direct control measures cannot be applied. As an example, there is the case of the southwestern winter wheat grower whose stand of wheat is only fair, because of drought at planting time or winter injury. He is undecided whether to permit the crop to continue growth to maturity or to pasture it off or cut it for hay and plant the land with a substitute summer crop of corn, sorghum, field legumes, or cotton. His neighbor is undecided whether this is likely to be a season of abundant yields justifying him in purchase of a combine for custom harvesting. Another neighbor is undecided whether this year the crop will justify the expense of constructing additional crop storage facilities, and the local grain elevator operator has similar problems. The local railroad agricultural agent is undecided as to the extent of provision to be made for disposal of the crop, and the banker would like to know how much credit he can allow on the security of the coming harvest.

To all these men, reliable forecasts of crop yields or yield factors are valuable aids, contributing toward a sounder agricultural economy. Plant disease is only one of the several yield factors. In itself it does not necessarily spell crop success or failure, even though its effects are commonly late in the growing season of the crop, when most other yield hazards lie behind. It would be folly to attempt to predict yields from a knowledge of this factor alone. Yet, it is a weighty factor. Plant disease forecasts in conjunction with long range weather and insect pest forecasts can be of great service to agriculture and the industries dependent on agriculture, and in whatever measure even one of these hazards can be forecast, to that extent a partial service is rendered.

Plant pathologists are unduly timid about disease forecasting, as though a single erroneous forecast would be ruinous to their reputation. The official weather forecasts have an accuracy of about 80%, yet no one questions their utility. A comparable margin of error is acknowledged in the "predictions of things to come" by leading news commentators, agricultural and industrial publications, economists, and those who conduct public opinion polls. Yet, these predictions are eagerly received and often put to good use. No one expects the forecaster of weather, news, prices, or plant diseases to be infallible; if his forecasts are correct four times out of five, they are of proven value and far preferable to no forecasts at all.

The latent plant disease forecaster may be inhibited for other reasons than fear of the consequences of an occasional error. Many plant pathologists who are in positions to forecast plant disease are in tax-supported organizations, and they may be restrained from forecasting lest it direct the taxpayer's attention to the temptation for public officials to take private advantage of their foreknowledge of crop prospects. In other cases, they may be deterred from making low-hazard forecasts by fear of criticism from poorly-informed agriculturists, who regard such forecasts as harmful because of their possible effect in reducing farm crop prices. But these objections to forecasting are economically unsound; they avoid a lesser, real or imaginary evil by accomplishing a greater one, -- depriving the men of the agricultural industry of information that would contribute toward more profitable and economic production and marketing.

While crop disease forecasts are of value to the farmer, the processor, the marketer, the manufacturer and distributor of fungicides, and all of the others who are concerned directly or indirectly with harvest returns, from a national point of view, such forecasts assume even greater importance. The economies of this nation and of those other nations that must depend on this one for agricultural produce, are dependent on our production levels. If these levels are threatened by disease or any other hazard, the sooner this can be foreseen the greater the opportunity will be for averting the losses by crop protection or compensating for them by substitute production practices or conservation measures. In this light, the forecasting of crop hazards, specifically, the forecasting of crop disease outbreaks and losses, is a national resource.

Chapter II

THE DEFECTS IN PRESENT PLANT DISEASE APPRAISAL PRACTICES

Plant disease surveys have never been highly organized and strongly supported, with the result that existing data on plant disease occurrences, intensities, and resultant losses are incomplete and non-representative. Lacking standard methods for scaling disease intensity and with little experimental basis for determining the losses caused by plant diseases, our estimates of these losses, in the few cases where we have them, are often in error, as has been seen when estimates have been compared with measurements. These defects in our knowledge of plant disease losses, and the reasons for them, are discussed in the present chapter.

THE FRAGMENTARY AND ILL-ASSORTED CHARACTER OF SURVEY AND LOSS DATA: -- No other country has made an attempt comparable to that of the United States to assemble extensive data on the distribution in time and space, intensity, and destructiveness of all principal diseases of crops (MORSTATT, 1937). In the United States the most extensive repository of these data is the mimeographed publication of the U. S. Department of Agriculture, the Plant Disease Reporter, the volumes and supplements of which have been regularly issued since 1917. We can regard the Plant Disease Reporter as the best source of disease prevalence and loss data now available.

The Plant Disease Reporter is an extremely valuable reference work. From it the plant pathologist may glean a wealth of data that are helpful in studies of disease occurrences, in space and time, and of the ecology of plant diseases. The shortcomings of these data, from our standpoint, are largely due to the incompleteness and non-uniformity of the reports, which are submitted voluntarily with such varying degrees of completeness, accuracy, and uniformity as may be possible or appear essential to the contributors. There is a tendency to report only extreme cases of disease outbreaks from which destructiveness averages cannot be derived. Many of the reports are of disease occurrence only, without information on its severity. Many others indicate severity by such general terms as "worse than usual", "very injurious", and "unusually prevalent" which convey little meaning to the reader who is unfamiliar with the average situation in the area concerned, and none to the analyst who is attempting to place disease severity on a numerical basis. In some of the reports an attempt is made to define disease severity by reference to a standard scale, such as the COBB rust scale (see page 244), but for a given disease the scales may differ in kind and accuracy, and in the majority of reports, if disease intensity is mentioned it is in terms of a verbal scale which may be understood only by the contributor himself.

It is often impossible to determine from the reports whether disease outbreaks are general over a wide area or localized on a few farms. The data from some agricultural areas are much less complete than those from other areas which are better staffed. Due to the personal research interests of individual reporters, the spectacular character of some diseases contrasted with the more subtle destructiveness of others, and other factors, we find some crops and diseases much better documented than others.

The strength of the Plant Disease Reporter is in its records of disease occurrences. Its data on disease intensities, for comparative purposes, are weaker for the reasons cited. The volumes contain many references to single instances of disease losses which are useful as examples of loss and to some extent roughly depict the relative injuriousness of the various diseases, but because of their incompleteness and lack of uniformity they have only limited value in attempting to gain a reliable comparative view of the destructiveness of the various diseases in one or several crops.

Annual crop loss estimates, issued as Supplements to the Plant Disease Reporter, from 1917 to 1939 and then discontinued, tabulate the losses caused by a few leading diseases and by "all diseases" in each of several major crops. These are compiled from the estimates of key pathologists in each State and vary from highly accurate appraisals, based on extensive surveys and a knowledge of disease intensity-loss relationships, to others, perhaps a majority, which are little better than guesses.

There is no other body of data on plant disease prevalence and losses comparable to the files of the Plant Disease Reporter. Isolated useful data are scattered through thousands of other books, periodicals, bulletins, and special survey reports, and are found summarized only in very infrequent cases, in the few papers devoted to studies of crop loss from disease. In general, the limitations of the Plant Disease Reporter data, from our point of view, are equalled or exceeded by the weaknesses of these other scattered references to disease intensity and loss.

THE VALUE OF RELIABLE ESTIMATES, VERSUS MEASUREMENTS: -- One sometimes hears criticisms of estimates as though they had no place in the activities of accuracy-loving scientists. As authoritatively defined, "an estimate is a judgment or opinion, usually implying careful consideration or research; a judgment made by calculation, especially from incomplete data; a rough or approximate calculation". So construed, with their limitations recognized, estimates may often be of value to scientists, though they are no substitute for measurements. This subject has been admirably discussed by NEIL STEVENS (1941b) who points out the basic value of estimates in business and economics and the legitimate use of approximate data even in such "exact" sciences as chemistry and physics.

Estimates or approximations are often preferable to no data at all. There are many instances in plant pathology and other sciences in which numerically exact data cannot be obtained; here it is estimates or nothing. Even when exact data can be secured this may be very costly as compared with estimates, and the latter may be preferred when a high degree of accuracy is not essential.

In crop disease loss studies, accurate measurements of loss can be made in experiments designed to determine the relationship between given disease intensities and loss. When it comes to extending these findings to extensive areas the result must be estimates. They will serve the useful purposes indicated in Chapter I if such estimates are extensions derived from measurements and if it is recognized both by estimators and those using the estimates that they are approximations, with certain limits of error but defensible within these limits.

In some cases in the past, plant pathologists have been reluctant to give numerical estimates of crop losses, contenting themselves with loosely generalized descriptive terms. If the estimate is "an opinion based on careful consideration and research", and if limits of error are recognized, it is entirely justifiable to report estimates in terms of bushels, tons, or percentage of crops, and if this is not done the estimate, however carefully arrived at, will have little practical use. The measurements of the effects of disease that are described and encouraged in the chapters that follow are designed to determine approximately the order of magnitude of losses from various diseases, and to narrow the limits of error, to a practical degree, in the loss estimates which must represent the final useful form of our loss statistics.

EXAMPLES OF ESTIMATES CONFIRMED BY OTHER MEANS: -- While time and experience have shown that some of the crop loss estimates of past years have been in serious error, there are a number of other cases in which loss estimates based on adequate surveys and on a knowledge of the relationship between disease intensity and crop loss have been confirmed by independent, objective criteria.

One such example, described by NEIL STEVENS (1940a), is that of wheat bunt, (Tilletia spp.) in which the total loss estimates of Plant Disease Survey collaborators showed the same trends as the official records of smut dockage by federal grain inspectors (Fig. 1). STEVENS and WOOD (1935) give a second example in their comparison of corn losses due to ear rots as estimated by Plant Disease Survey collaborators (Fig. 2) which also showed the same trends as the federal grain inspectors' records of railroad cars with more than 6% damaged kernels. In both of these examples the collaborators' estimates and the inspectors' records agree in trend but cannot be compared as to absolute loss levels, because different disease effects were being appraised, -- total loss on the one hand and percentage of damaged carloads on the other.

As we will see in Chapter VII there are many other independent sources of crop loss information. STEVENS has shown how old local newspaper accounts of the cranberry harvest and records of picker payrolls helped to reinforce his estimates of cranberry losses in past years. It would aid in determining the validity of loss estimates and often strengthen the reliability and increase the acceptability of estimates if more opportunity were taken to bring information from several independent sources to bear on loss appraisals.

THE UNRELIABILITY OF ESTIMATES WITHOUT EXPERIMENTAL BASES: -- When there is no experimental basis for knowing the amount of loss from a plant disease it is a mistake to dignify the opinion of the loss by calling it an "estimate"; more appropriate is the term "guess", which is defined as "an opinion without knowledge or means of knowledge." Certainly that definition applies to many plant disease loss statistics that have been published in the past, with the consequence that when the losses have been investigated experimentally the "estimates" have been found far too low or sometimes too high. Many examples of this could be cited, and the following are typical.

CHESTER (1946b) has reviewed the literature pertaining to estimates of losses from wheat leaf rust. Prior to 1926 this disease was generally regarded as negligible or even beneficial to wheat. Between 1926 and 1936, MAINS, JOHNSTON, CALDWELL, and others measured the loss

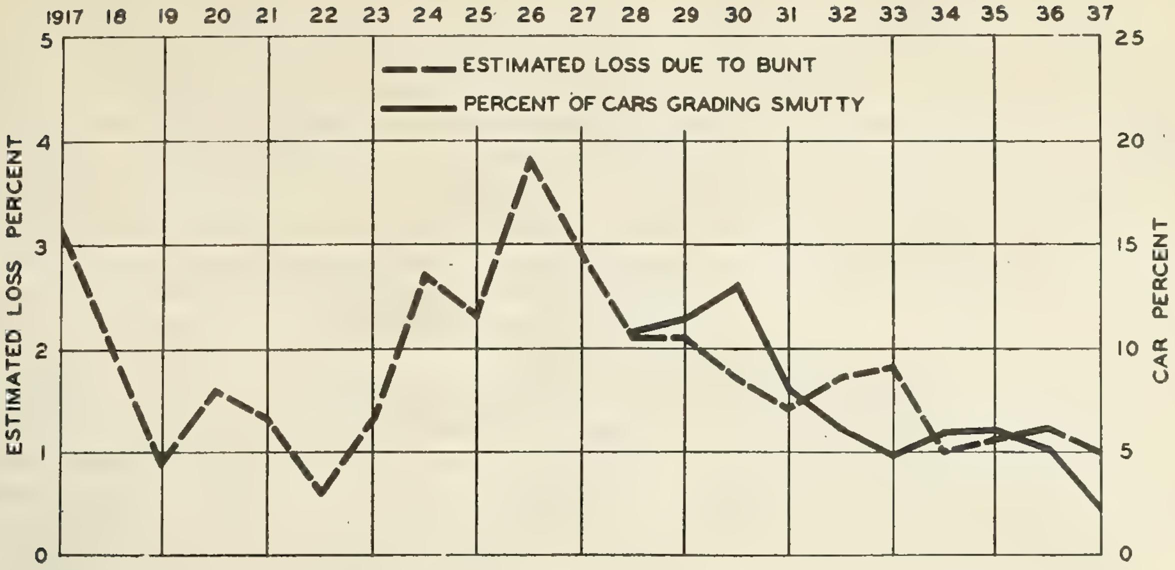
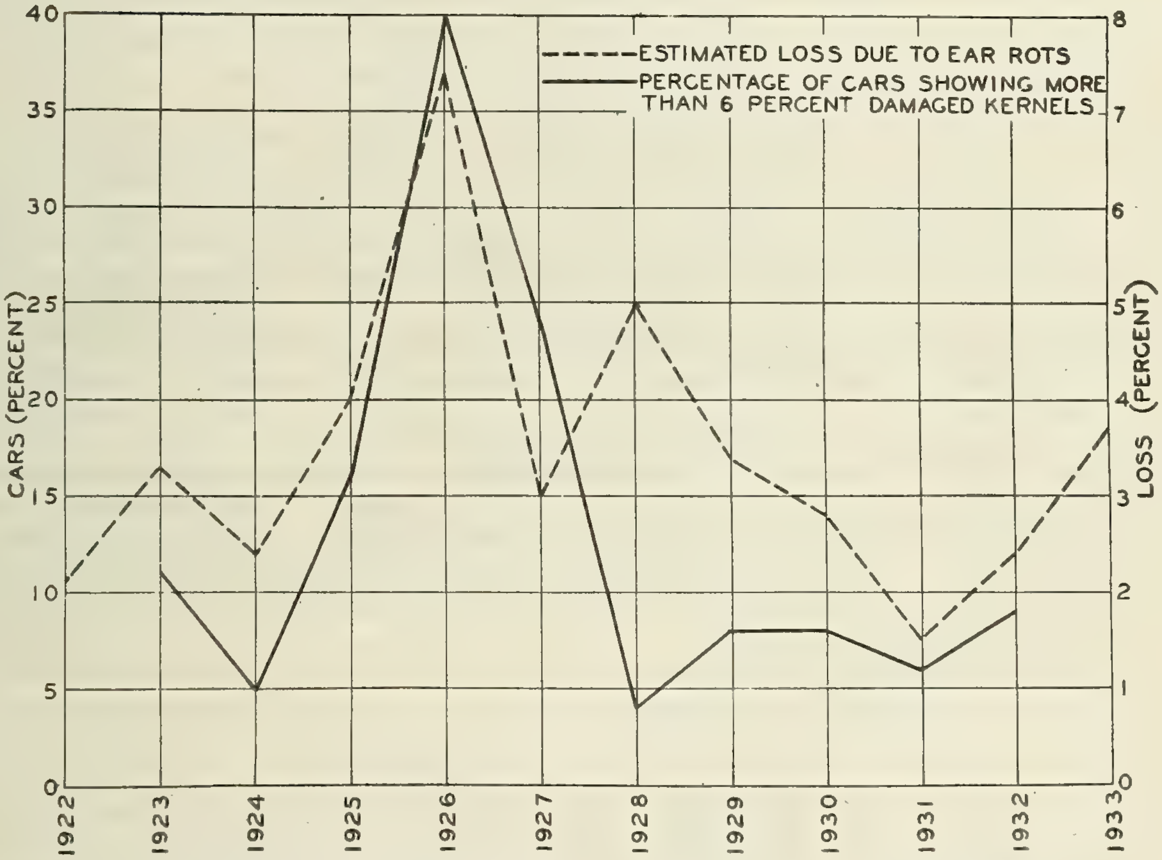


Figure 1. -- Estimated losses from bunt of wheat in United States (reporting area), 1917-1937, and percentage of cars grading smutty at all terminals, 1928-1937. (After NEIL STEVENS, 1940a.)



—— Percentage of cars showing more than 6 per cent damaged kernels.
--- Estimated loss due to ear rots.

Figure 2. -- Percentage oi cars of corn showing more than 6 percent damaged kernels, as indicated by reports of Federal grain inspectors of the Bureau of Agricultural Economics, for the years 1923 to 1932, inclusive. Estimated losses in corn due to ear rots for the United States as a whole, and compiled from reports from collaborators of The Plant Disease Survey. (After STEVENS and WOOD, 1935.)

from leaf rust by means of infection and fungicide experiments, and found that the disease reduces the crop by 35% if it destroys the leaves in the blossoming stage, with greater or less yield reduction associated with earlier or later rust attacks (see CHESTER, 1946b, Fig. 2). All of the earlier reports on leaf rust losses in the Plant Disease Reporter and other publications, and some later ones, must be regarded as gross underestimates in the light of these experiments.

HORSFALL (1930) mentions workers who believed that no damage was caused by powdery mildew of clover but his measurements showed that the disease reduces the crop by 1/3 to 1/4. The U. S. Bureau of Agricultural Economics (1944) indicates that diseases are almost negligible among the factors which lower cotton yields, yet we now have evidence that seedling blight alone, if uncontrolled, reduces the crop by 10 to 20%. EZEKIEL and TAUBENHAUS (1934) have concluded from careful studies that root rot causes a loss of 8% of the Texas cotton crop, and every cotton pathologist recognizes by dead plants and rotted bolls the additional heavy losses from the widespread wilt, bacterial blight, and boll rot diseases.

Gross errors in estimation of crop losses are not limited to those caused by diseases. For example, although WEISS (1940) has stated that insect pest estimates are generally too high, PEPPER (1947) has reported that spray trials with modern insecticides have revealed such remarkable yield increases in potatoes, sweet corn, and alfalfa that it is becoming apparent that older estimates of insect damage were extremely low.

Inaccurate crop loss estimates are harmful. If losses are not recognized or are underestimated, adequate efforts are not made to reduce the losses and they continue as drains upon the national economy. If wheat leaf rust destroyed no more than 5% of the national crop annually, a conservative estimate in the light of present knowledge, the loss in the 35 years, 1900-1935, during which the damage from this disease was considered negligible and little effort was made toward its control, amounted to 1 1/2 billion bushels.

Erroneous loss estimates give plant pathologists and agriculturists in general a false idea of the relative importance of the various crop hazard factors with the result that less important problems receive more attention than more important ones. Underestimates of loss deter manufacturers from producing equipment and materials for loss prevention. Overestimates may lead to wasteful efforts to combat hazards that actually may not justify the expense of their prevention. The many advantages of reliable crop loss information discussed in Chapter I become that many disadvantages when we have crop loss misinformation.

Even when an estimate is reliable within certain limits it may be misused or even metamorphosed into a statement of fact. For example NEAL (1928) states (p. 3) that "the estimated reduction of cotton yield in the United States because of wilt was 350,000 bales in 1925." In the summary of the same paper (p. 46) the statement appears: "the annual loss to the cotton crop in the United States is in excess of 350,000 bales." In this case an estimate for one year has been transformed into a statement of fact for all years. The Plant Disease Reporter, the presumable source of the estimate, places the average loss for the only six years for which data were available at that time at 330,000 bales, with only one of the six years showing a loss "in excess of 350,000 bales."

Another type of misuse of estimates, leading to an erroneous conclusion, is seen in an early paper by RIEHM (1910). In connection with a widespread outbreak of rye rust in Germany in 1891, 7500 questionnaires on rust losses were sent out to growers by the Deutsche Landwirtschaftliche Gesellschaft. Only 400 (5.3%) of these were returned. RIEHM assumed that the rusted acreage reports in this small fraction of returns constituted the total rusted acreage, and he compared this reported rusted acreage with the total estimated rye acreage and derived a figure for rust loss which was trivial.

He concluded by ridiculing SORAUER'S more substantial (and on the basis of present knowledge doubtless more reliable) loss estimates.

REASONS FOR INACCURATE ESTIMATES: -- There are numerous possible causes underlying inaccurate disease loss estimates, the chief of which are discussed below.

Failure to Allocate Loss To Its Actual Cause. -- When several factors may cause crop loss, and particularly when two or more such factors affect a crop simultaneously or in sequence, it may become very difficult to determine the relative and absolute effects of each factor. As a result it has often happened that loss which is actually due to one factor is ascribed to another. This is recognized as a serious fault in insect pest damage estimates (WEISS, 1940) as well as with plant diseases.

Every plant pathologist can cite his favorite examples of mistaken identity of loss factors. Texas root rot in the Southwest is very commonly ascribed to the effects of lightning or alkaline soil. Leaf and stem rusts of cereals are confused. The injury caused by minute insects and arachnids is often taken to be due to plant disease. Spray injury and fungus leaf diseases are frequently confused. When crop injury from the herbicide 2, 4-D was first seen it was everywhere thought to be due to viruses. The list could be continued indefinitely.

Among the loss factors the practical men of agriculture are most conscious of weather and soil effects, fairly familiar with insect attacks, and understand crop diseases least of all. It is only to be expected that an unexplained crop loss is ascribed to the factors with which the grower is most familiar, and that, as a result, diseases, with microscopic causal agents and effects superficially resembling those due to unfavorable environments, will commonly be attributed to some likely environmental influence or, sometimes, to insects. It follows that estimates of plant disease loss are not infrequently too low and those for the other crop hazards correspondingly too high. Occasionally, with spectacular diseases that cause little injury, the reverse may be true, the disease losses being overestimated.

A striking example of confusion of loss hazard is seen in the analyses of American wheat losses in 1938. In that year (CHESTER, 1946b, p. 20) the disappointing harvest returns in the Southwest were ascribed by different observers to leaf rust, stem rust, excessive moisture, late harvest, insects, hail, and late freezing injury, alone and in various combinations. Difficult as the interpretation of such a situation may be, it should be possible, as one by one hazard factors become better understood, to break these loss complexes down into their several components, and attribute to each its relative partial role in the loss.

Sometimes the problem is one of determining which of two or more similar diseases may be present. YARWOOD (1946a) cites numerous workers who disagree completely regarding the effects of "giant hill" on potato yields, some finding a major or minor yield decrease from the disease while others consider that the condition increases yields above those of normal hills. He considers that one reason for this discrepancy may be that the several investigators are dealing with conditions of different etiologies.

Failure To Appreciate The Destructiveness Of Factors That Are Relatively Constant From Year To Year And Not Spectacular Nor Widely Publicized. -- Diseases that occasionally break out with explosive force are less dangerous, in one respect, than those diseases that are always present to about the same extent. Like rats, weeds, taxes, soil erosion, and the common cold, we have come to consider these constant diseases as "normal" or inevitable. We tolerate them and often forget or never realize that their constancy and our acceptance of it may constitute their most dangerous feature. The occasional spectacular outbreaks, like fires, tornadoes, or plagues of locusts, arouse us to action, and we may often consider that these headline-making hazards are relatively more destructive when, if we average their effects in time and area, we find that the spectacular hazards are doing less damage than the others which fail to attract our attention because they are always with us. Our susceptibility to influence by the spectacular leads us to overestimate the losses from such hazards, while we underestimate the destructiveness of the common, constant ones. We find this true in every branch of plant pathology.

In forestry much more emphasis is laid on fire control than on pest control, yet forest pests destroy more timber than fires. From 1934 to 1943 insects and diseases are estimated to have destroyed 622 million cu. ft. of American timber, while fires destroyed 460 million (WYCKOFF et al., 1947). Similarly, decay of construction timber causes more loss than fire, but its replacement is considered as "normal", and our expenditures for decay control are trivial compared with those for fire prevention. The practical forester regards a few spectacular diseases as diseases. Wood decay, which destroys more timber than any other cause, he considers as normal and inevitable cull. The drain from enphytotic diseases is assumed in "normal forest growth".

In the marketing of agricultural commodities much the same situation prevails. "Few people, even pathologists, realize what enormous quantities of fruits and vegetables are lost through disease, decay, and other preventable causes between the producer and the consumer." Thirty years have passed since SHEAR (1918) made that statement, yet it might have been made today as market loss records will testify. Spoilage claims paid by railroads, board of health produce condemnations, the dump piles behind processing factories, and even the family garbage disposal, all point to the millions of bushels of fresh produce that leave the farm never to be consumed by humans, and all this enormous loss, sometimes half or more of shipments, is considered "normal marketing shrinkage", "part of the game", to be paid for by the consumer.

Turning to diseases in the field, we find a similar disregard of those diseases that are not spectacular or well advertised. This has been the case with leaf rust (Puccinia rubigo-vera var. tritici) of wheat as brought out in the following quotation from WOOD and NANCE (1938):

"In areas where leaf rust is most important it occurs practically every year to a greater or less extent, with the result that its effect on yield is apt to be overlooked except in epidemic outbreaks.......Because it occurs to some extent every year it does not focus the attention by a spectacular outbreak as does stem rust. In contrast to the apparent suddenness with which stem rust often attacks, leaf rust is apt to appear early and to develop steadily throughout the season .....Possibly this contrast with stem rust is a chief factor responsible for minimizing leaf rust as a cause of loss...........

"It is probable that if the loss from stem rust were spread over a period of years instead of being concentrated in destructive outbreaks, the disease would attract much less attention than it does. Suppose, for example, that the loss in Minnesota, instead of varying from a trace to 57%, had been 11% annually, which is its present average and the highest for any state. Would it not be considered a routine loss, subject to the 'familiarity that breeds contempt' rather than a calamity to be feared?"

The same "familiarity that breeds contempt" may be seen for many other types of diseases including defoliation diseases of meadow crops (HORSFALL, 1930), bacterial blight of cotton, powdery mildews of peas and some other crops, and root deterioration with premature death such as is common in many crops. It goes without saying that these considerations influence disease loss estimates, even by competent crop appraisers, -- losses from the disease that is spectacular or has a good press agent are fully estimated or even overestimated, while those of diseases that may be quite as destructive, or even more so, but are common and constant, are underestimated.

Lack Of A Disease-Free Standard. -- If a disease is invariably present in a crop the amount of loss which it causes may be underestimated or overlooked because of the lack of a contrast with disease-free plants. For many years this was the case with the latent mosaic of potatoes, as discussed on page 196. Measurements of loss are sometimes difficult because there is no disease-free standard and it is necessary to compare two degrees of disease, rather than diseased with disease-free plants. This has been a difficulty in some of the potato virus loss studies, such as those of MURPHY and McKAY (1924) and of WERNER (1925). If, as some believe, there is invariably a certain amount of decay in the root systems of "normal" plants, we may be failing to detect significant losses from this cause. Foliage diseases in hay crops are further examples.

In all these cases it is possible to measure the loss by experiments in which the invariably-present disease is controlled, using one or another of the techniques described in Chapters VIII and IX. Where this has not been done the reason is usually a psychological one; contrasts between diseased and disease-free crops are not observed in nature; the diseased crop is regarded as a normal one, and therefore the incentive to investigate the losses caused by these omnipresent diseases has been lacking.

Lack Of Negative Data To Temper Reports Of Epiphytotics. -- There is a common and natural tendency for crop reporters to stress the more destructive occurrences of hazard factors and fail to report the absence or minor effects of these hazards. This is recognized as an outstanding weakness of insect pest surveys (HYSLOP, 1927) and applies equally to plant diseases. Severe outbreaks are news; the absence of outbreaks is not. The result is that one can and does get a distorted impression of the importance of diseases from popular or technical crop news publications.

Leafing through the volumes of the *Plant Disease Reporter* one is impressed by the frequency of articles with such titles as: "An epiphytotic of *Rhizopus* soft rot of tomatoes", "A sudden outbreak of late blight", "Severe damage from corn stalk rots", "Unusual disease occurrences", "Two epiphytotics of *Verticillium* wilt", "High percentage of strawberry fields showing red stele infection", and "Northern anthracnose will cause heavy losses to the red clover hay crop this year" while there is less frequent occurrence of titles such as: "Evidence indicating less loose smut in 1945 than in 1944".

This situation calls for particular care in analyzing the reports, with an effort, which is not always aided by the reporter, to place the unusual outbreaks in their proper setting among seasons or areas in which the disease is minor or negligible. This is assisted by organized reporting in which each reporter is requested regularly to indicate the severity or mildness of various diseases, thus contributing to a file of data in which each unusual oubtreak is given its due proportionate importance, the practice followed until recently by cooperators of the Plant Disease Survey in their annual reports.

Correlation Of Certain Diseases With Seasons Of High Potential Yield, Which Obscures The Actual Losses Sustained. -- Any given ecological factor may favor both crop growth and disease, be unfavorable to both, or favor either one at the same time that it is unfavorable to the other; each of these four combinations has a distinct effect on apparent crop loss from the disease, with the greatest apparent loss resulting from factors which favor the disease and interfere with crop growth.

In general, plant diseases fall into two groups, (a) those which are favored by low vitality in the host plant, such as some of the root decays and wilts, and foliage diseases that are caused by organisms of only moderate virulence, and (b) those diseases that develop most aggressively on plants in a high state of vigor, such as rusts, many downy mildews, and bacterial diseases of succulent tissues. In the former case low yields are made lower by the disease, and this leads to an exaggeration of the loss caused by the disease, while in the latter case the disease loss is more or less compensated for by the high potential yield of the vigorous crop, with the result that losses from such diseases are underestimated or even disregarded unless the disease reaches ruinous proportions. The plant pathologist sometimes even finds himself in the difficult position of defending a substantial loss estimate in a crop which has actually yielded more than "normal", though less than its potential yield, during a very favorable growing season.

This situation is most characteristic of areas in which some one environmental factor is the outstanding limiting condition both to crop yields and to disease development. In dry-land areas this factor is commonly rainfall. During years of abundant rainfall potential yields are increased, perhaps even more than enough to offset the increased loss from rust or other diseases that are simultaneously favored by the increased rainfall. In areas where soil is low in fertility, fertilization may increase yields enough to minimize or offset the attendant increase in loss from diseases that are favored by soil fertility. A few examples will bring this out.

In 1941 speckled leaf blotch of wheat (Septoria tritici) was epiphytotic in winter wheat areas, destroying 40 to 50% of the foliage, but the outbreak occurred in a cool, moist spring and the widespread damage was somewhat obscured by the favorable effect of the abundant rains (CHESTER, 1947). EZEKIEL and TAUBENHAUS (1931, 1934) have found that Texas root rot of cotton is most destructive in years of high rainfall which increases the potential yields so as to mask the full yield-reducing effect of the disease.

In 1938 the most severe recorded epiphytotic of leaf rust was estimated to have reduced the Oklahoma wheat crop by 29%. In this well-watered year the average yield was 11.0 bushels per acre as compared with 11.2 bushels for the preceding 10-year average, which was in a cycle of drought. Many considered the rust-ridden crop of 1938 as practically "normal", failing to appreciate the potentialities of this crop, with abundant rainfall, had not leaf rust duplicated the crop-depressing effects of Oklahoma's arch-enemy, drought, during that year (CHESTER, 1946b). The same year JOHNSTON in Kansas wrote: "The leaf rust damage will probably be underestimated because of ample rains which will raise the general yield level", and TEHON found the same to be true in Illinois.

The practical men of agriculture find it difficult to accept estimates of substantial losses from disease in years in which yields are higher, or at least no lower, than average. The effect is for plant pathologists themselves to underestimate the losses rather than expose themselves to disbelief. Under such conditions, if reliable loss estimates of plant pathologists are to be secured and accepted they must be supported by experimental evidence, such as can be obtained by comparing yields of disease-resistant and -susceptible varieties or those of susceptible varieties with and without chemical protection, during seasons of this type.

Correlation Of Certain Diseases With Freedom From Other Hazards. -- If, as sometimes happens, there is a positive correlation between the yield-depressing effect of a disease and the yield-elevating effect of freedom from another disease or hazard, the two effects may cancel one another, or if the second effect be greater there may actually be a net yield increase associated with the disease. The following two cases are in point.

CLINCH and MCKAY (1947) in Ireland found that mild strains of potato virus X produced no significant decrease in potato yields, but rather a tendency to increase yields. In these tests there was an attack of late blight late in the season. The X-virus-infected potatoes ripened prematurely and thus escaped the more serious menace of late blight which significantly lowered the yields of the virus-free checks. The same "beneficial" effect of the mild X-virus strains or any other disease or factor which accelerates maturity might be expected to reduce losses from early frosts.

YARWOOD (1946a) in California observed that potatoes with "giant hill" were more resistant than normal potatoes to "decline", a serious yield-depressing factor in his experiments, caused by species of Verticillium and Rhizoctonia, as well as having some resistance to early (Alternaria) and late (Phytophthora) blights. As a result, the giant hill plants yielded more than plants without the giant hill defect, which suffered losses from these other diseases.

We can readily see from these reports the importance of a complete analysis of yield factors in order properly to interpret the role of any one of them. We cannot conclude that these factors, X-virus in the one case and giant hill in the other, are harmless or beneficial. In both cases other workers, under other conditions, have demonstrated their harmfulness. It is clear that disease loss studies that do not consider the whole complex of yield factors may produce quite misleading and erroneous loss appraisals.

Lack Of Correlation Between Field Loss And Lowered Quality. -- An estimate of loss due to a plant disease must include all of the losses sustained, both in the field and in shipment, storage, and marketing. Appraisal of loss at one of these stages without consideration of the others may result in serious errors in loss estimates. There are two contrasting types of cases.

The first case is that in which the field loss is greater than that indicated by the condition of the harvested crop. If we rely too heavily on grain inspection records for our loss estimates in cereals we may find that we are overlooking serious field losses that are not adequately brought out in bin or carlot inspections. When wheat, for example, is well cleaned, many bunt balls or nematode galls which it may contain are removed. Examination of this grain will then suggest a much smaller amount of disease in the field than was actually present.

Table 1. Losses from wheat bunt (*Tilletia* spp.) and wheat nematode (*Anguina tritici*) as seen in grain inspection, compared with field losses.

Wheat bunt (HASKELL and BOERNER, 1931)				Wheat nematode (CHU, 1945)	
Number smut balls in 50 gm. seed	Grade	Dockage (¢/bu.)	Average % of smut in field	% weight of galls of total weight of seed	Actual yield reduction
0	Clean	0	1.5	01 - .09	5%
2-	Clean	0	3.8	2. - 2.9	30%
2-5	Light smutty	1-2	6.6	6. - 6.9	54%
5-10	Medium smutty	2-10	8.0	8. - 8.9	69%
10+	Heavy smutty	20±	11.8		

Representative data on this point are given in Table 1. Wheat is graded "light smutty" if it contains 2 to 5 bunt balls in 50 gm. of seed. This would indicate only .04 to .16% smut in the field were it not for the fact that many bunt balls are removed by cleaning the grain. In this case there would actually be 6.6% smut in the field which equals approximately 6.6% yield reduction. Even more striking is the case of wheat nematode where 30% loss in the field results in only 2 to 3% nematode galls in the grain. The extreme case is that of loose smut where there is no indication of disease in the grain even when there is a high percentage of loss in the field.

Reports of the Federal grain inspectors are important sources of information on cereal disease losses. Since grain inspection indicates much less loss than actually occurs, estimates of loss based on grain inspectors' reports are likely to be much too low. Also, if grain is smutty or otherwise diseased the grower is penalized and the purchaser exerts pressure on the grower to eliminate the disease. With a disease such as loose smut of wheat there is no dockage, since the disease does not show in the grain, and the purchaser is unconcerned. The result is that growers tend to attach disproportionate emphasis to diseases that result in dockage, and actually they will disregard serious loose smut losses while striving to reduce less consequential bunt losses. This situation shows how discrepancies in field loss and condition of the harvested product tend to distort loss estimates.

There are cases of the opposite sort, in which negligible field loss from a given disease is followed by a serious loss from the same disease later. McNEW (1943j) brings this out strikingly in the case of tomato anthracnose (*Colletotrichum phomoides*). A very few anthracnose-infected tomatoes in the crop will produce such a high mold spore count in canning that unless these few diseased fruits are removed the pack will be declared "unfit for human consumption" according to government standards. Removal of these few diseased tomatoes doubles or triples the cost of picking, since if even a small amount of anthracnose is present every fruit must be carefully inspected. The necessity for trimming the fruits before processing further increases the cost. If tomato anthracnose loss is appraised in the field purely on the basis of percentage of sound fruits, as has frequently been done in the past, the loss estimates will be far too low.

In plants that are grown in seedbeds and then sold as transplants it often happens that little or no seedbed loss is followed, even unbeknown to the seedbed grower, by serious secondary losses in the plantings of the purchasers. This is frequently the case with late blight (*Phytophthora*) and bacterial leaf spot (*Xanthomonas vesicatoria*) of tomatoes, bacterial leaf spot (*X. vesicatoria*) of peppers, and root knot (*Meloidogyne* spp.) of vegetables, ornamentals, and woody plants. Here, too, appraisal of the diseases in the seedbeds alone leads to gross underestimates of losses.

Subjective Errors Of Judgment Due To Inadequate Or Biased Training And Experience. -- This subject has been well discussed by P. R. MILLER (1946) who points out that a large majority of growers unintentionally either exaggerate or minimize disease losses in about equal proportions. Exaggeration may be due to hope that this will call attention to disease and that price increases will result. A minimizing of losses may be caused by the grower's fear that he may be regarded as a poor farmer if it is known that his crops have suffered severe losses from disease.

Agricultural scientists are prone to overestimate losses from the hazards with which they are most familiar or in which they are most interested, and to underestimate others. It is only natural for agronomists to lay particular stress on soil and climatic factors, entomologists on insects, and plant pathologists on diseases. Plant pathologists are sometimes poor estimators because of a tendency to overemphasize the diseases with which they have personally worked. Those in charge of disease-control "action programs" sometimes may intentionally exaggerate the importance of a disease to stimulate adoption of control practices by growers who might otherwise fail to use them.

CHESTER (1945b) has distributed a questionnaire asking plant pathologists to estimate the losses from 19 common plant disease situations, where in each case there was experimental evidence of the amount of loss caused. The average error was 16.6%, and there were almost exactly as many cases of underestimates as overestimates. The most marked overestimates were for diseases of a more or less spectacular nature, which have been well publicized, e.g., sugarcane mosaic and cotton root rot. In the case of corn smut (Ustilago maydis), a very common disease the loss from which has been carefully measured in a number of well-conducted experiments by different workers, all of whom found that a smutted corn stalk yields about 2/3 as much as a normal stalk, the loss estimates ranged from 1% to 60%, and nearly as wide ranges were obtained for the potato virus diseases, tobacco mosaic, tomato Septoria, and other defoliation diseases.

Plant disease losses are usually badly underestimated by those economists who lack training in plant pathology and whose estimates, in turn, are based on data from practical men of agriculture who also often lack this training. The following (Anon., 1926) are economists' estimates of average losses due to all diseases in the crops indicated, while in parentheses are given the plant pathologists' estimates of average loss from all diseases in the same crops, taken from the very conservative estimates of the Plant Disease Reporter (1917-1939 average): corn, 0.4% (9.8%); wheat, 5.2% (13.4%); oats, 2.8% (8.8%); apples, 4.6% (13.4%); barley, 2.7% (6.3%); potatoes, 5.6% (18.2%); cotton, 1.0% (14.5%); and tobacco, 1.5% (23.5%). Economists' estimates, as those of plant pathologists, are often unduly influenced by spectacular or obvious hazards, as seen in the cotton statistics (Bur. Agr. Econ., U. S. Dept. Agr., 1944) where estimates of losses from the boll weevil usually are between 10 and 30% of the crop while those of cotton diseases are almost negligible. Overestimates of loss are also sometimes due to anxiety stemming from reports of losses in neighboring districts.

Errors Due To Non-Representative Sampling: -- If loss appraisals are made by, or with the aid of, county agricultural agents, losses may be underestimated, since these men deal primarily with the best farmers, who make full use of agricultural science in preventing losses. If the estimates are made by, or with the assistance of, Farm Security agents, the reverse may be true; losses are overestimated because these men work chiefly with small-scale, handicapped farmers.

Unless a purely random method of sampling is employed there is a tendency for a plant pathologist's disease loss estimates to be biased by a complex of several factors. He is likely to stress those problems that are brought to his attention by others at the expense of problems which he must go out and find. His reliability is likely to diminish in proportion to the distance of disease problems from his headquarters. Reported disease outbreaks of purely local significance may be mistaken to be representative of large regions. In surveying for disease the observer will be most influenced by conditions on farms adjoining highways, where disease is likely to be under better control than on more remote farms. If his time is at a premium, he may not be able to sample large farm fields adequately, and may then be unduly influenced by roadside conditions in which diseases, like growth, show the well-known "border-effect". Like the county agent, the plant pathologist in apt to be in contact with too high a proportion of the best farmers, i.e., those who have enough interest in plant disease to ask advice.

Correction of the bias that results from such influences can be made if the estimator is conscious of his bias and its causes. Non-representative samples still have value if they can be weighted to correct for recognized error. The size and type of sample of a crop within a field, or of fields within an area, is considered separately in Chapter V, and here it is only necessary to point out that extensive studies on sampling procedures already provide us with the necessary background of information to enable us to obtain representative, unbiased data. It is an object of this book to encourage the use of approved sampling methods in disease loss appraisal.

Errors Due To An Unsuitable Method Of Appraisal. -- To estimate the losses from plant diseases correctly it is necessary that the estimator have in mind all forms of loss and the relative role of each. If attention is limited to only one aspect of the disease, the loss may be seriously underestimated. It would be a mistake, for example, to consider the percentage of seedlings destroyed by damping-off as a loss percentage. This must be corrected for at least two factors, the additional loss from injury in plants which survive, and compensation for seedling loss by growth of adjacent plants, especially where a heavy seeding rate has been used. Both quantity and quality loss features must be considered. Loss may be partly compensated for by reduced costs of harvesting and handling a diseased crop. While many observers consider the percentage of bunted tillers in a wheat field as equal to the percentage of yield reduction due to bunt, MOURASHKINSKY in Russia has reported that bunt also kills some plants, increasing the loss figure.

These few examples serve to bring out the fact that errors in loss estimates will result unless the appraiser is quite familiar with the disease itself, and with the various factors which tend to increase or decrease the true loss figure as compared with the apparent loss seen in some one conspicuous aspect of the disease. His method of appraisal must be appropriate if the loss estimate is to be reasonably accurate.

Errors Due To Duplication And Summation Of Loss Estimates At Different Stages In The Marketing Of A Crop: -- P. R. MILLER (1935) has indicated this as a source of error in estimates, illustrated as follows: "If 100 bushels of oranges were inspected at the wholesaler's and 5 bushels were decayed, and the remaining 95 bushels were inspected at the retail store and 10 bushels were decayed, the total loss from the 100 bushels would be 15 bushels or 15%. However, the recorded loss would be 5% (5 bushels loss from 100 bushels) in case these oranges were inspected only at the wholesaler's; or 10.5% (10 bushels loss from 95 bushels) if inspected only at the retailer's. If inspected at both wholesaler's and retailer's without a knowledge of its being the same shipment, the recorded loss would be 7.6% (15 bushels loss from 195 bushels). Obviously the recorded loss in any of these cases would be less than the actual loss".

There is the possibility of other cases in which the damaged produce is not removed from the shipment. If the loss is estimated at two points in the marketing of the produce and if it is concluded that there was X% loss at the first point plus Y% at the second point the resultant figure would be too high, since X and Y are the same loss.

Lack Of An Experimental Basis For Estimation. -- In most cases the amount of loss from a plant disease cannot be judged merely by inspection of a diseased crop. Often the injuries are so subtle that a trained observer is misled. The only way of obtaining an accurate estimate, in such cases, is by the use of the results of loss measurement experiments.

Before the measurement of losses from wheat leaf rust, plant pathologists commonly underestimated this loss by 1000%. HORSFALL'S (1930) measurements of hay disease losses showed that these are very much greater than had been suspected. The same has been seen in the case of potato latent mosaic (see page 196). One form of gas injury to plants is called "invisible injury", and this form of loss was unrecognized until measurements showed that growth is retarded by amounts of gas that are too small to produce leaf symptoms. The measurements of VALLEAU and JOHNSON (1927) showed that the value of tobacco which was infected with mosaic at setting time was reduced 25.1%, "a difference which could hardly have been predicted at cutting time". In the case of pea seedling disease, M^CNEW (1943e) has found it almost impossible to detect a loss of 10% or 15% by visual observation alone, yet this is much more than the minimum amount of loss warranting control measures. Lack of measurements of decay often lead to excessively low estimates of timber cull, according to WEIR (1918), and WYCKOFF et al. (1947) point out that there is no experimental basis for estimating the loss from many forest diseases. On the other hand, the failure to consider the regenerative abilities of plants and the compensation for the loss in healthy plants adjacent to diseased ones (page 318) leads to overestimates of loss.

These examples, which might be multiplied manyfold, show clearly that plant pathologists cannot trust their eyes or even their experienced judgment in estimating disease loss where there is no experimental basis for knowing the amount of loss caused by a given intensity of disease.

Fear Of Prejudicial Effect Of Loss Reports On Agricultural Industry. -- Occasionally one hears of resistance to the publication of disease loss information for fear that it may reflect unfavorably on a producing area. KNAPP (1927), for example, has indicated that in Holland it is considered inadvisable, from the standpoint of the export trade, to publish statistics on plant diseases. The many local check lists of plant diseases and the long-established practice of the United States and Canadian Plant Disease Surveys of disseminating this type of information, indicate that suppression of plant disease statistics fortunately is not the rule.

At the Root Knot Nematode Conference in 1937 (BARSS *et al.*, 1937) the question was raised whether the publication of data on the distribution of this pest might not make trouble for producers, interfering with their sales. H. A. EDSON of the Plant Disease Survey replied that this is a familiar problem and that it is possible for disease data to be sent to the Survey, not for publication, but for consultation by scientists. He then said: "There is some deliberate suppression of information, due (1) to fear on the part of commercial interests, and (2) to the fear of quarantine regulations, especially of state quarantines. Taking a wide view, the best course would seem to make all information immediately available."

Dr. EDSON'S view is to be indorsed; the solution is not to suppress needed information but to educate those who would suppress it. Suppression of plant disease distribution and loss data is detrimental to the many valuable uses of such data as outlined in the preceding chapter.

Chapter III

SOME PRINCIPLES AND PROBLEMS OF PLANT DISEASE APPRAISAL

DESIDERATA OF METHODS FOR APPRAISING PLANT DISEASE LOSSES: -- To be most useful the methods for appraising plant diseases should meet certain requirements. In particular they should be concerned with losses, not merely disease intensities, and they should be comprehensive, complete, accurate to a practical degree, comparable, and objective. These qualifications are taken up individually below.

Disease Appraisal Methods Should Measure Disease Intensity And Translate This Into Crop Loss. -- If a disease causes total destruction of plants or of the marketable parts of plants its appraisal may be comparatively easy, since there is agreement between disease incidence percent and loss percent, and simple counting may suffice to determine both incidence and loss. It is quite natural, as P. R. MILLER (1946) has indicated, that it is for such totally destructive diseases that we have the most reliable loss estimates, and the same thing has been observed in attempts to secure livestock morbidity and mortality data (Anon., 1948).

The preponderance of available data on the importance of plant disease are prevalence or intensity data. In the better reports, *e.g.*, those of TEHON (1927) and TEHON and STOUT (1930), there are data on both prevalence (percentage of plants affected) and intensity (degree of attack on individual plants), and these two values are combined to give an overall index of disease attack. This is a measure of severity of disease attack; for example, in dealing with foliage diseases it gives a measure of the average amount of leaf tissue destroyed, but it is not a measure of commercial loss, as the authors clearly point out. Their interest lay primarily in a study of the epiphytology of certain diseases over a period of years, and for this purpose their disease severity data were entirely adequate. They have even called attention to the fact (1930, fig. 25 and pertinent discussion) that in the cases of peach scab and brown rot, scab (*Cladosporium carpophilum*) showed the greater intensity but brown rot (*Monilinia fructicola*) produced the greater commercial loss.

Such data have great value in interpreting the effect of weather on disease destructiveness and from some other pathological points of view, particularly when they are as complete and objective as in the cases cited. While, in their present form, they do not translate disease intensity into loss, it should be possible, once disease intensity-loss ratios have been determined experimentally for each disease in question, to convert these basic data into loss estimates. Whenever experiments have shown the relationship between given disease intensities and consequent losses, there is opportunity of going back through the records of disease intensity and, by applying loss-conversion factors to the intensity data, of obtaining the loss statistics which have almost exclusive importance for the useful purposes outlined in Chapter I.

Meanwhile it is clear that if these useful purposes are to be served we cannot be content with limiting disease appraisal to disease severity. Reliable disease intensity data are necessary but these are only half the requirement; we must meet the whole requirement by finding and using means for translating disease intensity into disease loss, and this must be done not only for those cases in which there is a simple numerical relationship between attack and loss, as with totally destructive diseases, but also for the more common and more difficult cases in which the crop is injured but not destroyed, in which there is a more complex relationship between disease intensity and the loss it occasions.

Disease Appraisal Methods Should Be Comprehensive. -- They should embrace all major diseases of all major crops, otherwise the assembled data will have only limited value for the important purpose of comparing loss hazards in order to determine the wisest course in research, educational, and action programs.

This is an ambitious objective but not a visionary one, although years of effort and the cooperation of many plant pathologists will be required. If each pathologist, in his own specialized field of research, would consider the determination of losses a standard part of the thorough investigation of any plant disease, worthy of as much attention as he now gives to nomenclature of pathogens, pathological anatomy, or other academic phases of his studies, and if a very few pathologists would undertake the acquiring and synthesis of loss data as a major project, the task could be accomplished and the potential benefits discussed in Chapter I would be realized.

Disease Appraisal Methods Should Have A Practical Degree Of Accuracy. -- The end-products of disease appraisal are estimates. The value of reliable estimates, as contrasted with exact measurements, has already been discussed (page 210). There is no need or practical possibility for plant disease appraisal figures to have the degree of accuracy that is required, for example, in the auditing of bank accounts. As one seasoned pest appraiser puts it: "You don't need to use a micrometer caliper in making a gate peg." At the other extreme, the gross errors in loss estimation such as were mentioned on page 212 serve no useful purpose and may be harmful. "To the uninformed who take them at face value, crop loss estimates are very impressive but equally dangerous" (P. R. MILLER, 1946). Between these extremes there is a golden mean, where loss estimates are sufficiently accurate to be useful, reliable within moderate limits, but without reaching an uneconomical degree of precision.

The width of these limits depends on the appraiser's judgment. They can be made narrower by more extensive sampling and more thorough experimental testing of disease intensity-loss ratios. In most cases if an estimate is correct within a ±15% margin of error it should be suitable for practical purposes. As an example, corn smut reduces the yield of smutted stalks an average of 33%. If the loss in individual appraisals varies between extremes of 28% and 38% (± 15% variance from the mean of 33%), the range is still sufficiently narrow to enable us to place smut in its approximate rank among corn diseases and, by applying this figure to survey data, to estimate the bushel loss from corn smut with reasonable accuracy, sufficient for the purposes of loss estimation. This would be defensible and would be preferable to the extreme guesses of the injury from corn smut submitted by collaborators of the Plant Disease Survey (page 217) ranging from 1% loss to 60% loss.

The proposed figure, ±15% margin of error, is arbitrary, and is given only to suggest a desirable order of magnitude of the permissible error. In some cases the range would necessarily be wider because of variability of loss ratios for a given disease or great difficulty in determining losses. In other cases, as with the cereal smuts, it might be very much narrower. The width of the permissible range of error of estimates depends on several factors, including the experimental basis for estimation, variability of loss from given diseases, purposes of the estimate, and practical considerations. Increasing the precision of estimates is expensive and is not warranted beyond the degree of precision that gives reasonably dependable results.

Disease Appraisal Methods Should Be Comparable From One Worker, Location, Or Season To Another. -- Two stages are involved: (a) comparable or uniform practices in appraising disease intensity, and (b) the use of standard, experimentally determined conversion factors to translate disease intensity into disease loss.

We have already made a little progress in the first of these objectives. The modified COBB rust scale (see page 244) has been used by nearly all American workers for appraising cereal rust intensities, for some 30 years. There is some lack of uniformity in the manner in which this scale is used, but even with this limitation the reports of rust intensities in terms of a standard scale greatly increases the usefulness of rust reports, making it possible for one worker to have a fairly clear conception of rust situations appraised by others, and permitting the summarizing of rust data from many locations and workers in tables of comparable data, as is regularly done with data from the Uniform Rust Nurseries.

MCKINNEY"s index of infection (see page 253), a standard method of combining disease prevalence and intensity into a single figure, has lately been adopted by many workers, dealing with a variety of diseases, and represents another important step toward uniformity in reports. HORSFALL and HEUBERGER (1942a), applying this method to a tomato defoliation disease, found that it was statistically reliable and gave very similar results when used by three independent observers.

In the various cooperative experiments in plant disease control, involving workers in several States, a uniform method of reporting disease intensity is usually adopted. In cooperative root knot nematode work, for example, the cooperators are each furnished a photographic scale of several degrees of root knot severity, and this is used as a basis for a uniform numerical system or reporting data.

But there are far too few instances of disease intensity reports of a uniform type. The Plant Disease Reporter contains a great majority of reports which can never be compared or synthesized with any satisfactory results because the observers have either failed to mention use of any recognizable standard of disease intensity measurement, or have used original standards that have meaning only for themselves.

The second stage in the evolution of a comparable system of disease appraisal consists of the development, experimentally, of conversion factors that permit the translation of disease intensity into disease loss. Many of these have already been derived; many more others await development. Adoption of their use should not be too difficult a problem, since they need to be used only by those who desire to secure loss estimates. The basic data are those on disease intensity, which may be gathered by many observers who are not concerned with the calculation of loss estimates. Here the principal problem is the encouragement of research by specialists on each of various diseases, aimed at determining disease intensity-loss relationships, and the research on a sufficiently broad and accurate basis so that the conversion factors derived will be acceptable and considered reliable by those who wish to use them in making loss estimates.

Disease Appraisal Methods Should Be Objective. -- They should be so set forth that their use will not be influenced by the bias or point of view of the observer. This can be accomplished if a standardized procedure of randomized sampling is followed, if the scaling of disease intensity is done by use of a standard disease intensity scale, if the results are summarized in a uniform fashion, and if disease intensity data are converted into disease loss statistics by use of generally accepted, experimentally derived conversion factors.

We have seen the great discrepancies between reported loss estimates, and have recognized that personal bias is a leading factor in producing these discrepancies. Bias is inevitable, and the truly scientific observer recognizes bias as an ever-present danger in his work. Just as he welcomes an opportunity to test his research results on "unknowns", he will welcome objective criteria for disease intensity and loss appraisal. It is an important aim of the present study to contribute toward the adoption of such objective criteria at each step in the procedure of disease loss appraisal, and these several steps are discussed in detail in later chapters.

Disease Appraisal Methods Should Embrace All Forms Of Disease Loss. -- With many plant diseases the loss which they cause is complex, consisting of several components, each of which must be measured and given its proper place in estimating the overall loss. The quantity of yield is perhaps the easiest of these components to appraise, and often is the only one considered. Quality of the harvested crop is next in importance, though often disregarded in loss estimates, and this is considered separately in the following section. Still less commonly considered are such effects of disease as increasing the cost of handling, harvesting, and marketing the crop, and the cost of direct disease control measures in those cases in which there is no loss in the crop itself when the disease is controlled. Seedling diseases sometimes cause no direct reduction in yield, the loss factor here being the waste of seed required to produce a satisfactory stand or the expense and disadvantage of making a second planting.

Bacterial blight (Xanthomonas malvacearum) of cotton is a case illustrating the complexity of loss. The disease destroys seedlings, necessitating increased planting rates, seed treatment, or replanting. It injures stems, depressing the vigor of growth. It partially destroys the leaves, reducing photosynthesis, with consequent reduction of fruit formation, although if defoliation from the disease is very late in the season it may be regarded as an advantage, facilitating harvesting. The disease attacks the bolls, and while it does not usually destroy them, it opens the way for boll-rotting fungi to enter the bolls and weaken or destroy the lint, resulting in both lowered yields and quality of the harvested crop. Long and thorough study, and measurement of the loss fractions due to each of these components, is required before a reasonably accurate appraisal of the loss from this disease is possible.

Whether loss be simple or complex, determined with ease or difficulty, it is clear that loss appraisal practices must consider all of the loss components, from planting to final disposal of the crop. Because some cases are difficult to analyze is not a signal for a defeatist reaction to the whole problem, but rather a challenge to analyze these difficult cases, since the discovery of the amounts of loss in such cases may entirely change our conception of the damage being done by different diseases, and may justify new efforts and new approaches to the control of those disease problems where the loss is serious, though complex and obscure.

CONSIDERATION OF BOTH AMOUNT AND QUALITY OF THE CROP IN LOSS ESTIMATES: -- Most commonly loss estimates are based on the volume of yield alone. This may result in estimates that are far too low, when, as often occurs, the quality as well as the quantity of the crop is reduced by disease. An outstanding example is the effect of stem and leaf rusts on wheat. In his extensive sulfur-dusting experiments to measure rust damage, GREANEY found that lowered grade or quality, sometimes to the point where the grain is unfit for milling, is a major aspect of rust losses.

Loss of quality as a result of tobacco mosaic has been studied by a number of workers (VALLEAU and JOHNSON, 1927; McMURTREY, 1928, 1929; WOLF and MOSS, 1933; THUNG, 1940; and JOHNSON and VALLEAU, 1941). McMURTREY'S data are typical. He found that when tobacco became infested with mosaic one month after transplanting the acre yield was reduced 25%, but the quality was so lowered that the price per 100 lbs. dropped 40%, reducing the acre value by 54.5%. Here the reduction in quality was even more important than the yield reduction. Objectivity in the tests was secured by having the quality graded by two tobacco buyers who did not know the experimental treatments.

There are some cases in which quality reduction may be the only form of loss. This is true of diseases that disfigure or blemish fruit without either reducing yields or contributing to spoilage, such as scab of peaches, flyspeck (Leptothyrium pomi) of apples, or mild cases of apple blotch (Gloeodes pomigena).

The quality factor may be a difficult one to appraise, as pointed out by DUNEGAN (1945), since the loss depends on grading or culling practices that vary from one season to another. In years of bumper crops the fruit is graded more critically, and there is a greater penalty for low quality than in years of light crops. DUNEGAN cites bacterial spot (Xanthomonas pruni) of peaches, in which case during some years fruit with numerous spots sells readily while in other years one or two spots are considered a sufficient cause to throw the peach into the cull pile. The relation between lowered quality and market quality requirements is quite involved, and a more extended account is reserved for discussion in connection with the economic effects of plant disease (Chap. XII).

Nursery Stock And Ornamentals. -- Nursery stock constitutes a special case of quality requirement since it is subject to health inspection before sale, to prevent spread of disease. It is not infrequent for large lots of nursery stock to be disqualified for sale because they are carrying, or are suspected of carrying, disease which may have led to no other form of loss in the nursery. As a rather extreme illustration, a nursery was prohibited from selling 50,000 marketable peach trees because a single mosaic-infected tree was found in the nursery. When the trees were released from restriction a year later they were too old for sale and the loss was total. In cases of this kind the loss depends entirely on the inspector's rulings, and is independent of field loss or yield reduction.

Ornamentals constitute another special case of quality requirement, in which the aesthetic value of the plant dominates over the other loss factors, and may have little relation to the health of the plant in the ordinary sense. If the petals or leaves of a rose or lily plant, for example, are even slightly spotted, the plant becomes unsaleable and the loss is total, even though the disease is actually doing little or no harm to the plant as an organism.

Of all types of crops, our data on losses of ornamentals are least complete, and the chief reason for this may be the peculiar importance that is attached to the appearance of these plants, rather than volume of production. Here a study of sales experiences rather than of culture of the crop may provide the most useful information on losses. At present we have little more than isolated instances by which to evaluate losses in ornamentals. A valuable contribution to plant pathology, from the standpoint of this book, could be made through a detailed, statistical study of the economic effects of diseases of ornamental plants.

Gross Damage As The Product Of Disease Prevalence X Destructiveness. -- The loss caused by a disease is a function of its injuriousness to individual plants or fields and of its prevalence over the appraisal area. If a long-time average loss is to be estimated, the prevalence of the disease from one year to another must also be considered. Long-time average loss estimates are most useful in planning research, education, and regulatory work, and accordingly the estimates normally will be concerned with all three of these factors.

It frequently happens that a disease which is most destructive in certain locations or years is not actually the most damaging from a broader point of view. In potato, for example, the virus diseases leafroll and yellow dwarf are much more destructive to individual plants or to heavily infested plantings than are the potato mosaics. Usually the mosaics are so much more prevalent, however, that their net effect in reducing yields is greater than that of the more spectacular virus diseases. Similarly, of all the organisms causing cotton seedling disease in the Southwest, the anthracnose fungus, Glomerella gossypii, is most virulent, and most rapidly destroys the plants. Yet this fungus is not nearly as prevalent as somewhat less aggressive cotton seedling fungi, such as Rhizoctonia solani and Fusarium moniliforme, so that these latter are considered to be more important than the anthracnose fungus in causing seedling loss in this area.

In many references to disease loss, given in justification of the economic importance of a disease, there is mention of the estimated loss in certain years during which the disease was epiphytotic, without reference to the years in which the disease was inconsequential. It would be misleading to point to the estimated 55 million bushel loss of potatoes from late blight in 1938 without noting that in none of the nine years preceding was the estimated loss as great as 10 million, or better, giving the average loss for the 25 year period for which estimates are available.

Individuals, growers or agricultural scientists, are likely to lay much greater stress on the local destructiveness of a disease than on its prevalence; they may be uninformed of the latter. The consequence is a tendency to overrate the importance of diseases which attract attention because of their locally devastating attack, but actually are not sufficiently prevalent to warrant concentrated work at the expense of other diseases which are not quite so noticeable but, because of their widespread occurrence, are actually causing greater loss.

INTERPRETATION OF THE PARTIAL AND JOINT EFFECTS OF TWO OR MORE CONCOMITANT LOSS FACTORS: -- When two diseases or other factors attack a crop simultaneously the loss is usually greater than that caused by one factor alone. These cases frequently lead to serious errors in estimating loss since, without loss measurements, there is a tendency to lay disproportionate stress on the destructiveness of one of the factors, particularly the one that is most obvious or the most recent in appearance, or the factor to which the observer, through training and experience, has given greatest attention in the past. There are many cases of recorded loss data in which it is now difficult or impossible to ascribe the loss to its true causes because more than one major loss factor has been functioning.

Any factor which leads to variability of yields from year to year is harmful, even though the long-time yield average may be satisfactory. This phase of the economics of plant disease is discussed more fully in Chapter XII, but here it should be pointed out that some diseases tend to increase the variability of yields while other diseases contribute to more uniform yields by largely confining their attack to what would be bumper crops. In this special case, two diseases of a crop acting over a period of years and in various locations may have an additive effect in increasing variability of yield or their effects may be in the opposite direction, actually stabilizing yields, as pointed out by HARTLEY and RATHBUN-GRAVATT (1937). If one disease is favored by hot weather (as potato tipburn) and another by cool weather (as potato late blight) their combined effect on yield variability will be less than that of either disease alone.

If two loss hazards do not regularly occur together it may be comparatively easy to discriminate their respective effects in producing loss, since it will usually be possible to find or produce plantings in which either one of the hazards, alone, is present. By comparing the loss produced by each hazard with the loss from their combined effect, the partial role of each can be determined. The problem becomes more difficult when the two hazards are almost invariably present together.

A most useful procedure in the latter case is the experimental determination of loss using varieties of the crop that are resistant to one hazard but susceptible to the other. This has been done with the potato viruses and with the cereal rusts. In the case of potato, practically all plants grown, except new seedlings, are infected with the latent mosaic virus. Whenever they become attacked by a second disease the loss-effect is the result of two diseases combined. As MURPHY and MCKAY (1924) showed, this double infection makes it difficult to interpret many of the data on losses from potato viruses.

This problem was solved by SCHULTZ' discovery of the potato seedling 41956, which is resistant to latent mosaic but susceptible to other viruses, and using this seedling SCHULTZ and BONDE (1944) have been able to determine the separate and combined effects of the two viruses that together produce mild mosaic. Others have applied the same technique to other potato virus complexes.

For many years wheat in America was commonly attacked simultaneously by leaf and stem rusts (Puccinia rubigo-vera var. tritici, P. graminis var. tritici), and there was confusion as to the part played by each disease in the loss caused by the combination. GOULDEN and ELDERS in 1926 attempted to distinguish the losses caused by these two diseases by using 146 wheat varieties and determining the regression of yield on each disease. Because of a positive correlation between the two diseases they had difficulty in demonstrating the negative correlation between yield and leaf rust. The practical solution to this problem came with the introduction of varieties of wheat that were resistant to stem rust but susceptible to leaf rust, combined with the use of sulfur dusting to secure rust-free control plots. When this was done, especially by Canadian workers, the role of leaf rust in contributing to the damage caused by stem and leaf rusts combined was clearly brought out.

SALLANS' (1948) paper on losses from common root rot (Helminthosporium sativum) in wheat is an excellent illustration of the use of correlation and partial regressions to determine the individual and combined effects of root rot, pre-season rainfall, June-July rainfall, air temperature, and insect damage on wheat yields. It revealed that root rot was second only to June-July rainfall in causing yield variability, and that the yield-depressing effect of root rot, hitherto obscured by the other more obvious hazards, was actually much greater than had been suspected.

Another approach was used by CHESTER (1946a) in a study of losses caused by cotton wilt (Fusarium oxysporum f. vasinfectum) and potassium deficiency. This consisted of the analysis of a large body of data giving yields and wilt percentages of many varieties of cotton during a number of years, and comparing this with data from fertilizer tests. The study showed that when cotton suffers from wilt and potassium deficiency, up to 25% wilt the loss fractions from wilt and the deficiency are about equal, while above this wilt percentage, a greater part of the loss is due to wilt.

Still another approach was used by M^cNEW (1943j) in distinguishing the losses caused by anthracnose (Colletotrichum) and leaf blight (Septoria) in tomatoes. The fungicide, Fermate, controls anthracnose but does not control leaf blight, and spraying tests could therefore be used to measure the loss caused by anthracnose, though leaf blight was also present.

Numerous other examples might be cited, but these suffice to show that it is possible, by selection of suitable techniques, to break down complexes of loss factors into their several components and determine the part of each in the complex. In agriculture we deal more often than not with loss complexes, and the analysis of these deserves particular attention as one of the important problems in loss studies.

ECOLOGICAL INFLUENCES ON THE DISEASE INTENSITY-LOSS RATIO: -- If a given intensity of a disease at a given stage in development of the crop produces the same percentage of crop loss regardless of season or location, the problem of loss appraisal will be much simpler than if the loss percentage for a given disease intensity varies considerably from one year or location to another. It is to be expected that if loss measurement experiments are carried out in different locations and years some differences in disease intensity-loss ratios will result. Here we are concerned with the amount of variation in the ratios for different types of disease, the causes of this variation, and the question of whether the variation falls within the permissible range of error in loss-estimates or whether it is so great that loss measurements have only local or seasonal significance.

Disease Intensity-Loss Ratios In Different Years And Locations. -- There are many instances on record in which the loss caused by a given intensity of disease is relatively constant when it is measured in different years and locations. One might expect such constancy especially where the loss in an infected plant is total, and this appears to be the case with the cereal smuts. LEUKEL (1937), for example, in many measurements of loss caused by bunt in wheat, in different years and locations, concluded that "there was a high degree of correlation between the percentage of bunt in the crop from untreated seed and the percentage reduction in yield." Similarly SEMENIUK and ROSS (1942) found that the reduction in barley yield was directly proportionate and equal to the percent of loose smut (Ustilago spp.) with no significant differences in three widely separated locations.

With leaf diseases and injuries there also is frequently a rather constant relationship between degree of injury or involvement of the leaf and yield reduction, provided we compare equal amounts of injury at a definite stage in development of the crop. This is brought out in studies of corn leaf injuries conducted in different years in three States (Table 2). Rather uniform losses in different locations have been reported by M^cNEW (1943g) for tomato leaf blight (Septoria) and by J. D. MOORE (1946) for cherry leaf spot (Coccomyces). The results of numerous measurements of the loss caused by wheat leaf rust have been given graphically by CHESTER (1946b, Fig. 2) and show values that are well clustered about the averages for loss when wheat is defoliated at various developmental stages, despite the very different experimental conditions in the tests.

Table 2. Yield reductions due to corn leaf injuries in different locations and seasons.

	Relative yield of grain per acre (%)		
Treatment	Illinois, 1 year (DUNGAN)	Iowa, 2 years (ELDREDGE)	Nebraska, 9 years (KIESSELBACH & LYNESS)
No treatment	100	100	100
All leaves removed at ligule	8	5	6
End halves of all leaves removed	57	67	77
All leaves shredded	84	57	76
All midribs broken near ligule	77	80	82
All leaf blades cut to midrib near ligule	80	90	84

A number of measurements of the loss from corn smut have been reported. On the whole these are in good agreement, though the tests were made by different investigators in different years and locations. The reduction in yield per stalk is given by HITCHCOCK and NORTON (1896) at 34.5%, IMMER and CHRISTENSEN (1928) 39% (average for all types of galls and not corrected for the frequency of the different types of galls), JORGENSON (1929) 39% in selfed lines and 50% in F_1 crosses, IMMER and CHRISTENSEN (1931) 35% from galls of all types and 30% from all types of stalk galls, I. J. JOHNSON and CHRISTENSEN (1935) from 25% loss from single boils to 50% loss from multiple galls, and F. L. SMITH (1936) 31% loss. MENZIES and STANBERRY (1947) determined 22% loss from terminal boils in detasseled corn alone, so that their results are not exactly comparable with the others, and GARBER and HOOVER (1928) found a 25% loss from corn smut on the basis of barren stalks alone, but F. L. SMITH (1936) has shown that small boils and medium boils below the ear cause loss without barrenness, indicating why the results of GARBER and HOOVER are somewhat below those of the other workers.

For an entirely different type of disease, wood decay, R. M. BROWN (1934) has reported that in his studies of aspen there was a high correlation between volume of rot and various other tree characteristics but none between rot and site or soil type, and HEPTING (1941) found no significant differences in the amounts of cull from fire wounds of a given size, regardless of site or study area.

The Office of Cereal Crops and Diseases of the U. S. Department of Agriculture has published a table (KIRBY and ARCHER, 1927) to assist observers in estimating wheat stem rust losses, giving percent loss for each stage of rust intensity at different growth stages of the crop. Recommendation of use of such a table implies the belief that a given intensity of rust at a given growth stage is regularly followed by a relatively constant amount of loss, regardless of year, location, or other variables. CHESTER (1946b) has published a comparable table for losses from wheat leaf rust. This principle is opposed by RUSAKOV (1926), in Russia, who has contended that the relation of plant injury to crop loss varies so much from one geographical area to another that "for each region its own scale must be prepared from artificial inoculations of plots that are uniform for fertility and with uniform varieties of cereals".

GREANEY and his coworkers in Canada (1933b, 1941) have taken an intermediate position. For 9 years at Winnipeg, by means of sulfur-dusting experiments, they measured the loss from stem rust in Marquis wheat. Finding that the regression of yield on percent rust was linear, they could determine the percent loss in yield due to each 10% of rust. These values, for each year, were used in calculating the total loss from rust in Manitoba and Saskatchewan, and similar work was done with oats stem rust. Each 10% of rust, in the various years, produced 9.7, 7.4, 6.9, 8.2, 7.9, 3.1, 6.7, 7.3, and 9.2% yield reduction. These values do not show excessive variation from year to year. One cause of such variation as does occur was the fact that during some years leaf rust damage was present, to complicate stem rust-loss relationships. While GREANEY et al. have recognized certain sources of error, they consider that the method adds precision to loss estimation, and their belief in the validity of a wide application of an experimentally derived disease intensity-loss ratio is seen in the fact that for each year the ratio obtained on one wheat variety at one location was applied to an area which regularly produces 200, 000,000 bushels of wheat.

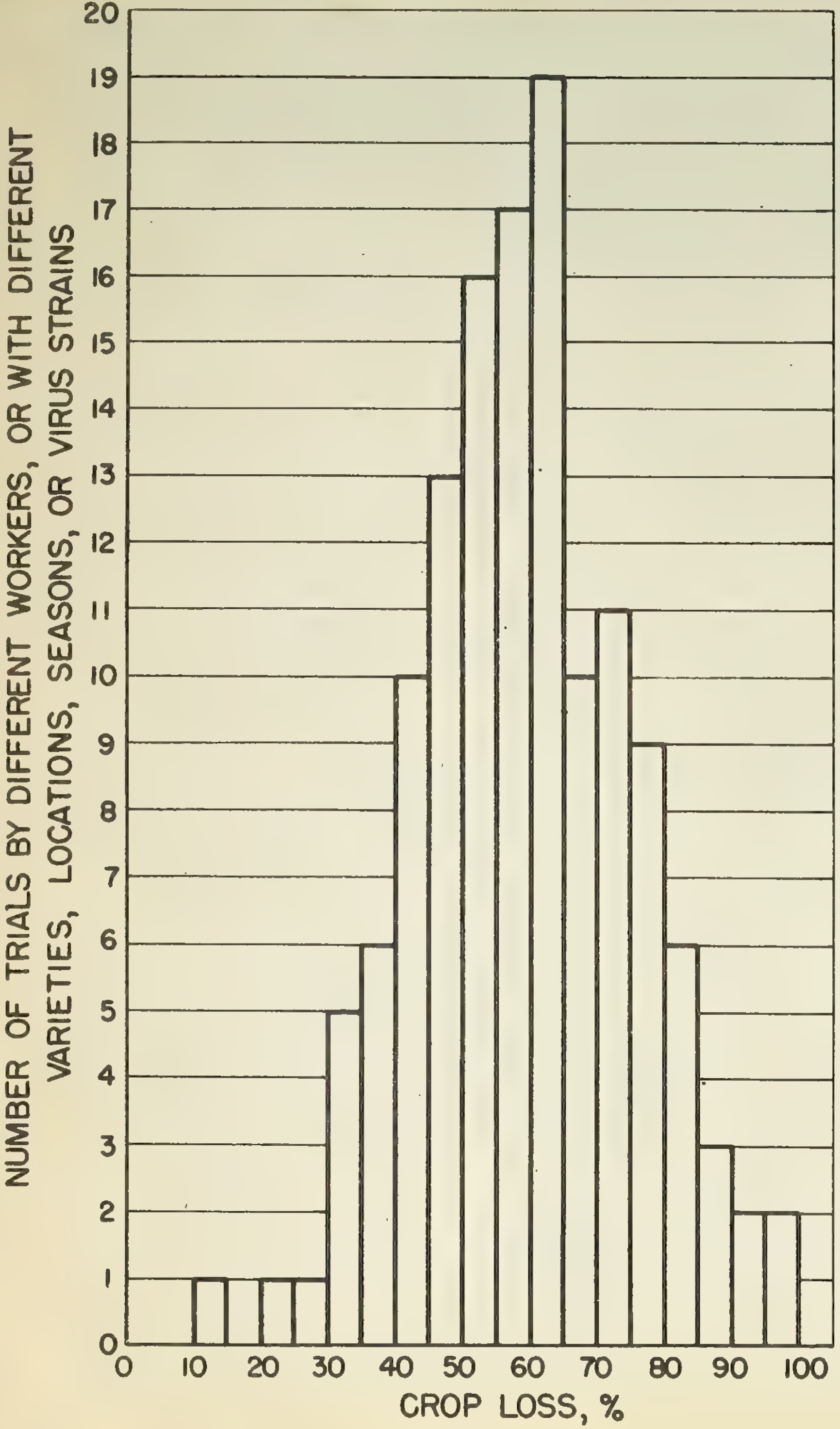
The case of potato leafroll is one for which we have many loss data from different workers, potato varieties, locations, and seasons. The measured amounts of loss from 100% leafroll in 132 tests are shown graphically in Figure 3. These are based on 29 published accounts.

Analysis of these data by J. H. McLAUGHLIN shows that the mean for all measurements is 59.59% loss with a standard error of $\pm$ 1.41, which implies that for similar bodies of data the mean loss is expected to be between 58.18 and 61.00% in 2 out of 3 cases.

There are many factors responsible for the range of loss percentages in the case of potato leafroll. A universal loss constant in the vicinity of 60% might not be applicable in isolated instances when the true loss percentages are far higher or lower than this. Yet, in loss appraisal we are more interested in the volume of loss over large areas, embracing many years, environments, and crop varieties, than in exact determination of loss in single fields. If the figure 60% be taken as a universal loss constant in this case, we can confidently place the volume of loss caused by this disease in its proper order among potato diseases, and we can justify calculations of the magnitude of the loss on a broad scale by the high statistical probability that when losses in many locations, seasons, and crop varieties are considered together, the mean loss will not be far from this figure.

This case brings out the important principle that although there may be considerable discrepancy between two isolated loss measurements of a given disease under different environments, that is not a valid deterrent to efforts at securing universal loss constants, since a large body of loss data, such as we have for potato leafroll, shows a good normal distribution around a mean, which may be used in the same manner and with the same confidence as the agricultural economist uses means of crop yields, with full appreciation that yields in individual fields may be far higher or lower than the means.

Effects Of Climatic Factors On Disease Intensity-Loss Ratios. -- Differences in disease



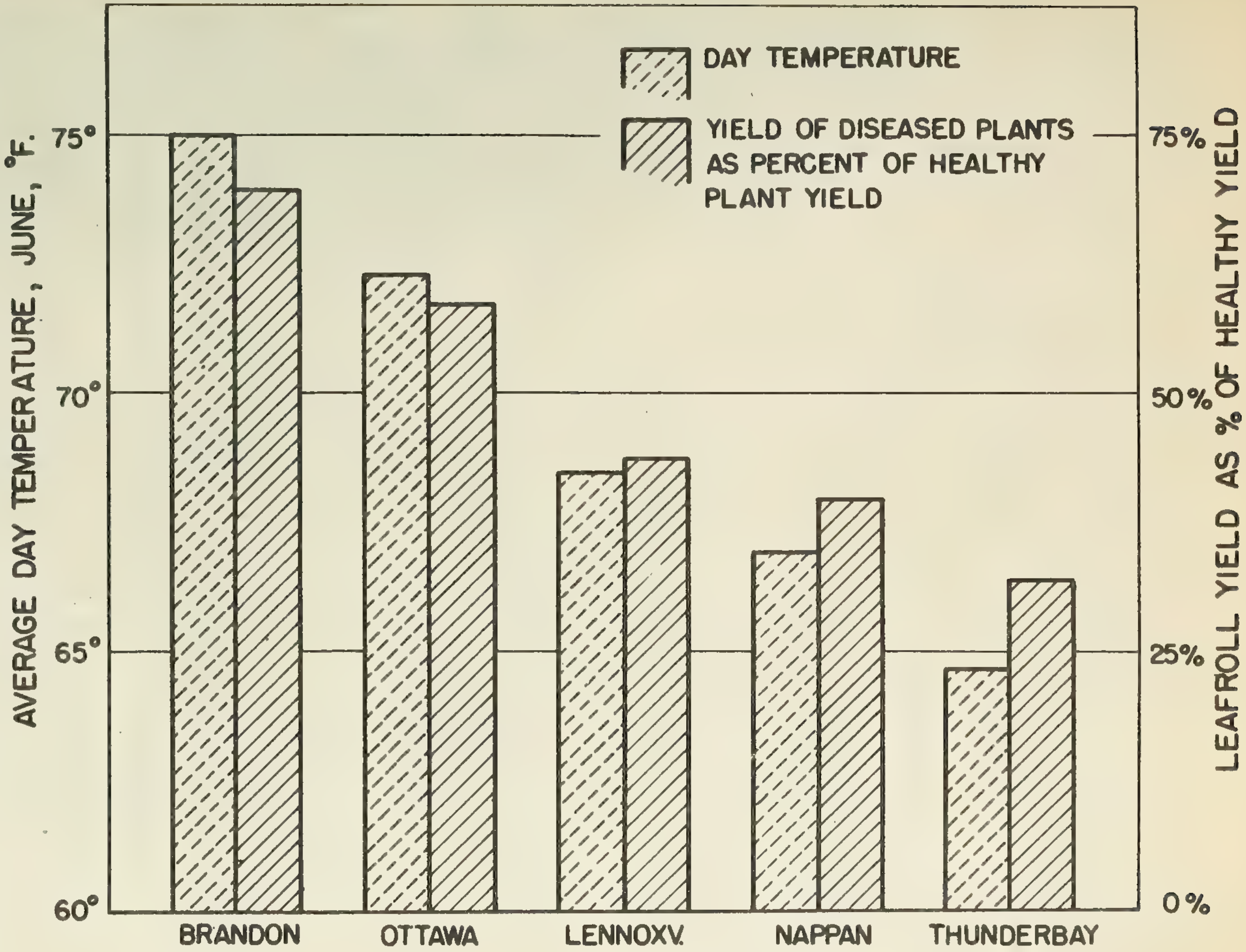


Figure 4 (above). Relation between temperature and percent crop reduction caused by potato leafroll at 5 Canadian stations. (Arranged from P. A. MURPHY, 1921.)

Figure 3 (left). Distribution of 132 recorded measurements of loss from 100 percent potato leafroll, based on 29 published accounts.

intensity-loss ratios from one location or season to another, where they occur, are due to differences in climatic, edaphic, biotic, and cultural factors, alone or in combination. In this and the two following sections an attempt is made to distinguish the effects of these factors.

A number of investigators have stated that the amount of loss caused by a given concentration of disease may vary with the water supply. In the case of Texas root rot in cotton, EZEKIEL and TAUBENHAUS (1934) found that under irrigation the intensity-loss factor is only about 1/2 that for cotton grown under natural moisture conditions. However, under the varying rainfall of different seasons and locations, after a 12-year study they concluded that the "loss-estimation ratio" (a factor which is multiplied by the percent of plants killed at the time of the first picking to give loss percent) varied only from .85 to .95 with rainfall and that an average ratio of .9 was sufficiently accurate for use in calculating the annual loss from root rot in Texas.

In very dry summers, after there has been adequate rainfall earlier in the season, some crop scientists and growers feel that there is an advantage, or at least little harm, in some degree of defoliation. If this is true, diseases which attack leaves might be expected to cause greater relative loss during moist seasons than in dryer ones. LUDWIG'S data on cotton (1927) show that defoliation at any time is harmful, but that the greatest percent of crop reduction from defoliation occurs in the wetter environments. He defoliated cotton at two dates in dry, moderately irrigated, and very wet plots, and when the percent of loss caused by defoliation is calculated from his data it is seen that with early defoliation the loss of seed cotton was 26.0, 51.2, and 60.6% in passing from the dryest to the wettest plots. With late defoliation the corresponding figures were 0.8, 6.1, and 10.0% loss, and similarly, greater loss ratios with increasing moisture are seen in his data on number of bolls, weight of seed, and weight of lint.

This is an isolated instance and the existing data relating moisture to disease intensity-loss ratios are far too few to permit any generalizations. For the present we must proceed from one crop and disease to the next, entirely on an empirical basis, with the expectation that as data of this sort accumulate we will be able either to develop certain general principles governing the moisture-loss relationship or, if not, we can at least determine this relationship for important individual cases, as the Texas workers have done for cotton root rot. We may expect to find much variation in these relationships, depending on the physiology of the crop, the nature of the disease, and the organs harvested, As an example, MOLOTKOVSKY (1945) in Russia holds that when potato growth is checked by midsummer heat and drought, yields are increased by mowing the vines. This is not unexpected, since under these conditions respiration and the consumption of carbohydrates may exceed photosynthesis and food storage.

In some cases differences in temperature may be expected to produce important differences in disease intensity-loss ratios. Figure 4 shows how the percentage of crop loss increases as the temperature falls in the case of potato leafroll.

P. A. MURPHY (1921) observed a comparable, though less striking relationship between increase in temperature and decrease in loss percentage in the case of potato mosaic. It is generally true of virus diseases that disease symptoms, which include yield reduction, are most marked at low temperatures, and that they diminish or even become entirely masked at high temperatures. This would seem to explain higher disease intensity-loss ratios from virus diseases in general when loss measurements are made in cool localities and seasons.

In cases of disease which destroy plants early in the season, the loss is somewhat compensated for by the growth advantage in adjacent plants, a subject which is considered in detail in Chapter X. In the present connection, however, it should be mentioned that LIVERMORE (1927) has reported that this compensating effect is very much influenced by soil and climate.

Effects Of Edaphic Factors And Crop Vigor On Disease Intensity-Loss Ratios. -- The data relating soil properties to disease intensity-loss ratios are also scarce, although a number of investigators have suggested that the soil may influence these ratios. GRAM (1923), in his study of the effect of environment on potato leafroll, furnished data which indicate that the losses for a given intensity of disease were much more uniform when 12 Danish locations were compared during the same season than when different seasons in the same location were compared. Similarly, McNEW (1943a) has presented data which show that in one variety of peas the loss percentages in yields which are controllable by seed treatment varied only in a minor fashion (31.5, 40.0, 36.7, 30.8%) in experiments involving essentially the same disease intensity in variously fertilized and unfertilized soil. In a second variety, however, the loss was 22% in unfertilized soil but only 8% in fertilized soil. In the case of sugar beet yellows, HULL and WATSON (1947) found that although soil fertilization greatly affected yields, it had little influence on the percentage yield reduction due to the disease.

In contrast to these results there are several reports which indicate that crops under poor growing conditions have higher disease intensity-loss ratios than more vigorous crops. With mosaic of greenhouse tomatoes, HEUBERGER and NORTON (1933). have pointed out that uniform infection by this disease produced significantly greater loss when the plants were growing under somewhat unfavorable conditions in a bed, than under better conditions on the greenhouse bench. SCHULTZ, BONDE, and RALEIGH (1934) also have indicated that given intensities of virus diseases have a less depressing effect on potato yields under the ideal growing conditions of Aroostook County, Maine, than under the less favorable conditions of Long Island, and LECLERG et al. (1944) made a similar comparison between lower losses from spindle tuber and leafroll of potato in Maine and higher losses in Louisiana.

In apparent contradiction to these results, HEUSER and BOEKHOLT (in LUBISHCHEV, 1940) have advanced the supposition that under good growing conditions cereal leaves are fully functional and that removal of part of them has a more serious effect than comparable removal of the supposedly less efficient leaves of poorly growing plants. LUBISCHEV asserts that this view is not compatible with the data from rye defoliation experiments, and SWANSON (1941) has brought out clearly the fact that in sorghum the leaves are much more efficient in producing grain during seasons of limited rainfall than in moist seasons when the plants grow more vigorously.

Effects Of Biotic And Cultural Factors On Disease Intensity-Loss Ratios. -- We are again faced with non-uniformity in the scanty data relating disease intensity-loss ratios to biotic and cultural factors. In the case of sugar beet yellows, the time of sowing has little effect on the losses, according to WATSON et al. (1946), although T. W. WHITEHEAD (1924) advances different cultural practices as a cause of variation in measurements of loss from potato leafroll.

The percentages of loss in potato from comparable amounts of late blight are greater if the crop is simultaneously affected with other diseases, in the experience of BEAUMONT and LARGE (1944), while McNEW (1943f) measured very similar loss percentages from tomato leaf blight (27.8, 23.8%), whether or not the crop was also protected with an insecticide.

In the case of the potato viruses some doubt has been cast on the validity of most or all of the early studies of loss, since the X-virus has been almost universally present in many commercial potato varieties, and the losses reported as due to leafroll, mosaic, or other viruses have actually been based on comparisons between leafroll, mosaic, etc. plus X-virus, with supposedly healthy checks containing X-virus.

Antibiotic organisms may also cause variations in the loss constants. This is well illustrated in a study of cereal root rot by GREANEY and MACHACEK (1935). They observed that when the harmless saprophyte, Cephalothecium roseum, was introduced into infection experiments with the root rot fungus, Helminthosporium sativum, the aggressiveness of the latter was decreased and there was less injury to wheat seedlings as shown by their greater dry weights.

VARIETAL INFLUENCES ON THE DISEASE INTENSITY-LOSS RATIO: -- Does the disease intensity-loss ratio vary in an important degree from one crop variety to another? If so, what are the reasons for this variation, and how may we circumvent the difficulty in loss appraisal practice?

Fifty sources of data on this question have been consulted, and these show a wide range of situations, varying from cases in which practically no difference in loss constants is seen in different crop varieties to the other extreme in which a given disease, at a given intensity and with other factors comparable, may cause yield reductions ranging from 0% to 71% (sugar cane red rot, Colletotrichum falcatum) or from 14% to 95% (potato leafroll).

Only minor differences in loss constants from one variety to another, under comparable conditions, have been reported for such varied diseases as tomato streak (L. K. JONES and BURNETT, 1935), butt rot and top rot in oak species (HEPTING et al., 1940, 1941), damping-off in castor beans (STEVENSON, 1947), defoliation of apple and pear varieties (MAGNESS, OVERLEY, and LUCE, 1929, 1931), citrus psorosis (TIDD, 1944), mild mosaic of potato (BONDE et al., 1943) potato X-virus (SMITH and MARKHAM, 1945), and sugar beet yellows (HULL and WATSON, 1947).

Minor to considerable differences in loss constants of different potato varieties have been found in the cases of spindle tuber (SCHULTZ and FOLSOM, 1923; YOUNG and MORRIS, 1930, McKAY and DYKSTRA, 1932; BONDE et al., 1943), "mosaic" (SCHULTZ and FOLSOM, 1921; WHITEHEAD and CURRIE, 1931), and curly dwarf (WHIPPLE, 1919).

Very marked differences in loss constants between varieties are reported for cowpea mosaic, (5.7-52.0%, Anon., 1942), sugar cane red rot (0.0-71.0%, EDGERTON et al., 1937), and soybean defoliation (17.0-51.0%, etc., GIBSON et al., 1943).

In the case of sugar cane mosaic a wide range in loss constants from one variety to another has been reported by BRANDES (1919), LEE (1929), EDGERTON et al. (1937), and M. T. COOK (1947), although in Brazil FREISE (1930) has stated that the decrease in sucrose caused by cane mosaic is independent of variety.

Potato leafroll is a unique example of a disease for which we have a wealth of data on loss constants based on some 30 publications. K. M. SMITH (1946?) has classified 22 British potato varieties in three groups according to the percentage loss caused by leafroll, with 80% or more loss in 7 varieties, 50 to 80% loss in 11 varieties, and less than 50% loss in 4 varieties. Inconsiderable varietal differences in the leafroll loss constants, under comparable conditions, have been reported by SCHULTZ and FOLSOM (1921), TUTHILL and DECKER (1941), BONDE et al. (1943), and LECLERG et al. (1944, 1946). Somewhat greater differences were found by MURPHY (1923) and BONDE and SCHULTZ (1940), while a very wide range of leafroll loss constants in different varieties, in accordance with K. M. SMITH'S grouping mentioned above, is given by WHITEHEAD and CURRIE (1931) who report losses from 100% leafroll of 14.0 to 95.0% in 1924 and 26.0 to 97.6% in 1929.

In comparing loss constants of different crop varieties we distinguish two situations. First, there is the comparison between disease-resistant and susceptible varieties where resistance is expressed as a reduction in intensity of disease (percentage of plants attacked or tissues involved). A valid comparison may only be made between equal intensities of disease. In this case, if resistant and susceptible varieties are growing side-by-side, subject to the same inoculum potential, there will be a marked difference in percentage of crop loss because the varieties are diseased to different extents, and not because of the ability of one variety to suffer less than another when infected to the same extent. In this category belong many of the variety comparisons with respect to rusts, smuts, root knot, and the wilt-resistant varieties in which an occasional plant succumbs. This situation presents no difficulty in crop loss appraisal provided our loss conversion factors are based on disease intensity.

The second, and more difficult situation is the case where resistance to crop loss is due to differences in the nature of reaction of different varieties when diseased to the same extent. In this case resistant varieties express their resistance by tolerance of disease, rather than relative freedom from disease. If this occurs to an important degree we cannot have universal loss constants, since a given intensity of disease will produce much less loss in the tolerant varieties than in others.

Tolerance of disease may take various forms. We see it in the more drought-resistant cereals, which can withstand the excessive loss of water caused by rust and powdery mildew infections and produce fairly good yields despite this handicap. A good example is the reaction of two varieties of wheat in the experiments of SALMON and LAUDE (1932), which were unlike the other 22 varieties tested in that one produced a high yield though heavily infested with leaf rust, while the other yielded well in spite of a high intensity of Septoria leaf blotch.

Another form of tolerance is related to the vegetative cycle of the variety. This will be considered more fully in a later section, and here it is only necessary to point out that if two varieties suffer the same intensity of disease at a given time, one may sustain less loss if the time of appraisal is closer to its time of crop maturity than in the other, later-maturing variety.

When a disease kills some plants outright, leaving adjacent plants unharmed, the adjacent plants are favored by the greater growth space provided, and to some extent will compensate for the loss of the missing plants. In corn (KIESSELBACH, 1922; BROWN and GARRISON, 1923), and doubtless in other crops, this compensating ability differs among varieties and a variety in which this characteristic is highly expressed will suffer less loss from a given percentage of disease than other varieties. This represents another form of tolerance.

Very clear-cut cases of tolerance are seen in those diseases where intensity is total, where the plant is either entirely (systemically) infected or not at all. This is very well illustrated in the virus diseases, and particularly those that are established in vegetatively propagated plants, where time of infection is also a constant. While the physiological explanation is not forthcoming, it seems clear that when two crop varieties are infected with the same virus strain one may show more marked symptoms of injury than the other, and this greater or less tolerance may underlie some, though not all, of the differences in loss constants seen in virus diseases.

In other cases of virus disease, such as sugar cane mosaic, some plants have the ability to recover from the infection, which represents another varietal characteristic that may cause variability in loss constants (EDGERTON et al., 1937).

We have seen that with virus diseases, particularly those of potato and sugar cane, some investigators have found fairly high uniformity in the loss constants for a given disease in different host varieties, while other workers have reported great differences in these constants. These discrepancies may be due to several causes, including varietal tolerance to disease, the presence of more than one virus in experimental plants, inaccurate diagnosis of virus diseases, and differences in the virulence of the virus strains concerned in different experiments or different host varieties.

EFFECT OF PATHOGENIC STRAIN ON THE DISEASE INTENSITY-LOSS RATIO: -- Potato and sugar cane viruses are perpetuated for indefinite periods in the process of vegetative propagation. The loss from such a virus as leafroll in a given potato variety is a function both of the varietal response and the virulence of the particular strain of leafroll virus that happens to be present in the variety. When two leafroll-infected potato varieties are compared, differences in the loss constants may be due to varietal differences in tolerance of the virus, differences in aggressiveness of two virus strains, or a combination of the two. When, in addition, the diseased varieties and "healthy" checks are found also to contain the ubiquitous X-virus, or even different strains of the X-virus in the several varieties and checks, we can see that there is ample opportunity for variation in loss constants.

The X-virus does exist in the form of many strains, and BALD (1943b) has shown, in a highly significant study, that the different strains cause losses ranging from 12% to 45%, the loss percentage being characteristic of the strain and of the degree of symptom expression. The effect of virus strains in producing different loss ratios has been recognized by some of the investigators who have published data on this problem and who have referred to their viruses by such terms as "severe leafroll", "mild leafroll", etc.

It has also been recognized by those who have worked with sugar cane mosaic that observed differences in losses have been due not only to response of the cane varieties but also to the presence of cane mosaic strains of different virulence (EDGERTON *et al.*, 1937; M. T. COOK, 1947).

CONCLUSIONS ON THE FACTORS AFFECTING DISEASE INTENSITY-LOSS RATIOS: -- The question of the extent to which intensity-loss ratios for given diseases vary under the influence of different environmental, varietal, and pathologic factors cannot be answered by any broad generalizations, on the basis of the limited data so far available. For some diseases, the losses from which have been rather thoroughly studied, given intensities of disease produce similar percentages of loss quite consistently, despite the fact that the loss measurements have been made under widely varying conditions.

For purposes of appraising plant disease losses we need to have standard disease intensity-loss constants wherever it can be shown that the variation of these constants from one environment, variety, or pathogenic strain to another is not greater than the permissible range of appraisal error. It is becoming evident that with some diseases we can have and use such universal constants (cereal rusts, smuts, certain virus diseases, etc.). With some other diseases it is likely that the disease intensity-loss ratios will vary so greatly under different conditions that a universal loss constant cannot be used. In these cases there are several possible procedures: to determine the constant in one location for each season and then apply it to a broad area, as GREANEY did for wheat and oat rust; to determine the average constants for each of several large areas and use these annually as regional constants; or a combination of the two, as would be the case if the intensity-loss relationship for a given disease in a single State were to be determined for each season and then applied to estimation of the loss from the disease in that State and season only. The latter is not too laborious for routine practice. The measurement of the loss constant is obtained through a relatively simple field experiment which would require only a small fraction of the time of an investigator who is chiefly interested in one or a few diseases of a single crop within a limited area, in conformity to present-day professional specializations.

There is no indication, from the data thus far available, that differences in the disease-tolerance of varieties of a crop will lead to widespread difficulty in the derivation and use of loss constants. In various types of diseases it is apparent that the disease intensity-loss ratios for numerous varieties of a given crop are sufficiently uniform for our purpose, and that there is no necessity for deriving individual loss constants for each variety. When we occasionally encounter a case, such as that of potato leafroll, in which there is a wide range of degrees of loss depending on variety, the practical problem of loss appraisal can be solved by the simple device which K. M. SMITH has used, of classifying varieties into a small number of groups, each with its uniform group loss constant within a practically useful range of error.

The range of error of the loss constant will determine, among other factors, the range of accuracy of the loss estimate. For some diseases in which the intensity-loss ratios are quite variable we may be forced to accept loss estimates which have fairly wide ranges of error, but which may still have some value in determining, even roughly, the magnitude of loss.

It would be folly to assume that for each disease there can be determined a loss constant which will be independent of crop environment to even a practical degree. It would be equally extravagent to reject all use of loss constants because losses from given intensities of some diseases are highly variable from one environment to another. The loss constants are a kit of tools, some of which are sharp, others dull, while still others are lacking, but such a kit is far preferable to no kit at all.

Some of the lacking tools can be supplied and some of the dull ones can be sharpened as our source data on crop loss measurements increase. The potential value of loss constants is great enough to warrant concerted and industrious efforts to determine them, for many diseases in many environments and varieties.

RELATION OF DISEASE INTENSITY TO LOSS IN CONNECTION WITH THE VEGETATIVE STAGE IN WHICH THE CROP IS ATTACKED: -- It is patent to every plant pathologist that the effect of a given intensity of disease will vary greatly according to the stage of development of the crop at the time this disease intensity is reached. Considering this fact it is curious that in many reports of plant disease occurrence the crop stage is not indicated, and as a result the data may have little comparative value. The data of a disease occurrence, which is more often given, is not sufficient, since plants pass through their several growth stages at entirely different times according to location and season.

Experiments on artificial defoliation of plants to simulate the effects of disease, insect injuries, or hail damage, which are discussed at length in Chapter IX, have shown a similar trend in all the crops studied, -- corn, onions, barley, oats, flax, sorghum, wheat, and soybeans. In all cases, the loss of leaves in midseason causes the greatest reduction in yields, while if the defoliation is progressively earlier or later in the course of plant development, the loss produced is progressively less, until it becomes negligible in plants that are defoliated in the early seedling stage or at submaturity. This effect is proportionate to the fraction of leaves removed but similar in character regardless of the degree of defoliation. When disease attack is on the organs which are to be harvested, a different relationship holds; here the proportionality between attack and loss frequently becomes greater with the approach of harvest time.

The literature abounds in reports of a positive correlation between time from disease attack to harvest and amount of loss produced, from midseason onward, as is well seen in the leaf diseases of potato and tomato, the root rots of cotton and cereals, and the cereal rusts. There have been occasional detailed studies of this phenomenon, such as that of EZEKIEL and TAUBENHAUS (1934) who determined the reduction in yield from cotton plants that were killed by Texas root rot at weekly intervals from June to September, the loss grading from total to none during this period.

The tables for estimating losses from wheat stem rust (KIRBY and ARCHER, 1927) and leaf rust (CHESTER, 1946b) are devices based on the tenable assumption that loss from rust becomes progressively less with increasing delay in reaching any given intensity. This assumption is borne out, not only by common observation, but also by such experiments as those of MAINS (1927, 1930) and JOHNSTON (1931) with wheat leaf rust, or of BEVER (1937) with wheat and barley stripe rust (Puccinia glumarum).

As early as 1915 GASSNER was using and recommending a method of appraising cereal rusts in which both rust intensity and plant growth stage were scored, and this method was adopted by G. J. FISCHER (1929) and a few others, but has never been commonly practiced. In 1936, GASSNER and STRAIB proposed the concept of "injury coefficient", an expression of the percentage decrease in yield per week from attack of rust of a given strength. They found, for example, that for moderate stripe rust the injury coefficient was approximately 3% and for severe stripe rust 5%. Granting that these coefficients would be likely to vary with location and season, they do represent a useful attempt to bring the time factor into the orbit of rust appraisal in a workable fashion.

Consideration of the vegetative stage of the crop has also been emphasized in Russia (RUSAKOV, 1927, 1929b; TOUMARINSON, 1934), where it is recommended that cereal rust appraisals be made several times during the growing season so that the data will show the rust intensity for each variety in comparable growth stages, not merely on one calendar date, when some varieties may be barely headed while others are well advanced toward maturity. RUSAKOV has presented data showing one order of rust intensity for wheat varieties according to appraisals on a single date, with a different, and more correct, order when each variety was appraised in the same (heading) stage.

For virus diseases, numerous investigators agree that the amount of loss is directly proportionate to the earliness in the life of the plant when it becomes infected. This has been found true of tobacco mosaic (VALLEAU and JOHNSON, 1927; McMURTREY, 1928, 1929; WOLF and MOSS, 1933; JOHNSON and VALLEAU, 1941), tomato mosaic (NORTON, 1914; HEUBERGER and NORTON, 1933), current season infection of potato leafroll (L. K. JONES, 1944), sugar beet yellows (WATSON et al., 1946), and bean mosaic (FAJARDO, 1930). In the last case the loss may vary from none to total depending on the growth stage at which the plants contract infection, while for tobacco mosaic McMURTREY (1929) has measured losses in acre value that ranged from 57% loss in plants inoculated at transplanting time to 13% loss from inoculation two months later, at topping time.

In forest pathology it is elementary that the amount of loss from wood decay varies directly with the age of the tree at the time of infection, and with other perennial crops the loss must frequently be considered as a function of the length of time, in years, during which the plant has been subject to disease. With the systemic virus diseases of fruit and other trees the loss in any year depends on the number of years since infection, and even with local, annual diseases the loss must be reckoned in terms of the number of years of attack preceding the present year, as shown for cherry yellows by J. D. MOORE and KEITT (1946).

These examples clearly indicate the importance of considering growth stage of the plant in disease appraisal if results of different observations are to be comparable and if we are to have a logical basis for converting disease intensity into disease loss. This principle has a broader application in pathology, since, as BEAUMONT and LARGE (1944) have indicated, in disease control experiments disease intensities must be recorded in terms of the stage of plant development if the control data are to be fully useful.

THE TEMPO OF DISEASE DEVELOPMENT: -- The outcome of a horse race is determined not so much by the position of the horses at any given moment as by the speed at which they are running. So, too, with plant diseases; a single inspection of disease may give very little indication of the dynamics of disease development. Just as an experienced seaman can determine the course and speed of a distant ship by signs that are meaningless to the landlubber, so the phytopathologist can learn to recognize the evidences that a plant disease is accelerating, static, or decelerating in intensity. It is important that we give attention to the dynamics or tempo of disease development, since this increases our ability to foresee future loss, sometimes early enough to permit the intervention of loss-preventive measures.

Study And Recording Of Disease Tempo. -- The tempo of disease is studied by the simple device of appraising disease intensity at regular intervals during the growing season, using a method of scoring disease intensity that will permit a valid comparison of the successive readings, plotting the data in such a form as will graphically illustrate the tempo, and correlating the trends with the ecological and pathological factors which determine the dynamics of disease.

It may be necessary to make thorough and time-consuming searches to reveal the early steps in disease development. In studying the tempo of cereal rusts, for example, the work should begin long before rust becomes obvious, to obtain numerical values for the important early generations of rust increase. This may require examination of as many as 1000 to 5000 leaves or culms, selected at random. The data should include not only records of the amounts of disease present, but also information on the character of the infections, since this gives useful information on the energy of disease increase. It is important to note, in addition to the number of lesions, their type, -- whether they are old and more or less inactive or whether they bear evidence of having recently developed with more incipient lesions in the process of formation.

Disease frequently increases at a geometrical rate as time advances by arithmetical steps. Therefore a logical and useful way of plotting disease tempo data is on semi-logarithmic coordinates with disease intensity on a logarithmic ordinate and time on an arithmetical abscissa, as in Figure 5. If disease intensity is expressed as percent, the probability scale (logarithmic in each direction from the 50% point, as in Fig. 3 in HORSFALL, 1945, reproduced here in Figure 14, page 248) is preferable.

BARRATT (1945) suggests the following procedure in studying the tempo of disease development as an aid in evaluating fungicides or genetic differences in plants. Disease readings, using a graded scale of disease intensity, are taken at regular intervals during the growing season. The average disease at each reading is graphed on arithmetic-probability coordinates to give the seasonal disease trend. From the trend curve, which often approximates a straight line, the number of days necessary for a variable to reach any given level of disease can be ascertained by interpolation. As a variation (HORSFALL, 1945) the time scale (absicca) may be logarithmic, with time considered as a dosage factor. The purpose of the probability and logarithmic coordinates is to use scales which are most characteristic of the biological phenomena being studied, disease increase commonly being at a logarithmic rate. These are more likely to show straight-line relationships between disease and time, permitting extrapolation, which is not effectively done with the customarliy sigmoid curves that result when disease tempo is plotted on an ordinary double-arithmetic grid.

The following method of recording disease tempo has been used by BALD (1937) in work with the spotted wilt virus disease of tomatoes. The "infection rate" is a quantity independent of the numbers of plants already diseased; it gives the number diseased relative to the number remaining healthy. It is calculated by subtracting the natural logarithm of the number at the beginning of the period, and dividing by the number of days or weeks to give daily or weekly infection rates. Major changes in the infection rate are associated with important factors influencing infection, such as weather or availability of vectors.

Principles Seen In Studies Of Disease Tempo. -- Studies of the tempo of development of different diseases bring out certain principles. One of these has been suggested, namely that while the amount of new infection during any period depends on the amount of infection at the beginning of the period, the rate of infection is independent of the number of plants already diseased. Many disease organisms increase from minor to destructive amount by a series of generations of increase. The increase factor, whether 10-, 100-, or 1000-fold per generation, is a value that is peculiar to the biology of the pathogen and is independent of the amount of disease already present until it becomes limited by a lack of new host tissues to attack. In such a case the tempo of the disease may be expressed as the rapidity with which these generations succeed one another.

CHESTER'S (1946a) analysis of the tempo of cotton wilt (Fusarium), illustrated in Figure 5, shows that the tempo of wilt development for a large number of cotton varieties in one location and season is quite constant, regardless of their resistance or susceptibility to wilt. In contrast, the tempo of this disease for all varieties in one location and season differs markedly from that of a comparable group of varieties in a different season. In the same paper are given tempo curves which indicate that although various fertilizer treatments raise or lower the level of wilt infection of one variety of cotton in a given location and season, there is no marked change in the tempo. This analysis shows that the tempo of development for this soilborne disease appears to be a function of the seasonal weather, unrelated to varietal disease reaction or to soil fertility, and that from one season to another the tempo of disease development varies widely but uniformly for all varieties in one soil or for one variety in all soils.

Airborne diseases may also display this principle, as brought out for potato late blight in Figure 6. Here the differences in tempo for one location in three seasons are much greater than those for four locations in one season.

In dealing with perennial crops, the tempo of diseases which reduce the stand may be measured in years. An excellent example is bacterial wilt (Corynebacterium insidiosum) of alfalfa, a soilborne disease which usually does not become apparent until alfalfa stands are about two years old, and then progressively destroys the plants through succeeding years until the stands become unprofitable.

Data on the tempo of alfalfa wilt have been supplied by SALMON (1930), GRABER and JONES (1935), WIANT and STARR (1936), and WEIHING et al. (1938). Figure 7, based on data in the latter paper, is typical of the results obtained by all these workers. It shows the steady march of the disease, with each semiannual stand count showing roughly 75% as many plants as in the preceding count.

If the plant disease appraiser can regard any pathological situation not as a static, isolated event but as a momentary stage in a dynamic process, or as a single frame in a moving picture, he can obtain a much more accurate loss appraisal, because he visualizes not only present indications of loss accomplished, but also the inevitable loss of the future as the disease proceeds.

Our data on disease tempo are far too few but they show how tempo studies can contribute to loss forecasting. From such information as that given in Figure 7, one can anticipate, with sufficient accuracy to be useful, the profitable life of wilt-infested alfalfa stands and the annual decrease in their value. In England, WATSON, WATSON, and HULL (1946) have studied the tempo of the sugar beet yellows disease, have found a linear relation between time and disease loss, and, as a result, have developed a method for forecasting yields which is helpful in planning beet sugar factory operations. The forecasting of future forest decay, which has become a well-founded practice, is an application of the same principle, since annual decay increment is just another way of expressing the idea of tempo in the case of wood decay.

But the utility of disease tempo studies is not limited to loss forecasting. BARRATT (1945) has shown the value of having a mathematical expression of the "intraseasonal advance of disease" (i.e., tempo) in evaluating fungicide performance and differences in the reactions of crop varieties toward disease. That tempo studies may shed light on the nature of disease resistance in crop varieties is brought out by a comparison of tempo in cotton wilt and tomato wilt. In the former case (Fig. 5) the tempo curves for resistant and susceptible cotton varieties are approximately parallel, indicating here that the rate of increase of disease is independent of varietal resistance although the amount of disease is much less in the resistant varieties. In contrast, WELLMAN'S data (1939) for tomato wilt (Fusarium oxysporum f. lycopersici) (Fig. 8) show a rapid tempo of disease increase for a susceptible variety, a slower tempo for a partly resistant

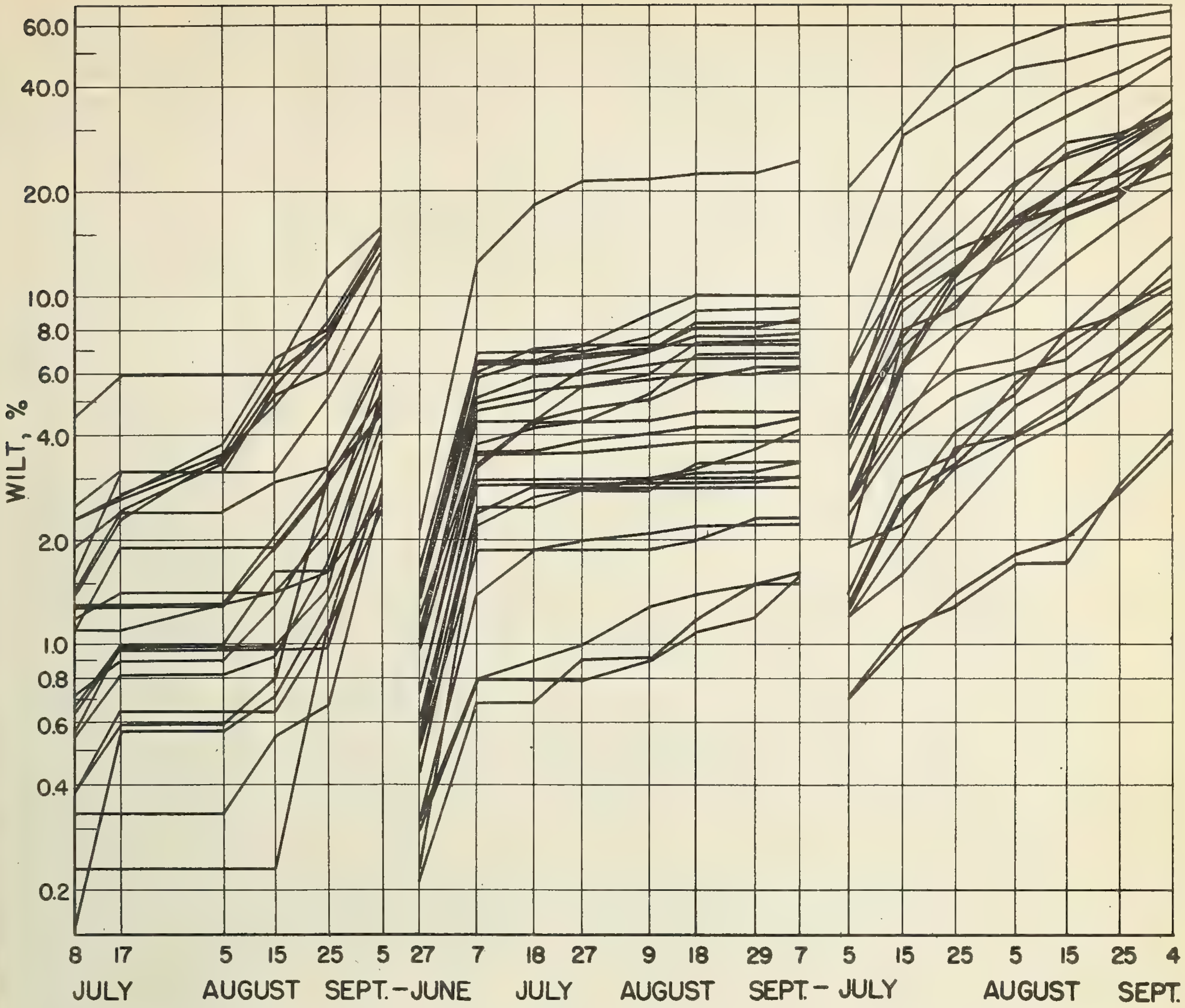


Figure 5. Tempo of cotton wilt development as indicated by tests of 26 varieties in each of 3 seasons at the Cotton Branch Experiment Station, Arkansas. (After CHESTER, 1946a.)

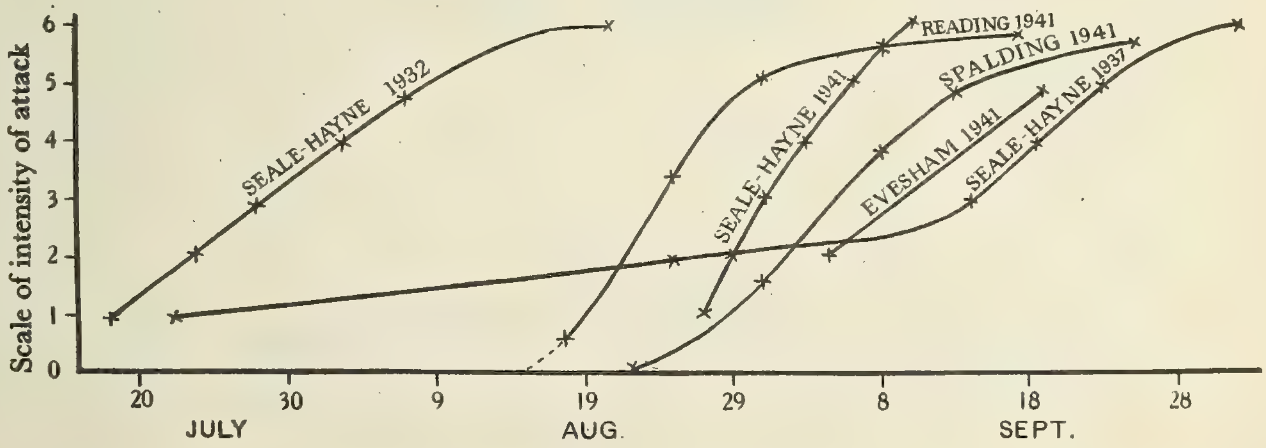


Figure 6. Tempo of potato late blight during 3 seasons at one location and one season at four locations. (After W. C. MOORE, 1943.)

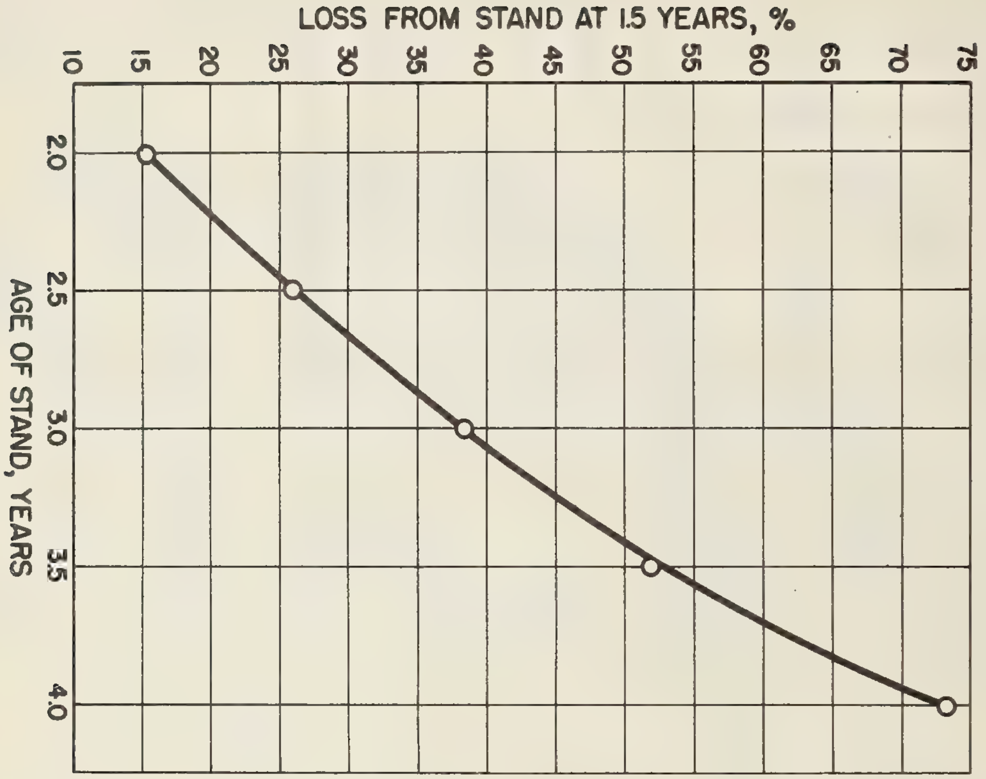


Figure 7. Tempo of stand loss from alfalfa wilt. Averages of 5 tests with average of 7 strains of alfalfa in each test. (From data of WEIHING *et al.*, 1938)

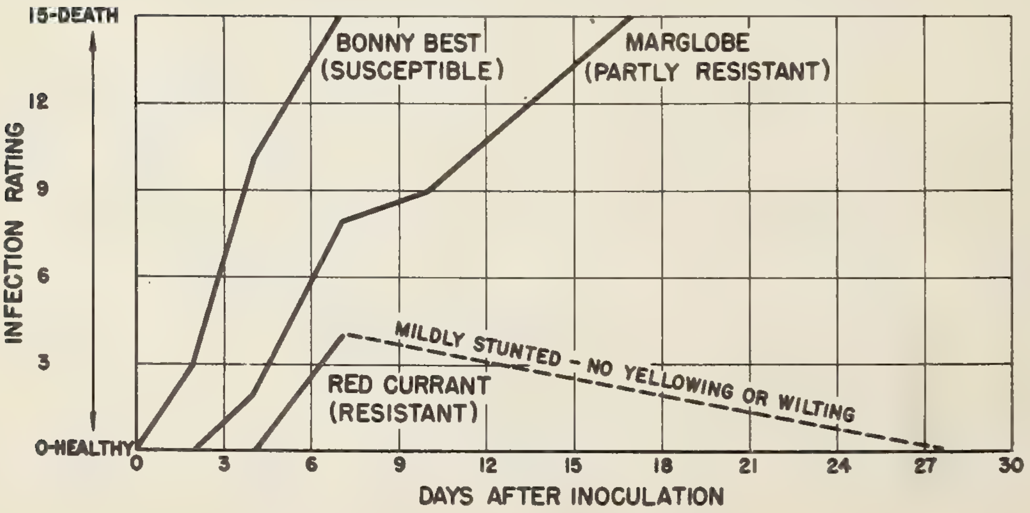


Figure 8. Tempo of tomato wilt development in 3 varieties of different wilt reactions. (*After* WELLMAN, 1939)

variety, and a tempo curve of entirely different character for a highly resistant variety.

As in many other sections of this book, this one can do little more than introduce the topic, point out the usefulness of, and need for, studies of disease tempo, and deplore the fact that "so many have contributed so little to this very important subject." There is golden opportunity for productive work in this branch of plant disease science that links loss appraisal with the ecology of plant disease.

Chapter IV

TECHNIQUES FOR DETERMINING PLANT DISEASE INTENSITY

INTRODUCTION: -- Basically the problem of plant disease loss appraisal consists of measurement of disease intensity and translation of this into loss. The present chapter is concerned with the methods of measuring and recording disease intensity while the following chapter deals with sampling and the organization of disease intensity surveys.

By disease intensity is meant the *amount of disease present* on a plant, in a field, or in a geographic region, without reference to the *damage caused*. BRIERLEY (*in* BEAUMONT *et al.*, 1933) has protested that the phrase "measurement of disease intensity" is ambiguous, comprising two distinct conceptions, distinguished as " 'extensity' which is largely a matter of distribution and rate of increase of the disease, and 'intensity' which is largely a measure of lethality or damage done to that portion or product for which the given crop is cultivated."

These conceptions are followed in this book, but not BRIERLEY'S terms, since they are inappropriate by dictionary definitions, which interpret intensity as "quantity or amount" and extensity as "quality of extension". The concept which BRIERLEY designated "intensity" is here termed damage, destructiveness, or loss.

TEHON and STOUT (1930) have distinguished two components of disease intensity. They limit the term "intensity" to the amount of disease on individual plants, and couple this with "prevalence", the percent of plants affected, to give the disease index as a measure of the *amount of disease* present. NAUMOV (1924) has analyzed the problem somewhat differently. He distinguishes the degree of infection of the population, as percent, and the degree of infection of plant parts, which may be 100% or unity with those diseases where the plant or plant part is either totally diseased or totally healthy (head smuts, plum pockets, etc.). If the plant parts are partially infected, the degree of infection may be expressed as percent (ergot) or a scale of infection may be used (rusts). He has divided all cases of disease into two classes: (a) where infection of plant parts is total and we are interested only in the degree of infection of the population, and (b) where we are interested in the degree of infection of the plant parts, as in rusts, mildews, leaf spots, and some scab diseases. He has recognized that some diseases fall into different classes at different times. There should be recognized a third, intermediate class, in which a part of the population is infected with disease which on any one plant, destroys some fraction but not all of the commercially valuable organs or tissues. As we will see, the methods of appraising disease intensity vary from one to another of these three classes of disease.

In plant pathology there are many points at which measures of disease intensity are needed, as in scoring disease reactions of crop varieties or response of plants to disease control measures or in studies of the epiphytology of plant disease, as well as in loss appraisal. It has frequently happened that methods of determining disease intensity have been worked out for other purposes than loss studies, and the latter can often profit by taking advantage of techniques of disease intensity measurement that have been developed for some other, distinct use.

Methods of appraising the intensity of plant diseases for the most part have developed Topsy-fashion, without any general plan or coordination, each worker devising or adopting the methods that have appeared suitable, with the result that studies or data of several workers on a single problem cannot be compared, because different measures of disease intensity have been used.

There have been a few cases in which workers have been directed or urged to use a uniform system of scaling disease intensity, as in the case of the U. S. Department of Agriculture's field notebook for scoring cereal diseases, and in recent years plant pathologists of the British Mycological Society have been striving toward uniform methods of scoring such important diseases as cereal smuts, apple scab, and potato late blight.

The American Phytopathological Society made an abortive effort in this direction from 1917 to 1920 (*Phytopathology* 7: 149; 8: 179; 9: 182; 10: 265). In 1917 there was appointed a "Committee on Standard Chart for Percentage Estimates of Injury to Diseased Plants" with instructions to develop such devices and report at the next annual meeting. In 1918 this committee reported that it was making progress, and it was continued. In 1919 it made no report. In 1920 the committee: "Finds the chart now in general use by the Office of Cereal Pathology, U. S. Department of Agriculture, best adapted for most phytopathological purposes. It therefore brings this chart to the attention of the Society and recommends it as worthy of more general use." (This was the modified COBB scale designed for and limited to use with cereal rusts; see page 244 and Figure 12). The committee was then discharged.

NUMBER OR PERCENT OF DISEASED PLANTS, ORGANS, OR TISSUES AS A MEASURE OF DISEASE INTENSITY: -- When diseased plants or plant parts are total losses and not partial losses, or when all diseased plants or plant parts are partial losses to the same degree, counts of diseased plants or plant parts and conversion of the counts into percent give accurate measures of disease intensity. Thus we find this method of scoring disease intensity most useful and reliable in dealing with: (a) diseases where the entire plant is rapidly killed, with few plants exhibiting partial loss, as in Fusarium wilt diseases of cotton and other crops, bacterial wilt of alfalfa, Texas root rot, barley stripe, and damping-off of seedlings; (b) cases in which diseased plants, while not killed, are all injured to approximately the same extent, as in virus diseases of vegetatively-propagated plants, excluding current-season infections; (c) instances in which the percent of infected plants is well correlated with the degree of injury, as with corn smut (see page 225); (d) diseases which cause total, not partial, destruction of the commercially valuable parts, as with the head smuts of small grains; (e) diseases in which plants or organs, even if lightly infected, are total losses from the commercial standpoint, such as crown gall of nursery stock, ear smut of sweet corn, brown rot of stone fruits, celery stalk blights, and the anthracnose diseases of tomato and watermelon; and (f) cases in which diseased plants or tissues are so rare that differences in degree of infection have little statistical significance.

The reverse procedure, of counting and determining the percent of healthy plants or tissues, is standard practice with some diseases of these types, for instance in studies of seedling disease where counts of emerged, healthy seedlings constitute the record.

Disease intensity (or loss) data on crop commodities after harvest, expressed as number or percent of market units, are often very helpful in comparing disease in different seasons or localities, though they do not represent total disease intensity because the most heavily diseased products do not enter market channels. Examples of useful data of this type include the Federal Grain Inspector's reports of numbers of carlots of smutty wheat, ergoty rye, and blighted barley, or shipping-point records of numbers of carloads of watermelons rejected for shipment because of anthracnose.

Numbers of diseased plants alone, even when percent of disease is not known, may at times be quite useful. It is very significant, for example, to have the records that in 1944, 20,000 elms in Dayton, Ohio and 10,000 in Columbus, Ohio were killed by the virus disease phloem necrosis.

When a disease is very scarce it may be impractical to determine percent of infection and the number of infected plants found under stated conditions may be the only available record. It is customary in reporting very light infestations of cereal rusts, for example, to note the number of rusted plants or plant parts found in a search of 10 minutes, 30 minutes, etc. The British workers frequently make use of conversion constants by which the number of diseased plants found within a given small area can be converted into approximate percent of infection, assuming a constant stand. With potato virus diseases, 0-0.1% is scored if one infected plant is seen within a 12-yard radius, and 0.1-1.0% if one diseased plant occurs within a 4-yard radius. For sugar beets the corresponding radii are 7 and 2 yards (Anon., 1943).

Descriptive scales of disease intensity are discussed in a later section, but it can be mentioned here that such scales sometimes are based on percent of disease incidence, as in WALKER and HARE'S survey of pea diseases (1943), where their scale of root disease was: "trace" = 1%, "slight" = 1-5%, "moderate" = 5-20%, and "severe" = 100% of plants with roots affected.

Wherever its use is valid, the recording of disease intensity as percent of plants or organs affected has the distinct advantages that it is uniform from one worker to another, provided a diseased plant or organ is properly defined, and that it is easily understood by all. But even the simplest methods have pitfalls, and in this case one is sometimes confused by reports of disease being present to the extent of a given percent when we have no means of knowing whether this is percent of plants with disease in any degree, percent of leaves, fruits, or other tissues affected, percent of leaf or fruit area involved, or percent with reference to some arbitrary scale, such as the COBB cereal rust scale. This fault may be seen in some of the reports of curcurbit downy mildew intensity.

The number or percent of diseased plants or organs is a less suitable measure of disease intensity when different plants or organs differ appreciably in their amounts of disease, or when, for any other reason, the amount of damage is not correlated with the percent of diseased plants or organs. Of the many cases of this kind there may be mentioned the cereal foot and root rots and rusts, leaf and fruit spot diseases in general, corn ear rots, wood decay, and root knot.

KOEHLER (1945) has pointed to the inexactness of many reports of corn ear rots which state only the percent of ears rotted in any degree, and has suggested the need for data on the estimated number or percent of kernels rotted per ear. Similarly HORSFALL and HEUBERGER (1942a), in dealing with tomato defoliation diseases, consider that data limited to the percent of diseased leaves have too low precision because of the varying number of lesions per leaf.

In cases such as these, a combination numerical method is often used. A good typical example is the method used by TEHON and STOUT (1930) in surveying fruit diseases, in which records were taken of percent of trees affected, percent affected leaves, twigs, or fruits per tree, and average percent area, per organ, occupied by the disease. From such data a rather exact overall figure of disease intensity can be derived.

Another good device, where plants or organs differ in degree of attack, is to record the number of plants or organs in each of several disease percent classes, as 0-10%, 10.1-20%, ... 90.1-100%, and reduce this to a single numerical expression of disease intensity. HORSFALL (1945) has pointed out the advantage, in this case, of using classes based on the ability of the human eye to discriminate differences, such as the series: 0-3, 3-6, 6-12, 12-25, 25-50, 50-75, 75-87, 87-94, 94-97, and 97-100% disease. Classing of trees affected with wood decay is practiced in forest pathology, where the number of decayed or dead trees gives no true picture of the amount of decay or of loss.

Where loss is largely in the form of reduced commercial grade of a commodity, a good measure of disease intensity is the percent of products falling into each of several commercial grades. This is a common way of recording intensity of superficial diseases of potato tubers and fruits.

Where disease lesions are small and numerous, or coalescent, it is usually impractical to count or measure them, and some method of estimating must be used. Diagrammatic scales for this purpose are discussed below, and here it may be mentioned that the better scales, such as the COBB cereal rust scale, state for each grade of disease the percent of tissue involved by lesions, as found by measurement, which gives one the basis for translating scale readings into actual percent of diseased tissues.

With leaf-cast diseases the estimated percent of defoliation is a promising measure of disease intensity that has been too little used. It will be seen later that percent of defoliation is frequently well correlated with the intensity of disease on leaves that have not yet been dropped.

DESCRIPTIVE SCALES FOR EVALUATING DISEASE INTENSITY: -- Many workers, dealing with many kinds of plant disease, have found it advantageous to grade disease intensities in a number of arbitrary classes, which, if properly defined or described, represent a uniform method of data-taking and one which is comparable from one worker, location, or season to another. In the course of this study such descriptive scales, of varying quality, were found for sixty different diseases, and doubtless they have been used for many other diseases. The various types of scales used in appraising cereal rusts are considered separately in a later section.

The simplest type of descriptive scale, which, unfortunately, is still sometimes used, is to grade disease in three or more classes under such terms as "light", "moderate", and "severe", and sometimes, to make matters worse, the descriptive word is omitted and the undescribed classes are simply numbered or ascribed symbols such as "-", "±", and "+", or "+", "++", "+++", "++++". Such scales may be meaningless to workers other than the ones who devised them, since "moderate" disease in a region or season in which the disease is very prevalent may correspond to "severe" disease in a year or location with less abundant disease. In general such scales are useful only for recording relative disease differences observed by a single worker in a single location or season.

An example of such an inadequate scale is that adopted by the Alfalfa Improvement Conference (NEWELL and TYSDAL, 1945). This scale, designed by, and intended principally for the use of, agronomists, recognizes the classes: "1 (very little)"------"5 (medium)------ "9 (very much)", which are used, without further description, for scoring intensities of all alfalfa diseases, except bacterial wilt, in the Uniform Alfalfa Nurseries. All other alfalfa plant characters that cannot be recorded by percent are also scored on the 1-9 basis, which gives uniform-appearing records that can be easily averaged for many locations. In actual use this method of scoring disease is far from uniform. It may show relative differences between varieties, but whole groups of varieties or nurseries with similar amounts of infection may be rated as severely affected at one location and only lightly at another because the observers do not have a common understanding as to what constitutes "little", "medium", or "much" infection. This criticism applies to any scale in which the disease grades are not described so that independent observers can place similarly affected plants in the same disease class.

A descriptive scale may also be inadequate if the description of each grade is not realistic, recognizable, and usable in practice. This defect is illustrated by the prescribed grades of severity of infection of "miscellaneous diseases" of cereals in the "Cereal Disease Field Notebook" which was formerly widely used by U. S. Department of Agriculture cerealists and cooperators. This scale reads:

0 = absence of infection

1 = very slight, -- one or two specimens per acre
2 = slight, -- 8-10 specimens per acre
3 = considerable, -- 30-40 specimens per acre
4 = abundant, -- 25 percent to 50 percent of plants diseased
5 = very abundant, -- more than 50 percent of plants diseased

Here grades "4" and "5" are well understood. Grades "1" to "3" are meaningless, practically, since there are often more than 800,000 tillers per acre in a field of small-grain and it is obviously impractical to examine this many tillers, nor have these differences any practical importance. Furthermore, there is an enormous gap between grade "3" and grade "4". Grade "2" represents approximately five times as much disease as grade "1", grade "3" about four times as much as grade "2", and grade "5" about twice as much as grade "4", but grade "4" contains 2,000 times as much disease as grade "3", assuming that a "specimen" is a 5-tiller plant.

The need for, and striving toward, better scales of disease intensity are seen in the evolutionary improvement of scales, sometimes even in the methods of a single investigator. HORSFALL and his coworkers have made several improvements on their earliest methods of disease appraisal, and WILSON (1944), during six years of celery blight experiments, successively used four methods of scaling disease intensity, each better than the preceding one.

The following scale for potato late blight (*Phytophthora infestans*), developed by the subcommittee on disease measurement of the British Mycological Society is given as an example of a well-devised and useful descriptive scale, which should result in uniform, comparable disease records from different observers, locations, and seasons:

Notation	Degree of disease intensity
0.0	Not seen in field.
0.1	Only few plants affected here and there; up to 1-2 spots in 12 yd. radius.
1.0	Up to 10 spots per plant or general light spotting.
5.0	About 50 spots per plant or up to 1 leaflet in 10
25.0	Nearly every leaflet with lesions; plants still of normal form; field may smell of blight but looks green though every plant affected.
50.0	Every plant affected and about one half of leaf area destroyed; field looks green, flecked with brown.
75.0	About three-fourths of leaf area destroyed; field looks neither green nor brown. In some varieties the youngest leaves escape infection, so that green color is more conspicuous than in varieties like King Edward, which commonly show severe shoot infection.
95.0	Only few green leaves remaining, but stems green.
100.0	All leaves dead; stems dead or dying.

The value of such a scale is enhanced if it is accompanied by photographs or drawings illustrating the several grades, as discussed in the next section. Combination descriptive-diagrammatic scales have been developed for cereal root rots by GREANEY and MACHACEK (1935), for root knot by TAYLOR (1941), and for corn leaf blight by ULLSTRUP *et al.* (1945). Another helpful device is to have each scale class refer to a countable or measurable degree of disease, such as percent of leaf or fruit area involved in lesions or percent of roots affected by root knot.

Some workers have found it desirable to have two scales applying to different aspects of a disease, giving an opportunity to select the method best suited to the conditions of observation. TOWNSEND and HEUBERGER (1943), for example have described two methods of scoring the intensity of celery blight, one based on a classification of affected leaves and the other for scoring plots directly. Both had similar accuracy and the latter was chosen as being much more rapid. With leaf diseases one scale may be based on the degree of leaf involvement by disease and another on leaf death and defoliation, and with diseases that affect two or more types of organs, such as apple scab, it is helpful to have a scale for each of these.

In the preceding chapter it was pointed out that the stage of development of a plant at the time of its attack with a given intensity of disease is important in determining the amount of loss. Recognizing this, some investigators have made good use of companion scales, one for disease intensity, the other for growth stage. GASSNER'S growth-disease scale for cereal rusts is mentioned later. The double scale of ANDERSEN (1946) for lettuce tipburn is a good illustration of this type:

Tipburn severity ratings	Leaf age ratings
1 - Very slight spotting in 1-2 leaves of age 5-7.	Age 3 - Leaves 1-2 inches in diameter. No chlorophyll.
3 - Slight spotting in 2-3 leaves of age 5-7.	Age 5 - The larger leaves tightly folded in the head. Usually no chlorophyll.
5 - Slight spotting in most leaves of age 5-7.	
7 - Spotting in most leaves of ages 5-7 plus some slime.	Age 7 - The head wrapper leaves only partly devoid of chlorophyll.
9 - Spotting in large leaves of age 3 as well as those of age 5-7, with much slime.	

DISEASE INTENSITY STANDARDS: -- A high degree of uniformity in rating disease intensity is possible when use is made of standards, including photographs, drawings, or preserved specimens, representative of each of a series of grades of disease intensity. In the course of this study a score of these objective aids to disease intensity rating have been found, with or without supplementary descriptions, and of varying quality and usefulness. Many more are needed for uniform scoring of diverse plant diseases, so that each observer may know what others mean by their disease classes, so that we may know how severe is "severe".

Omitting, for the moment, the cereal rust scales, pioneer work in devising disease intensity standards was done by TEHON (1927) and TEHON and STOUT (1930) in connection with their plant disease surveys of Illinois. They have furnished us with excellent series of standards in the form of line drawings, illustrating disease intensity grades for Septoria leaf spot of wheat, halo blight of oats, cherry and plum leaf spots, diffuse and spot types of apple scab, apple blotch, the leaf phase of apple black rot, and bacterial spot of peach leaves. One of these is included here in Figure 9 and other scales mentioned in the present section are reproduced in the chapters on source data. Comparable standards for apple rust have been devised by BLISS (1933) and P. R. MILLER (1934). A planimeter may be used for measuring the areas of lesions and of leaves, or advantage may be taken of other technical aids such as the apparatus for making leaf drawings described by STANILAND (1946). Technical suggestions that apply to this problem will be found in the discussion of artificial defoliation experiments (page 309).

Figure 9. Diagrammatic scale for appraising black rot intensity on apple leaves. (After TEHON and STOUT, 1930. Courtesy, Illinois Natural History Survey.)

In construction of their leaf disease standards, TEHON and STOUT attempted to imitate the size, shape, and distribution of disease lesions, and measured the total area of all lesions on each standard leaf to obtain the percent of leaf tissue involved in lesions in each scale grade.

In another good type of diagrammatic standard the entire plant is shown, giving one a conception of the distribution of disease over the plant as a whole. This is very well illustrated by the scale for estimating

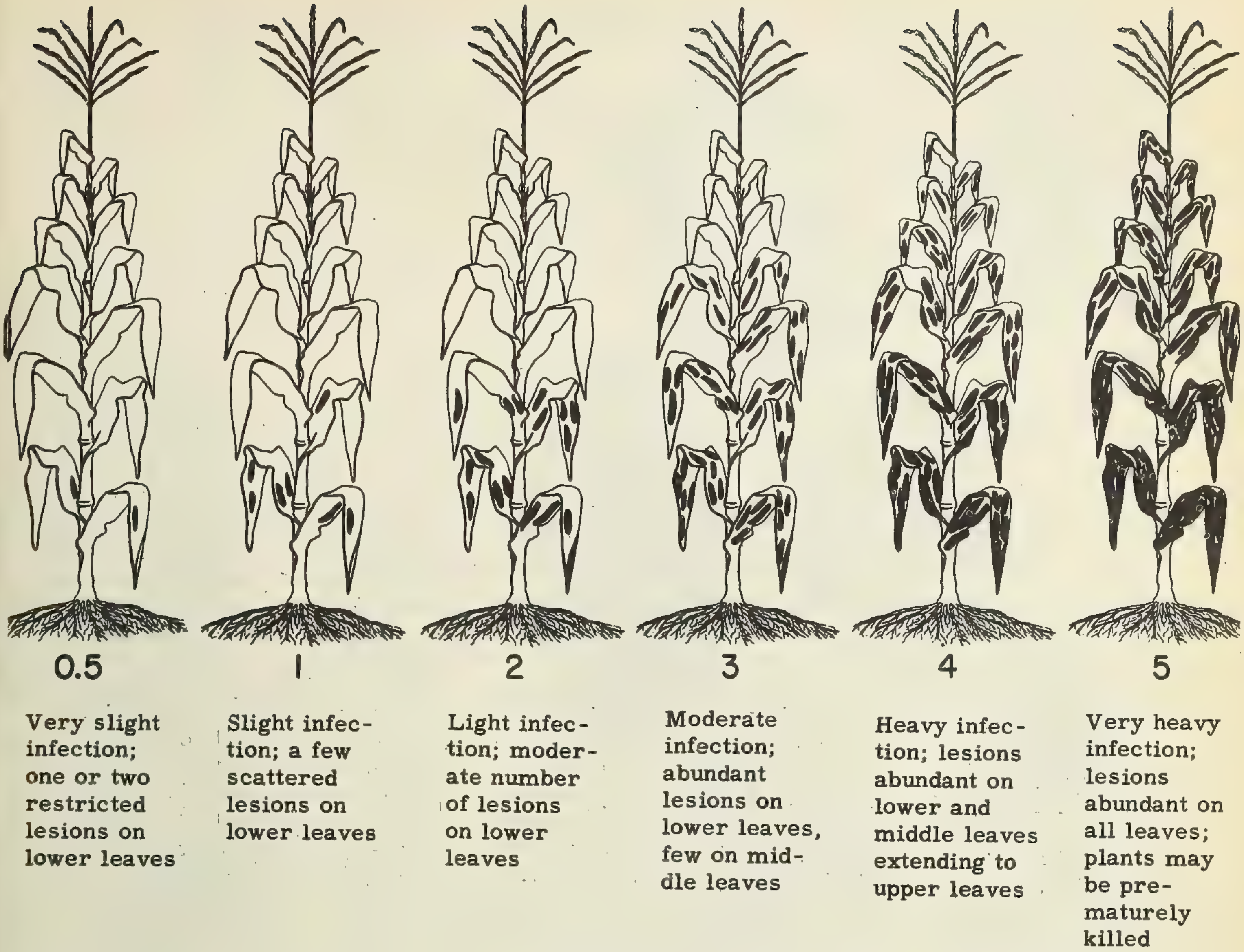


Figure 10. Diagrammatic scale for appraising intensity of Helminthosporium turcicum leaf blight on corn. (After ULLSTRUP et al., 1945). Courtesy, Bureau of Plant Industry, Soils, and Agricultural Engineering, U. S. Dept. of Agriculture.)

Helminthosporium turcicum leaf blight of corn prepared by the Committee on Methods for Reporting Corn Disease Ratings (ULLSTRUP, ELLIOTT, and HOPPE, 1945). The scale is presented in Figure 10 and is supplemented by descriptions of each of the six disease-intensity classes. A comparable diagrammatic scale of the stalks of tomato plants with 14 degrees of wilt attack (Fusarium) has been furnished by WELLMAN (1939). This, like some of the other scales, was originally planned to aid in scoring degrees of disease resistance, but may also be used in appraising disease for other purposes.

A number of other investigators have used actual photographs of diseased leaves, fruits, roots, or plants to compose graded series for rating disease intensities or reactions. Typical of these is the chart prepared by TRUMBOWER (1934), illustrating six degrees of attack of elm leaves by Gleosporium inconspicuum, presented here as Figure 11. He has also given a comparable scale for the Gnomonia ulmea leaf spot of elm, and other photographic scales that are available include those of rubber leaf blight (LANGFORD, 1945), root knot (BARRONS, 1938; TAYLOR, 1941), cereal root rot (GREANEY and MACHACEK, 1935), and bacterial blight of cotton on cotyledons, leaves, and bolls (RAY, 1945). For a somewhat different type of problem, VASUDEVA (1946) has published a series of photographs of five degrees of attack of potato by mosaic. In this case all grades of plants are totally diseased but each grade represents a different degree of plant reaction, owing to presence of different virus strains, and such a scale is helpful in determining loss since loss varies with severity of plant reaction.

CEREAL RUST SCALES AND THEIR USE: -- The first scale to be developed for appraising

Figure 11. Photographic scale for appraising intensity of Gloeosporium leaf spot of elm. (After TRUMBOWER, 1934).

cereal rusts was that of the Australian, COBB, in 1890-1894. It showed diagrammatically 5 degrees of rust intensity ranging from 1% to 50% leaf coverage by pustules and was used chiefly for leaf rusts. In 1917 MELCHERS referred to the "newly adopted U. S. Department of Agriculture scale", and in 1922 he and PARKER published a photograph of the "U. S. D. A. rust scale" which proved to be a slightly altered copy of the COBB scale with the addition of one degree of rustiness and the substitution of a series of percent equivalents with the highest value 100%, representing the maximum rust concentration and corresponding to actual coverage of 37% of the leaf surface with pustules. This modified COBB scale, which has also been called the "American scale" and the "scale of MELCHERS and PARKER", together with the original COBB scale, are presented here in Figure 12.

This scale became very widely used in America through distribution, by the U. S. Department of Agriculture, of a large number of copies of the "Cereal Disease Field Notebook", containing it, and it is still the basis for most American leaf and stem rust ratings. For more exact leaf rust appraisals WALDRON (1936) examined representative leaves under the low power microscope, counted and measured pustules in areas 11 x 20 mm, computed the areas occupied by pustules, and translated this into percent intensity according to the arbitrary percent values of the modified COBB scale.

The "Cereal Disease Field Notebook" directs workers to gather a number of leaves at random and examine a number of plants carefully for stem rust, compare with the diagrams, and record the rust intensities. This lack of specific directions has led to some lack of uniformity in rust reports, since one worker may select average leaves, regardless of location on the plant, another may confine attention to the rank of leaves most typically rusted at the time of inspection, and a third may deliberately select the more heavily rusted tissues. If a sample is intermediate between the 40% and 65% stages, one worker assigns the value 65%, since this is nearer; another (e.g., TEHON, 1927) assigns 40%, selecting the lower grade for intermediate samples by rule; while a third would report this sample by an estimated intermediate value, such as 55%.

The modified COBB scale has been criticized by some European workers, notably NAUMOV (1924) and RUSAKOV (1927) in Russia. The former objects that the scale is "rough, schematic, and rarely will one find such a distribution of pustules." This is true; stem rust and leaf rust pustules are entirely different in shape and the latter tend to be concentrated in some stem areas and scarce in others. In actual practice, however, this does not seem to be a handicap, as the writer has many times observed in comparing the rather uniform rust readings of the same samples, made by two or more independent observers who have been trained in comparable use of the scale.

RUSAKOV'S additional objection is that the modified COBB scale does not have a sufficient

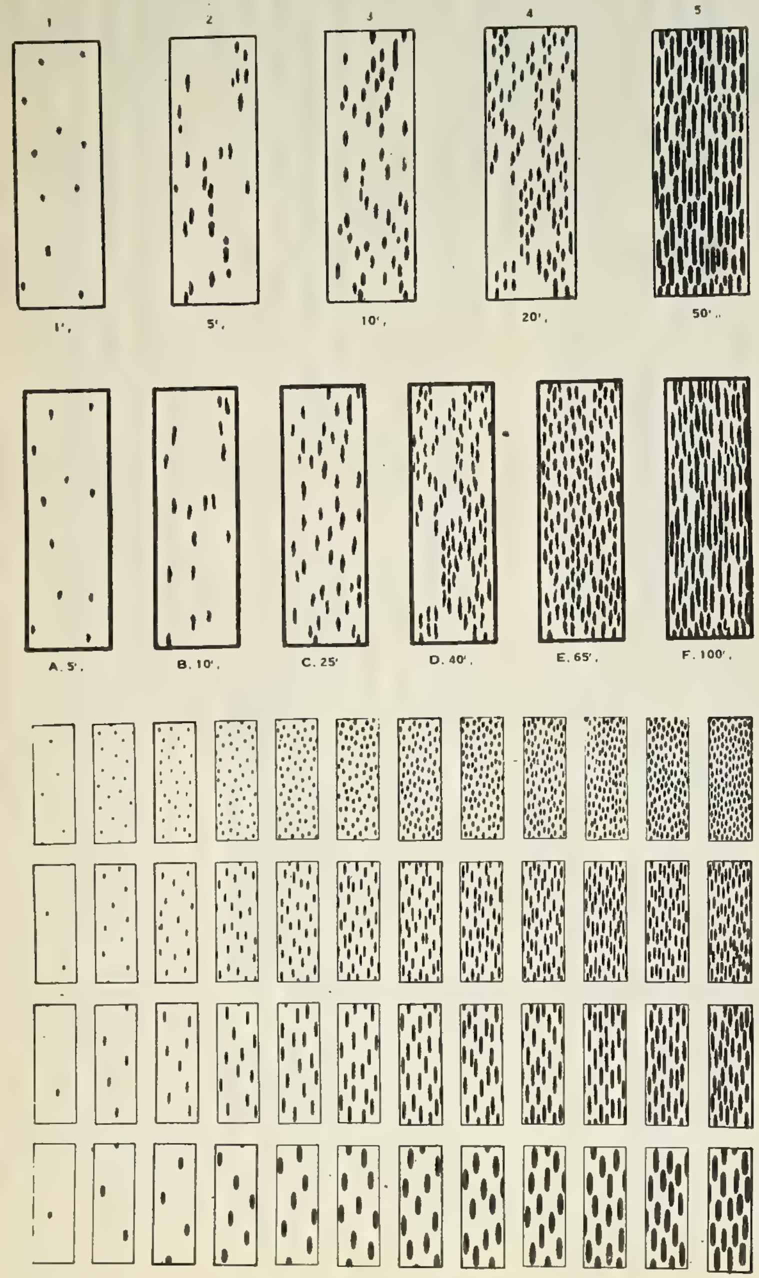
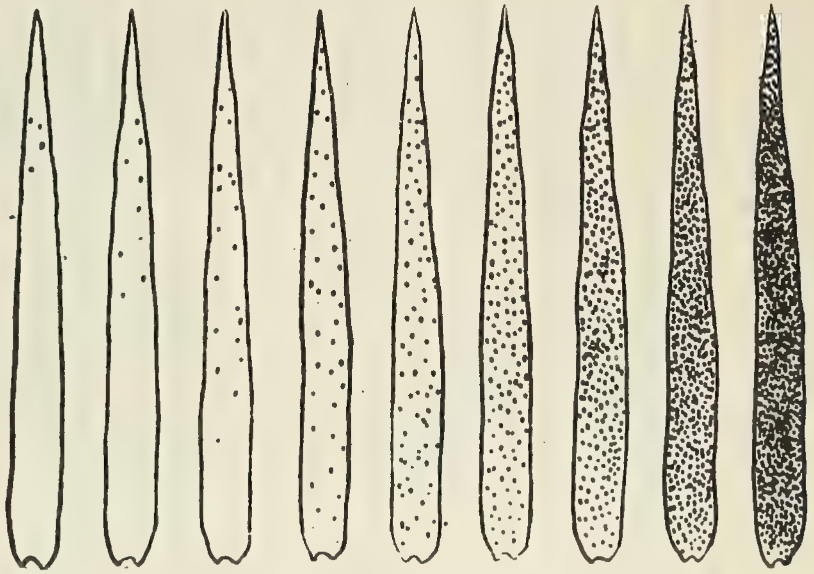


Figure 12 (left). Above: Original COBB scale for estimating cereal rust. (After COBB, 1890-94.) Center: Modified COBB rust scale of the U. S. Dept. of Agriculture. (After MELCHERS and PARKER, 1922.) Below: Canadian scale for cereal rust estimation. This was published in three sizes to facilitate rust appraisal under conditions of different pustule size. (After PETERSON et al., 1948. Courtesy, Canadian Journal of Research.)



RUSSIAN UNITS:	1	1½	2	2½	3	3¼	3½	3¾	4
EQUIVALENT TO NO. PUSTULES:	1-5	6-12	13-25	26-50	51-100	101-175	176-325	326-500	OVER 500
CORRESPONDING VALUES IN COBB SCALE:	—	—	—	1%	5%	10%	20%	—	50%
CORRESPONDING VALUES IN USDA MODIFICATION OF COBB SCALE:	—	—	—	5%	10%	25%	40%	65%	100%

Figure 13. Russian scale for cereal rust estimation. (After RUSAKOV, 1927.)

number of grades at the lower end of the scale, which is valid if one is concerned with rust reproduction at levels of low rust intensity, although with very small amounts of rust it is usually more accurate and just as convenient to count pustules as it is to estimate their number by use of a diagrammatic scale.

In an endeavor to proceed in the direction of greater accuracy in determining degrees of rust intensity, RUSAKOV (1926, 1927, 1929b, 1929c) developed a new diagrammatic scale, which has since been widely accepted and used by Russian workers. Figure 13 shows this scale, with its 9 grades of rustiness, the numerical symbols for noting each, the number of pustules per leaf corresponding to each grade, and the approximate equivalents on the modified COBB scale. It is seen that RUSAKOV'S scale includes three degrees of rustiness in the low rust range that have no counterpart in the other scales, in accordance with his observation that 10, 15, and 20 rust pustules per leaf respectively in the early period of rust development may lead to major differences in grain yields in the three cases.

The Russian scale has degrees of rustiness that progress in logarithmic order in accordance with the mode of rust reproduction and the ability of the eye to discriminate differences. Each stage represents approximately double the number of rust pustules per leaf as that of the next lower stage. To reduce the system of Russian units of estimation to values indicating the rustiness of whole plants, RUSAKOV has furnished the "equivalent units" shown in Figure 13, each unit corresponding to 250 rust pustules.

Most recently, PETERSON et al. (1948) have presented a new cereal rust scale, reproduced in Figure 13, with the advantages of showing 12 rust intensities for each of four classes of pustule size and shape. This is a step forward, but the use of logarithmic, rather than arithmetic intervals would be preferable, since the difference between the 70% and 80% grades, for example, is hardly perceptible, while that between the 10% and 20% grades is readily observed.

Parallel with the development of these diagrammatic rust scales, a series of descriptive rust scales have been proposed by other workers. The first of these was the scale of ERIKSSON and HENNING in 1896, which recognized four numbered degrees of rust intensity described as "trace", "sparse", "moderately abundant", and "abundant". A similar scale was recommended by YACHEVSKI in 1909, and another, but with six rust grades, by NILSSON-EHLE in 1911. LITVINOV'S descriptive rust scale (1912) had seven rust grades and was distinct in its application to the whole plant rather than to single leaves. The scale proposed by DUCOMET and FOEX in 1925 also had seven stages, ranging from "trace" to "enormous".

VAVILOV (1913, 1919, 1935) attempted to devise a scale reflecting both rust intensity and host reaction to rust, which assumes that there is a correlation between increasing number of rust pustules and increasing rust susceptibility. He published (1935) colored plates of his scales for wheat leaf and stripe rusts. The weakness of such a scale is the fact that rust intensity and rust reaction often are not correlated. There may be many resistant-type rust pustules on one plant and few susceptible-type pustules on another. Most present-day observers record rust intensity and rust reaction separately, and use the records for different purposes.

In 1915 GASSNER, agreeing with NILSSON-EHLE that four grades of rustiness do not give sufficient diversity, proposed an 8-grade scale (1 = minimum.....3 = weak.....6 = strong..... 8 = exceptionally strong) which had the novel and useful feature of being supplemented by a 10-grade scale of stages of host plant development, noted in Roman numerals. In his notation, "5 VIII", for example, indicated medium rust infection when the host plant was in the post-blossoming stage. This scale is also the first in which is recognized the importance of having rust grades arranged in logarithmic progression.

When rust intensity is at a very low level, some workers, such as RUSAKOV (1929a), report the number of rusted plants or of pustules found in a search of a given length of time, often five or ten minutes. This is not very satisfactory because of marked individual differences in power of observation. A better procedure is to collect leaves at random, sometimes several thousand being required for one observation, and record the number of pustules and of leaves. Since readings using the modified COBB scale can be expressed in number of pustules per leaf, this procedure gives figures which can be compared statistically over as great a range as a millionfold. For example, the level of rust in Stillwater, Oklahoma during the first week of April, 1948 was appraised at 1 pustule per 5000 leaves, while during the corresponding week of 1938 it was approximately 200 pustules per leaf, i.e., 1: 1,000,000.

The existence of so many rust scales is a reflection on the unsettled state of appraisal methods. If it is the prerogative of any worker to devise a new scale when existing ones are unsatisfactory, it is also an obligation for him to use an existing scale, when available and suitable, rather than to burden the literature and increase the complexity and lack of uniformity of disease intensity data by proposing new scales which have no significant advantage over existing ones.

The time-tested usefulness of the modified COBB scale, or, if preferred, the RUSAKOV scale or that of PETERSON et al., and their objective character, warrant their continued use as standard devices, with the discarding of all cereal rust scales which are not diagrammatic, and therefore vary with the conceptions of the users.

The procedure of cereal rust appraisal has been discussed by CHESTER (1944). Rust infestations, except in early stages, are usually quite uniform in individual fields of one host variety, and in ordinary surveying it is usually sufficient to gather a dozen leaves or stems at random and select the point on the scale which comes closest to the average rust intensity for the sample. Where rust is scarce or in the form of scattered infection foci, larger samples, up to several hundred leaves or stems, should be taken, and where it is at a very low level thousands of specimens may need to be examined and the leaves and pustules counted.

Several of the European workers have given more or less elaborate directions for separately scoring the various parts of the plant and then combining the scores to give a single numerical value to the plant as a whole. In some types of studies this is justified, as in investigating differences in the behavior of different host varieties, but the labor involved is so great that such a procedure strictly limits the appraising which may be done, and for surveying rust intensity on a broad scale it is believed that the advantage of being able to sample many fields over a broad area outweighs the advantage of having a highly precise measurement of rust on a few plants from very few locations.

In common practice of sampling for leaf rusts it is neither necessary nor desirable that the leaves be collected at random from all heights of insertion. Until after the blossoming stage, the uppermost leaves have not had time to become infected, while the lowest leaves do not give a true picture of rust intensity since they are no longer functional. It is best to select the samples from the one or two ranks of leaves that have had full time for rust expression, but which have not yet begun to die. It is usually quite obvious which ranks these will be, but if there is any doubt the samples may be taken from all probably useful ranks. It is very helpful to others if rust intensity reports given information on how the samples have been taken.

LOGARITHMIC VERSUS ARITHMETIC STAGES IN DISEASE INTENSITY SCALES; PROBITS: -- Many insect pests and agents of plant disease multiply at geometric rates as time advances by arithmetic degrees. Such behavior may be best recorded by using a logarithmic scale. In the case of rust diseases, for example, the increase from one to ten pustules per leaf consumes as much time and has as much importance biologically as the increase from 10 to 100 to 1000 pustules. A logarithmic scale attaches equal importance to each of these increases, while on an arithmetic scale the increase from one to ten pustules would appear to have no more significance than the increase from 991 to 1000 pustules.

The visual acuity of the human eye is also so adapted that we can perceive differences of equal spread on a logarithmic scale with more or less equal ability, but not differences of equal spread on an arithmetic scale. For both these reasons, then, a logarithmic scale is preferable to an arithmetic one in observing and recording absolute differences in disease intensity.

This principle has been observed in construction of a number of the better disease-intensity scales. With the cereal rusts, GASSNER'S (1915) scale has stages 1, 3, 5, and 7 corresponding to .05, .5, 5-15, and 40-50% leaf coverage respectively, and RUSAKOV'S scale is roughly logarithmic, with the number of pustules per leaf progressively increasing by the steps: 1-5, 6-12, 13-25, 26-50, 51-100, 101-175, 176-325, 326-500, and over 500. Leaf diseases of tomato, cucumber, grape, and potato are all rated by recent workers in Palestine on a scale of disease units of the form: 0, 0.1, 0.5, 1.0, 2.0, 4.0, 8.0, (REICHERT et al., 1942a, b, 1944; LITTAUER et al., 1946).

Where percent disease, rather than absolute amount of disease, is recorded, a probability scale is sometimes used. This is a scale in which the units pass through 1 1/2 logarithmic phases in each direction from the 50% point, on which equal linear distances are called equal probability units or "probits". This method of recording disease intensity was developed by HORSFALL and BARRATT (1945) and has been discussed at length by HORSFALL (1945).

Twelve grades of disease, in percent, are recognized, viz. grade 1 = 0%, 2 = 0-3, 3 = 3-6, 4 = 6-12, 5 = 12-25, 6 = 25-50, 7 = 50-75, 8 = 75-87, 9 = 87-94, 10 = 94-97, 11 = 97-100, and grade 12 = 100% disease. Plotting disease percent and grade on an arithmetic-probability grid gives the linear relationship shown in Figure 14, which is used as a calibration curve for converting graded disease readings into percent.

As HORSFALL has pointed out, such a series of grades follows the WEBER-FECHNER law that visual acuity depends on the logarithm of the intensity of the stimulus. "In grading plant disease the stimulus changes at the 50% level. Below 50%, the eye sees the affected tissue, but above 50% it sees the healthy tissue......Although it hardly seems possible at first that one can read differences of three percent at the end of the scale as easily as a difference of 25 percent in

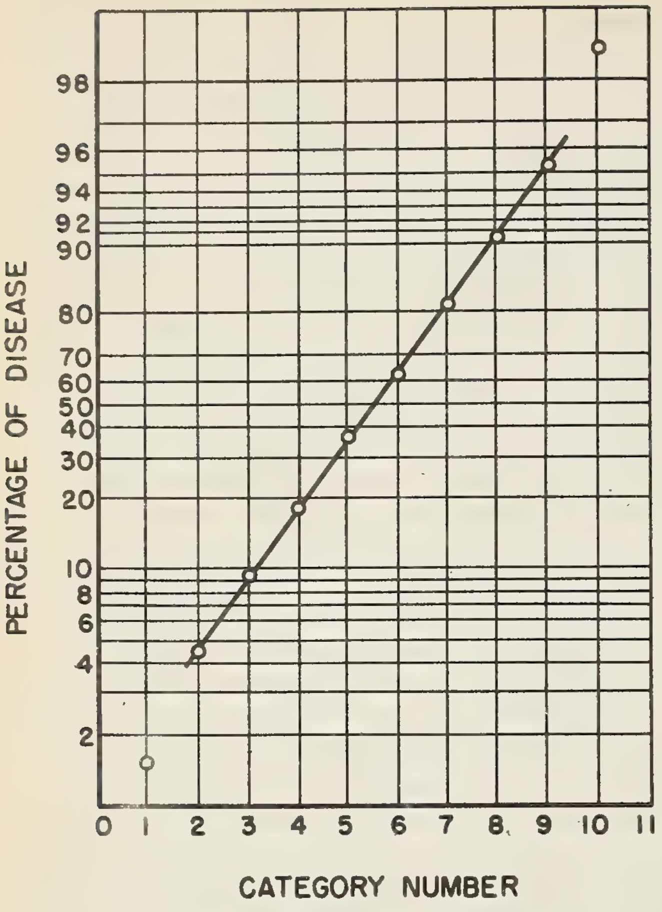


Figure 14. Calibration curve for converting graded disease readings into percentage, illustrating the use of the arithmetic -- probability grid. (After HORSFALL, 1945).

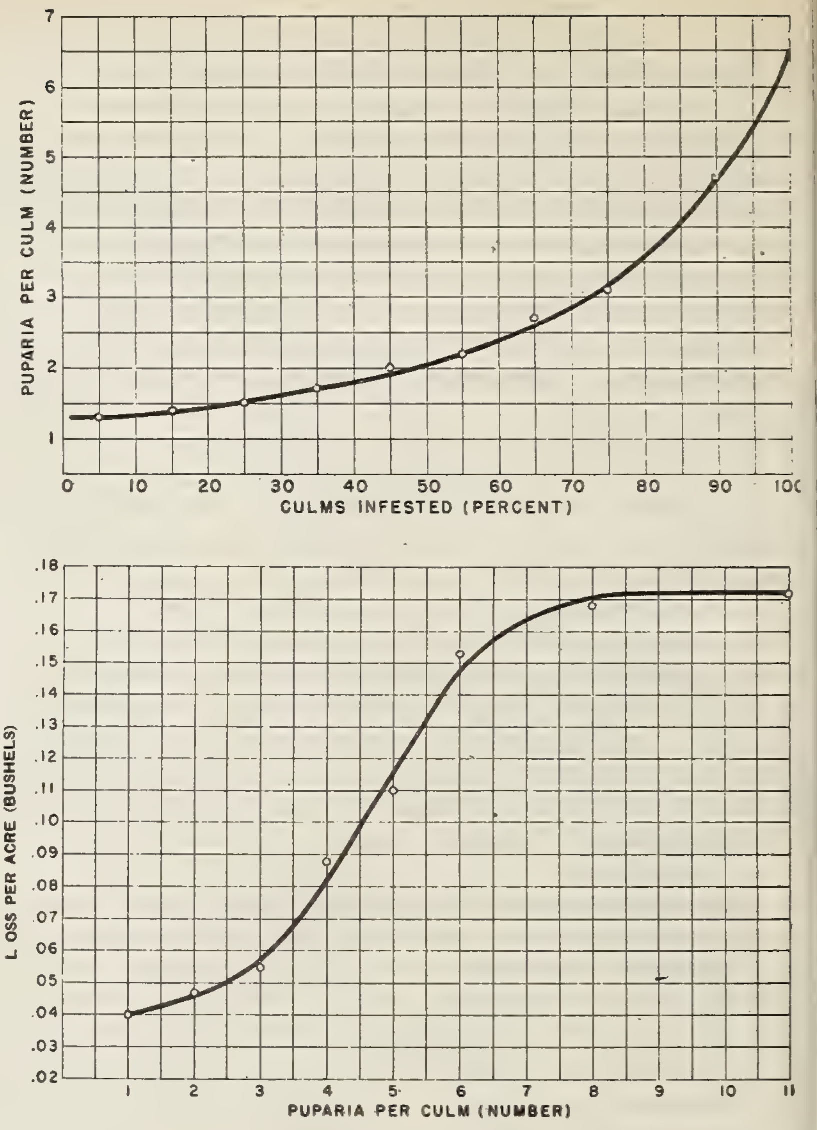


Figure 15. Curves relating percent of wheat culms infested with Hessian fly puparia, number of puparia per culm, and loss in yield. (After HILL et al., 1943.)

the middle, experience shows that actually is the case" (l.c., p. 39.)

HORSFALL'S probability series of disease grades appears to be well suited to use with some types of experiments, particularly in assessing field experiments with fungicides. But from the standpoint of disease appraisal, aimed at determining loss, it has a serious defect, since the different disease classes that are equally well discriminated have great differences in economic significance. The difference between 20 and 80% of leaf tissue destroyed has far greater economic significance than the difference between 2 and 12%, which ranges have equal emphasis on the probability scale. For practical loss determination we need more disease grades between 20 and 80% than between 2 and 12 percent, which this scale does not provide. The other horn of the dilemma is this: What is the use of having more grades than the eye can distinguish?

We obviously cannot do without subdivisions in the middle of the probability scale. The solution of this problem may be to use technical aids to estimation when working in this middle range such as diagrammatic scales, increased numbers of samples, and greater effort generally.

CORRELATIONS OF DIFFERENT EXPRESSIONS OF DISEASE: -- It would be very helpful in many cases of disease appraisal if two or more expressions of disease were well correlated with one another. If there should be a high degree of correlation between root decay and some aboveground symptom, for example, some of the labor and time involved in digging up and examining roots would be spared. If two observers should report intensities of a given disease in terms of two different expressions of disease which are well correlated, a valid comparison of the reports could be made.

An excellent illustration of tests to determine correlations and apply these to loss estimation is to be found in the work of HILL, UDINE, and PINCKNEY (1943), and although they were concerned with insect infestation, the principles of their investigation have general applicability in plant pathology. Several thousand wheat culms were examined in a study of Hessian fly incidence and effects, and from the data obtained there were constructed the curves reproduced in Figure 15. Part "A" of the figure shows the good correlation observed between percent culms infested and number of fly puparia per culm, while part "B" equally well relates the number of puparia per culm to yield. Equipped with this information, the appraiser could determine yield reduction by fly damage knowing either the percent infested culms in a field or the average number of puparia per culm (in case his sample was a bundle of infested culms without data on percent of field infestation), or he could derive either of these values from the other. There are very analogous problems in plant pathology, such as the relation between percent of scabbed apples to amount of scab per apple, or between number of disease lesions per leaf and percent of leaves diseased in any degree.

NAUMOV (1924) considers it to be a general principle that there is a high correlation between percent of plants infected with disease in any degree, percent of organs infected, and severity of infection per organ. Many investigators have suggested that this principle applies to diseases which they have studied, but there appear to be very few records of determination of correlations comparable to those with the Hessian fly. Some of the descriptive scales of disease intensity also suggest such correlations, as that of ULLSTRUP et al. (1945) for Helminthosporium turcicum leaf blight of corn, where the definitions of successive disease grades mention parallel increases in number of lesions per leaf and in number of diseased leaves per plant (Figure 10).

In his study of meadow crop diseases in 1930, HORSFALL regularly found a constant ratio between percent of healthy leaves, percent of leaves in various stages of disease, and percent of dead leaves. "If, for example, 60% of the leaves were infected, then about 15% of these would be dead, and the others would lie along an infection gradient from severely infected to healthy." In later work with tomato defoliation (HORSFALL and HEUBERGER, 1942b) he worked on the assumption that the percent of dead leaves is proportionate to the number of lesions, thus avoiding the excessively time-consuming work of counting individual lesions.

It seems very reasonable to suppose that there is often a regular correlation between these three measures of disease intensity, -- percent of plants affected, percent of organs per plant affected, and degree of infection per organ. Yet we cannot safely proceed merely on the basis of an assumption. If efforts could be made to determine the validity of these correlations for numerous types of disease, the results would have great value in disease appraisal, making it possible to select the easiest or most rapid of several alternate measures of disease intensity, or to convert data obtained by one type of measurement into estimates in terms of others.

As a good illustration of the value of correlations of this type, we have GODFREY'S (1934) study of appraisal of nematode populations in the soil. It is very time-consuming and impractical to do this by actually counting the organisms. GODFREY planted susceptible "indicator plants" in infected soil and demonstrated clearly that there is a high degree of correlation between percent of plants infected, number of nematode galls per plant, and nematode population in the soil. As a result it is possible to use the simple and rapid plant- or gall-counts and, by use of a suitable formula, to convert these into soil infestation values.

The prospect of establishing constant ratios between disease intensities of different organs of the same plant is subject to more exceptions. There are numerous diseases comparable to apple blotch in which there is independent variation in the amount of disease on leaves, twigs, and fruits. Apple varieties are classified differently according to their blotch susceptibility in these three types of organs. Apple bitter rot (Glomerella cingulata) shows the same situation. With such diseases as these, the several organs must each be appraised, since the amount of disease on one type of organ may give no valid index of the amount on another organ.

But we need not exclude the possibility of all correlations of diseased organs because they are lacking in some cases. HORSFALL and HEUBERGER (1942a) have shown a high positive correlation between tomato leaf damage and stem-end rot of the fruits, McNEW (1943i) has found late blight (Phytophthora) of tomato vines correlated with fruit rot, and LEWIS (1944) has reported a high correlation between spray injury of leaves and preharvest-drop of apple fruits.

Whenever, as in the latter case, the effect on one organ is the direct result of disease on another organ, a high correlation between the two may be expected. Numerous other typical examples are found in experiments on the effects of defoliation in reducing twig length and fruit, nut, or grain production (cf. SCHUSTER, 1933). A very practical use of such correlations is seen in the analysis of annual rings of trees to determine the occurrence and severity of defoliation and other plant injuries in earlier years.

With the cereal rusts there are some useful correlations apart from that between rust and plant development or yield. CONNERS (1936) has advanced the principle that leaf rust of wheat attacks leaf sheaths more lightly than the leaves but in direct proportion to the leaf attacks. "It is suggested that the percentage infection found thereon may serve as an index to the susceptibility of the variety when it is impossible to estimate the infection on the blades late in the season on account of their shrivelled condition." RUSAKOV (1929b) holds that there is a correlation between intensity of the uredial stage and that of the telial stage of cereal rusts and that the latter is frequently a more suitable measure of rust intensity than the more commonly used uredial stage. This cannot be invariably true, because there are some regions where the telial stage of wheat leaf rust, for example, rarely occurs. RUSAKOV (1926, 1927, 1929b) has also stressed the correlation between leaf rust intensity and degree of killing of leaves. RUZINOV (1934) goes still farther in maintaining that there is such a high correlation between disease and culm length in cereals that loss from disease can be determined simply by classifying culms according to length group. Culm length is so well known to be affected by genetic and other factors that it is doubtful that so much reliance should be placed on this one plant character.

Canadian investigators have given particular attention to correlations in connection with cereal root rot diseases, where such correlations would be very useful if demonstrated. The results are somewhat uncertain, which may be partly due to variation in the types of root rot studied. BROADFOOT (1934) attempted to correlate root infection of wheat with color of the crown area. In general the color rating agreed with the infection rating, but there were some disparities, where the infection was greater than indicated by the color. SALLANS (1935), working with common root rot of wheat and barley, found that subcrown lesions were more significantly correlated with grain yield reduction than were lesions on the underground parts. Later he and LEDINGHAM (1943) reported that internal crown lesions and external lesions of plants with common root rot were not well correlated.

In forest pathology we find some of the best instances and uses of the correlations between different aspects of disease. Wood decay is the leading problem. Direct examination to determine the amount of decay within standing trees is costly and impractical except on a sampling basis, yet is it necessary to know the approximate amount of decay in order to determine value of the timber for specified uses and optimal cutting time to avoid serious losses from decay. Therefore much attention has been paid to correlations between decay volume and external symptoms or signs.

The presence of the fruiting bodies of wood decay fungi on tree trunks is not a very useful character because these tend to develop late in the decay process and may not be present in cases of serious decay. One old scaling practice for aspen has been for the timber cruiser to cull "heavily" if the trees are more than 15 inches in diameter and bear fruiting bodies and "lightly" if they are 8-14 inches in diameter and lack fruiting bodies, but this is regarded as too vague for good practice (R. M. BROWN, 1934). In general, age and size of the tree are correlated with decay, and BROWN has reported that in aspen there is a high correlation between per cent volume of rot, rot diameter, height of tree, age of tree, and its diameter, regardless of site or soil type. These findings agree, in general, with the earlier ones of MEINECKE (1929).

An excellent study on correlations in oak has been made by HEPTING (1941) and his associates (HEPTING et al., 1940) following a preliminary investigation by HEPTING and HEDGCOCK (1937). In the case of top or trunk rot they found a good correlation between rot and rotten branch stubs, surface injuries, and blind knots on the bole. Fruiting bodies were too rare to serve as the basis for risk classification. They devised a series of decay classes described in terms of these external features, and graphically related the classes to amount of cull (Figure 16).

In studying butt rot in oak, HEPTING found a high correlation between fire wounds and rot, and he was able to present curves (Figure 17) and a formula relating age and width of the wounds to the amount of butt cull, so that the amount of cull at the time of surveying could be determined readily, and the amount of cull at any given future data could be predicted.

An even more detailed study of correlations between external signs of defect and internal decay has been made by ZILLGITT and GEVORKIANTZ (1948), making it possible to determine cull in northern hardwoods, particularly sugar maple, by use of a table correlating 31 types and degrees of external defect with amount of internal defect.

These few examples bring out the value to disease appraisal practice of a knowledge of correlations between different manifestations of a disease. Yet the cases in which such correlations have been studied are far too few. Here is a good opportunity for the investigators of various plant diseases to make important contributions that will simplify or facilitate the appraisal of plant disease intensity and loss.

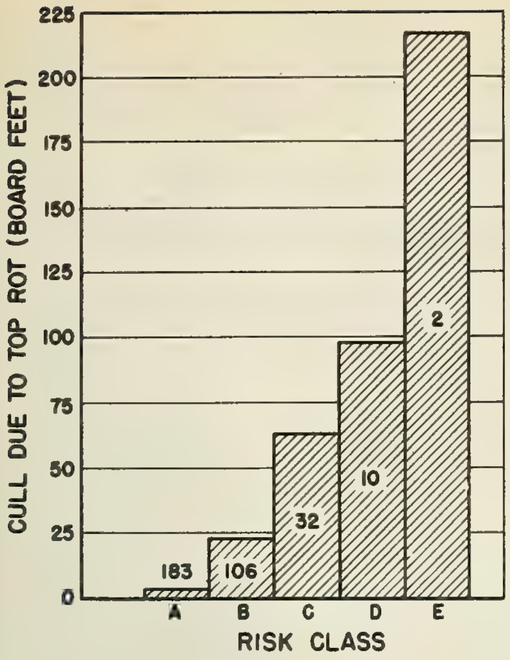


Figure 16. (left) Relation of risk class to cull due to top rot in Appalachian oaks. Classification of risk: A - No rotten stubs over 3" thick, no large surface wounds, no holes and less than 3 blind knots or healed stubs, anywhere on the bole up to 8 ft. above merchantable top; B - One rotten stub or large surface wound, or 3 blind knots; C - Two rotten stubs or large surface wounds, or 4 to 5 blind knots and stubs; D - Three rotten stubs or large surface wounds, or 6 to 7 blind knots and stubs; E - Four or more stubs and wounds or 8 or more blind knots and stubs. (After HEPTING *et al.*, 1940. Courtesy, Bureau of Plant Industry, Soils, and Agricultural Engineering, U. S. Dept. of Agr.)

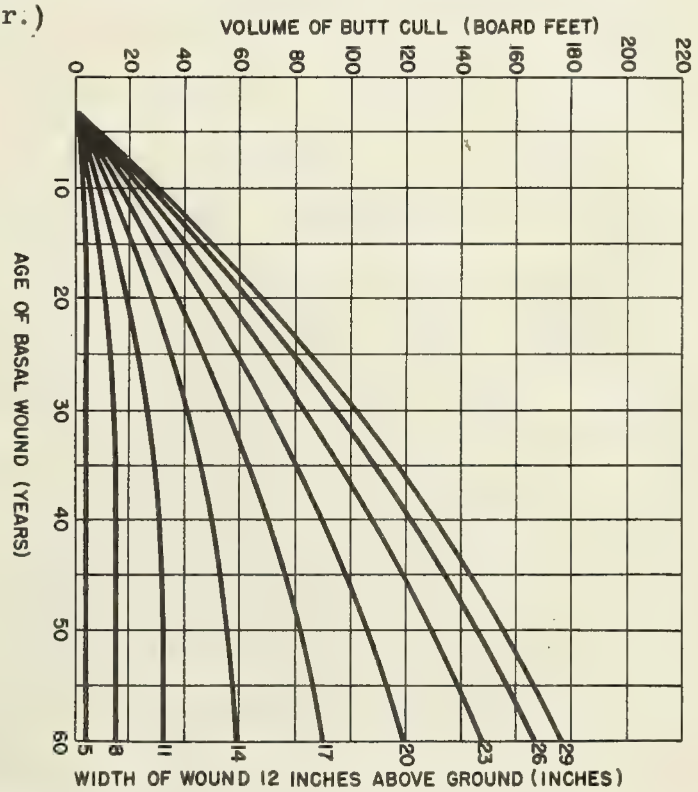


Figure 17. (right) Relation of butt - cull volume in board feet to age of basal wound for different wound widths, in Appalachian oaks. (After HEPTING, 1941.)

FOREST DISEASE APPRAISAL: -- This subject has been highly developed in forest pathology, having become a leading phase of forest mensuration. We have already seen instances of the progress in this field in the preceding section and in connection with disease forecasting. Since the subject of forest disease appraisal has been extensively treated in a number of text and reference books, it is not fitting to devote any considerable space to it here. The interested reader will find an excellent discussion of the subject in the chapter "Loss and Appraisal of Damage" in BAXTER'S book, *Pathology in Forest Practice* (1943).

Forest trees present certain unique problems in disease appraisal, including the irregularities in age, species, associations, terrain, and locations of trees, and the fact that wood decay, the leading problem, can be inspected directly only with much effort and expense. To solve these problems use is made of sampling techniques that are peculiar to forest pathology.

For determining the internal condition of a tree, use has long been made of the increment borer, which extracts a pencil-like core of wood, radially from bark to center of the tree, giving an index both of tree growth (annual rings) and amount and type of decay. Among new methods of internally sampling trees, RANKIN (1931) has described the use of X-rays and radiographs which successfully show slight amounts of decay in living trees. It would seem possible that radar might be used for the same purpose. Such methods avoid making injuries to the tree through which decay organisms could gain ingress, and might be particularly useful in determining the amount of decay in valuable shade trees.

Because of the uneven terrain and lack of roads in forests the autogyro and helicopter are particularly useful in determining the incidence of those diseases which can be recognized at a distance. A few years ago extensive surveys for the Dutch elm disease were made by autogyro, each suspected tree being located on a map and later examined minutely by a ground-crew.

In forest sampling, particular care must be taken to obtain truly random samples, because of the irregular distribution of the trees. One method is to sample every tree, fifth tree, tenth tree, etc., along a compass line.

MEASURE OF PATHOGEN CONTENT OF SOIL, WATER, AND AIR: -- Before undertaking culture of a crop in a location where it has not been grown previously or recently, it is frequently very desirable to determine the pathogen content of the soil. Serious losses may sometimes be avoided in this manner, and pathological soil sampling is therefore a necessary phase of disease appraisal. In general, one of three methods may be followed: (1) direct examination of soil to determine the presence of pathogens or their signs; (2) culturing soil with the aid of attractants or of culture media that have selective value in isolating particular soilborne pathogens; and (3) appraising the condition of health or disease of (a) wild plants growing in the soil in question, that are susceptible to the disease concerned or (b) indicator plants of susceptible species that are deliberately planted in the soil., outdoors or in the greenhouse, to determine the presence of given pathogens.

A good example of the first alternative is seen in the practice of sugar beet growers in the Sacramento Valley of California, who send soil samples to the Experiment Station laboratory at Davis for analysis of the content of sclerotia of Sclerotium rolfsii. A technique for quantitative determination of these sclerotia in soils was described by L. D. LEACH in 1934. A number of investigators have attempted to appraise the content of nematodes in soil by the direct method, washing and screening out the nematodes. GODFREY (1934) has found this to be too time-consuming and inaccurate for ordinary use, and has turned to the use of indicator plants, as mentioned below.

The second method is illustrated in YARWOOD'S (1946b) determination of the black root rot fungus, Thielaviopsis basicola, in soils by use of carrot slices covered with moist soil. Entomologists make extensive use of attractants in sampling for insects. Because most plant pathogens do not have power of free locomotion, this has little application in plant disease appraisal, but it would be interesting to determine whether attractants could be used in analyzing soil for the presence of plant-pathogenic nematodes.

The third alternative, that of examining wild or intentionally planted indicator plants, to detect the presence of pathogens, has many applications, and like the other two methods it could be developed profitably for more extensive use. Indicator plants are commonly used to determine the presence of root knot nematodes (Meloidogyne spp.) in soil. Wild hosts such as lamb's quarters may be helpful. The writer has frequently been called upon to analyze soil for root knot nematode content, to assist in selecting sites for nursery stock, orchards, or vegetable production. The procedure usually followed has been first to examine weeds on the location, and, if necessary, to take numerous soil samples and plant them, in the greenhouse, with several suspects, such as vetch, alfalfa, tomato, okra, and peas. The presence of the pathogen can usually be detected by knot formation in 25 to 30 days. Several species of indicator plants are used, in case the nematodes present exhibit host-group specialization.

This type of work has been put on a quantitative basis by GODFREY (1934), who has shown that it is possible to get reliable assays of the nematode populations of soils by making use of the high correlations that exist between percent of indicator plants infected, number of nematode galls per plant, and nematode population in the soil.

Analysis of soils for the presence of Aphanomyces cochlioides, cause of black root in sugar beets, by planting the soils with beet seed in the greenhouse, has been described by FINK (1948). He obtained a correlation of +.925 between percent of seedlings killed and field loss estimates, and the method therefore has promise in predicting sugar beet losses from this cause.

GOSS (1934) surveyed 100 Nebraska locations for presence of the organisms of potato scab and Fusarium wilt by planting a bushel of healthy potatoes at each location, to determine the prevalence of these soil-borne diseases in relation to cultural conditions.

These few examples illustrate the possibilities of including the sampling of soil in disease appraisal for determining and avoiding disease hazards. The field is one in which much more work could profitably be done.

Sampling of water to determine pathogen content has such great importance in human medicine as to constitute a subscience, -- water bacteriology. It is strange that there appears to be very little comparable work in plant pathology, limited to a few atypical cases, such as the study of seawater in connection with the wasting disease of eelgrass, Zostera marina. There are many situations in plant pathology in which water sampling might be helpful, as a study of runoff water in relation to the local dissemination of diseases, the pathological analysis of reservoirs and other water supplies to be used for irrigation, or the investigation of survival of plant pathogens in water, a subject that has received much attention in relation to human medicine. Plant Pathology has only one remotely analogous activity, the chemical analysis of water suspected of containing substances that are injurious to plant growth, such as alkalis, salts, and oil well or factory wastes, the latter frequently involving lawsuits.

Sampling of air for its microbiological content, initiated by PASTEUR, has been extensively used in studies of dissemination of such diseases as the cereal rusts and downy mildews. It has been helpful in understanding annual cycles of diseases and even in forecasting disease outbreaks. The subject has been reviewed by CHRISTENSEN (1942) and in part by CHESTER (1946b).

As ordinarily conducted, the method consists in exposure of adhesive slides at various altitudes, making use of low or high stationary exposure points or exposing the slides from kites, balloons, or airplanes. The living material adhering to the slides is identified microscopically and sometimes tested for viability by culturing. The results are correlated with prevalence and distribution of the organisms at the ground level and with meteorology and topography.

Each year the annual migration of cereal rusts northward in the Great Plains is studied by analysis of many such "spore traps" in an organized program by the "Rust Prevention Association" in Minneapolis. The data have not been released by bona fide publication; at times they appear to have been helpful in charting the mass movement of rust northward, but in many or most cases they seem to be a less reliable index of rust development than direct appraisal of cereal fields.

SUMMARIZING DISEASE INTENSITY DATA: -- Under this rubric are included two concepts: (1) the reduction of the various manifestations of a disease to a single value, summarizing the total effect of the disease on a plant or small population of plants, and (2) summarizing regional disease intensity data so that a single figure expresses the gross intensity of the disease in a community, county, state, or nation. We will consider these two concepts successively, with the several alternative procedures for each.

When a plant disease has either a totally destructive effect or no effect on a plant or the commercially valuable part of a plant, we have seen that simple percent of infestation is a good measure of disease intensity. In this case, as with the head smuts of cereals, there is no problem in summarizing disease intensity; the summary is simply the average percent of infestation. It is quite another problem when we are dealing with a disease which affects different plants or plant parts in different degrees. To enable the appraiser to summarize disease intensity in these more complex, yet common cases, various devices are used, as outlined in the following sections.

M^cKINNEY'S "Infection Index" And Its Modifications. -- This device, now widely used, was suggested by McKINNEY in 1923 for summarizing infection of wheat seedlings by root rot disease. Each seedling was classified in one of five classes, from healthy to severely diseased. Each class was given a numerical rating, in this case 0.00, 0.75, 1.00, 2.00, and 3.00 respectively. The "infection rating" then

$$= \frac{\text{Sum of all numerical ratings x 100}}{\text{Total number of inoculated plants x 3}}$$

The factor 3 was used in the formula because this was the rating of the maximal disease category, while the factor 100 converts the final rating to a basis ranging from zero for no disease to 100 where every plant is diseased to the maximal extent.

The McKINNEY index has become widely used for various types of diseases, including cereal seedling diseases and root rots (GREANEY and MACHACEK, 1934, 1935; SALLANS and LEDINGHAM, 1943; HO, 1944), charcoal rot of corn (SEMENIUK, 1944), root rot of peas (P. G. SMITH and WALKER, 1941), root knot (A. L. SMITH, 1941; A. L. SMITH and TAYLOR, 1947), early blight of celery (TOWNSEND and HEUBERGER, 1943), tomato defoliation (HORSFALL and HEUBERGER, 1942a), and onion smudge (HATFIELD et al., 1948).

When the class rating is expressed in percent instead of arbitrary numbers, the disease index may be simplified to the form:

$$\frac{\sum \text{(Class rating (\%) x class frequency)}}{\text{Number of plants or organs examined}}$$

which gives a mean value for disease intensity in percent, as of leaf area involved by disease. This type of disease intensity rating was used by TEHON (1927) and TEHON and STOUT (1930) in their surveys of Illinois cereal and fruit diseases and by BLISS (1933) and P. R. MILLER (1934) for apple rust. KENT et al. (1944) found this method of rating disease intensity for potato scab preferable to two other methods tried, including the one mentioned just below.

A similar modification, called by British workers the "disease severity index" and by RICHARDS the "coefficient of susceptibility", is simply the product of class rating by class frequency, divided by the number of organs or plants examined. This has the possible disadvantage of not being on a 0-100 basis. It is really a simple average of class ratings. It has been used for summarizing intensity of wheat root rot (SALLANS, 1948), alfalfa wilt (RICHARDS, 1937), corn smut and seedling blight (ULLSTRUP et al., 1945), grape, cucumber, and tomato leaf diseases (REICHERT et al., 1942a, b, 1944), and potato scab (KENT et al., 1944). Essentially the same results are obtained if the index of disease severity has the form:

$$\frac{\sum \text{(Class rating x \% plants or organs in class)}}{\text{Maximum class rating}}$$

and this has been used for rating root knot intensity by TAYLOR (1941) and his cooperators.

When the number of plants or organs to be examined is a constant, the index may simply be $\sum$ (class rating x class frequency), as used by CRALLEY and TULLIS (1937) in rating seedling disease in rice and, with slight modification, by RUSSELL and SALLANS (1940) for wheat root rot. An interesting variation has been described under the term "effective leaf index" by LEWIS (1944). This is the reverse of a disease index, obtained by arbitrarily numbering the disease classes with increasing numbers corresponding to decreasing injury.

The widespread use of the McKINNEY index, in original or modified form, testifies to its value. It reduces a disease intensity complex to a single expression that is open to statistical analysis on the basis that "although the estimates are not necessarily in direct linear relation to the amount of fungus present......they are reducible to a linear function of this amount" (MARSH et al., 1937).

Such an expression has many uses, among which are the evaluation of disease in different crop varieties, and of the efficacy of fungicides and other means of disease control. An example of the latter use is seen in the experiments of BONDE and SNYDER (1946) in spraying potatoes, where the effectiveness of any spray treatment, termed the "protective coefficient" was obtained by dividing the "infective indexes" (McKINNEY indexes) of Bordeaux-sprayed plots by the indexes of plots receiving other treatments.

In using the indexes, judgment is needed in assigning arbitrary ratings to the several disease classes. Where possible each class rating should reflect the relative intensity of disease or damage in comparison with ratings of other classes. Class ratings of 0, 1, 2, 3, and 4, for example, would be most appropriate if plants or organs in class "4" had four times the disease intensity of those in class "1", twice as much as those in class "2", etc. If care is used in assigning the class ratings, with absolute disease intensity properly considered, the indices themselves will have absolute, not merely relative, value. A logarithmic series of class ratings might often be preferable to an arithmetic one. If the absolute disease intensities of a class series are 0, 3, 8, 20, and 50, and the classes are assigned arbitrary ratings of 0, 1, 2, 3, 4, then indices of heavily diseased populations will not give a faithful expression of the much greater amount of disease in comparison with populations having lower indices.

The U. S. Department Of Agriculture "Coefficient Of Infection". -- With some diseases, notably rusts, degrees of disease resistance commonly are expressed by differences in type of reaction, as from large, freely sporulating rust pustules through types with smaller pustules to highly resistant reactions in which few or no spores are formed and the site of the infection is marked by a small chlorotic or necrotic spot. At the same time that reaction type varies, rust intensity, or the number of lesions of any type, may also vary. "Coefficients of infection" have been devised in attempts to reduce reaction type and disease intensity to a single value.

In recording the occurrence of rust in the uniform cereal rust nurseries, it is customary to take data on rust intensity, from 0 to 100% according to the modified COBB scale (page 244), and on rust reaction on a scale ranging from 1.0 (highly susceptible) to 0.0 (highly resistant), and multiply the intensity value by the reaction value to obtain the "coefficient of infection".

A very similar procedure was used by GOULDEN and ELDERS in 1926. KOEPPER (1942), working with alfalfa rust, derived a "coefficient of infection" by adding the values for disease intensity, reaction type, and length of incubation period, each on a 0-4 scale. Reference has been made in another connection (page 246) to VAVILOV'S attempt to devise a single cereal rust scale reflecting both rust intensity and reaction.

Rust intensity and rust reaction are usually two independent manifestations of disease. Intensity is a measure of the amount of disease present without necessary reference to host plant reaction. It is the factor of principal interest in studies of loss, epiphytology, and disease control by means other than altering susceptibility in host plants. Reaction type is a measure of host response, of primary interest in attempts to control disease by breeding for disease resistance and in pathogen specialization and variety reaction tests.

It is usually unnecessary and often a mistake to attempt to combine these two measures into a single value. A low "coefficient of infection" could mean either high disease intensity on a highly resistant variety or low intensity on a very susceptible variety. The coefficient can therefore be as misleading in determining variety reactions as it is in appraising the concentration of disease.

TEHON'S Disease Prevalence-Intensity Summations. -- For a number of years TEHON (1927) conducted statewide surveys of the intensity of cereal diseases in Illinois. For those diseases the intensity of which could not be determined by mere counting, the data sheets for each disease included both percent of culms affected and classes of intensity of disease on the individual culms. The average intensity of disease in a field, expressed as percent, was derived through the formula:

$$\frac{\text{Class rating (in \%) x culm frequency in each class x \% infected culms}}{\text{Total number of culms examined}}$$

In 1930 TEHON and STOUT published a report of their statewide surveys of fruit diseases in Illinois. In this case data were taken on percent of trees affected in a given orchard, percent of organs (fruits, leaves, twigs) infected per tree, and classification of infected organs in percent disease intensity classes, with the aid of diagrammatic scales. The results were summated in a fashion similar to that used for cereals. The methods of summating these data for counties and for the State are given on page 256.

TEHON'S method has the advantage of giving highly precise and accurate disease intensity estimates. Its chief disadvantage, as HORSFALL (1930) has pointed out, is that it is very laborious and time-consuming. Yet this may not be a serious disadvantage, for TEHON has shown that the method can be practically used on a statewide basis, year after year. The formulas for determining disease intensity suggest more effort than is actually required in many cases. With general outbreaks of some diseases, such as cereal rusts or apple scab, prevalence is usually 100%, which can be easily ascertained. Diseases such as smuts can be quickly estimated by simple counting. The time spent in travelling from one field or orchard to another is such a large element in the survey cost that a fairly thorough examination at each stopping point is justified. However, if the method could be simplified without undesirable loss in accuracy, this should be done. One method of simplification which deserves condiseration is the use of correlations. If a constant relationship could be shown, for example, between percent of trees affected, percent of affected organs per tree, and degree of attack per organ, then all of these values would not need to be determined independently.

NAUMOV'S "Average Infection Of Field". -- In 1924 NAUMOV in Russia suggested the procedure for summarizing disease intensity data shown in Table 3. Data are taken or estimates made of the values numbered 1 to 7. There are a number of special cases in which the procedure is simplified. If all plants are infected, $N' = N$ and $A = \frac{Fx}{m}$. In working with large populations of uniform plants as in cereal fields, N, for practical purposes, $= \infty$ and thus N and N' are expressed not in absolute terms but as percentages, N equalling 100%. When all organs on the plant are infected, $X = m$ and $P = F$; if at the same time all plants in the field are infected (a common case with cereal rusts and many other field-crop diseases), $A = F$, *i.e.*, the average infestation of the field equals the average infection of the organs of an average plant. For diseases in which d is unity or total (*e.g.*, head smuts), d can be omiited, and $P = x/m$. For ergot, d, the degree of infection of the different spikelets, is constant and can be omitted; here however, an additional step in the observations is required, *viz.*, determination of the total number of spikelets per head and the average number of these which are infected.

In principle the scheme of NAUMOV resembles that of TEHON, and the logical character of both, proceeding through degrees of infection of organs, plants, and populations, commends them to the thoughtful consideration of those who are interested in more accurate appraisal of disease intensities on a field, or larger area, basis.

DUCOMET and FOËX' Summary Value For Disease Intensity. -- In France, DUCOMET and FOËX (1925, 1928) have proposed a very elaborate procedure for reducing rust infection of a cereal plant to a single absolute value. Using a descriptive scale of 7 stages, from "trace" to "enormous", each organ of the plant is scored separately, including head (glumes, awns, rachis, grain), each internode, numbered from above downward, and each leaf and leaf sheath, which are numbered, with separate records of rust intensity on proximal, medial, and distal parts of each leaf. Each part scored is given a coefficient to weight the readings according to the importance attached to each, and the overall rust intensity is then calculated by use of prepared tables. At each examination six scorings per head and three each per leaf and stem are recommended, and it is advised that examinations be made at boot, heading, and post-blossoming stages, and 3-4

Table 3. NAUMOV'S (1924) method for summarizing disease intensity data, slightly revised.

1. Degree of disease per organ = d
2. No. infected organs per plant = x
3. Total no. organs per plant = m
4. No. infected plants per field = N'
5. Total no. plants per field = N
6. No. infested fields in region = Q'
7. Total no. fields in region = Q

Average infection of organs =

$$\frac{d_1 + d_2 + \ldots\ldots\ldots\ldots d_x}{x} = F$$

Average infection of plant =

$$\frac{Fx}{m} = P$$

Average infestation of field =

$$\frac{PN'}{N} = A$$

Average infestation of region =

$$\frac{AQ'}{Q}$$

times thereafter.

The method of DUCOMET and FOËX, which has also been used by RIVIER (1932), appears to be theoretically sound. It does reduce rust infection of the entire plant to a single, defensible value. Yet it is so complex and time-consuming that more accuracy may be lost through restriction of the number of examinations which can be made than is gained by the greater detail of each examination. Doubtless there are correlations between rust intensities on most of the organs or tissues which are separately scored, and if this is true it is unnecessary to score all of them in ordinary disease appraisal practice.

Summarizing Disease Intensities Of Regions. -- Up to this point we have been principally concerned with disease intensities on individual plants, plots, or single fields. In disease survey practice it is usually the objective to extend estimates to embrace larger regional units, such as counties, states, provinces, or nations.

With minor variations the same method is used by most workers. This, essentially, is a M^C^KINNEY disease severity index applied to large numbers of single plots, and has the general form:

$$\frac{\Sigma\,(\text{field rating class x acreage in class})}{\text{Total acreage}}$$

The field ratings are usually classified in a series of grades, from 0 to 100 percent disease intensity; but arbitrary grade values could also be used. TEHON (1927) and TEHON and STOUT (1930) have followed the practice of determining the mean disease intensities for counties by an analogous process, and then by weighting the county values for acreages of the crops concerned, have derived mean State disease intensities.

Reference to Table 3 shows that NAUMOV has used a similar device, based, however, on the number of fields rather than the acreage, as also seen in the works of WALKER and HARE (1943) and SAVULESCU and RAYSS (1935). This would suffice if the fields sampled are of sizes typical for the region, but might lead to error if the sample fields are not of representative size. Since county and State acreage figures are readily available from census data, the acreage basis can be easily and preferably used.

In the United States each State is divided into several crop-reporting districts for purposes of agricultural economics, and in Canada there are similar districts which do not correspond to the Provinces. Meteorological, yield, acreage, and other useful data are available by crop-reporting districts. Since each district is more uniform agriculturally than are political divisions, there will frequently be advantages, in planning surveys and summarizing disease intensity and loss data, in using the crop-reporting district as the basic geographic unit.

Plant Disease Intensity Maps. -- Disease intensity data may be usefully summarized in the form of maps. This is one aspect of the value of disease hazard maps, which has already been discussed (page 203). Most such maps, of which many have been published, show only disease occurrence, without information on the degree or intensity of a disease in various regions. Some disease intensity maps are available. Examples are the Texas root rot map of TAUBENHAUS and EZEKIEL (1931, Fig. 1) and the chestnut blight map given by BAXTER (1943, Fig. 38). In the volumes of the *Plant Disease Reporter* are occasionally found maps in which disease intensities are indicated for various States or for counties within a State, such as that of wheat leaf rust in Oklahoma prepared by CHESTER and PRESTON (1948).

WEIR (1918) and BAXTER (1943) have both pointed out the importance of disease maps in forest pathology, and the one presented by BAXTER in his Fig. 39 is a good illustration of a map showing the distribution of several diseases and types of injury although different disease intensities are not represented.

Punch-Card Systems. -- A device for summarizing disease survey data that has received very little attention from plant pathologists is the use of punch-card systems. Their probable usefulness for this purpose is indicated by their established value in organizing economic and other survey data obtained through use of the Iowa Master Sample (*cf.* page 268). They are much more than a file, since if disease intensity data are properly recorded on punch cards it is possible to summarize the data from any of numerous standpoints, by crop, region, year, disease type, etc., very rapidly. It would appear highly desirable that this versatile method of recording data be fully explored to determine its potentialities for plant disease survey purposes.

Chapter V

THE METHODS OF PLANT DISEASE SURVEYING

To be useful for the several purposes discussed in Chapter I, data on plant disease destructiveness cannot be limited to isolated cases, however dramatic these may be. For effective action on an area basis we must have representative cross-sections of the disease hazards involving whole counties, states, or nations. Such data can best be obtained by plant disease surveys, -- planned and uniform samplings throughout the areas involved.

Of late the term "survey" has fallen into some disrepute as a result of a few real or fancied cases of the misuse of public funds in trivial fact-finding. Protagonists of "action programs" sometimes criticize surveying because, while it provides facts, it does nothing to alter unsatisfactory conditions; it eliminates no slums, prevents no crime, sprays no plants. Such an attitude is short-sighted and may often lead to waste from misguided "action programs" with objectives determined by the spectacular character of minor problems. Yet it is an attitude influencing the success of plant disease appraisal, one that must be considered and overcome by demonstration of the practical value of surveys in revealing the absolute and relative magnitudes of plant disease hazards. No survey is perfect; all are subject to faults that arise from the complexity of the problem of surveying, inadequate financing, and human limitations. Yet, despite these imperfections, they have been of inestimable value, and this will increase as survey techniques improve.

ORGANIZATION AND PLANNING OF A SURVEY: -- Plant disease surveys can be thoroughly justified if they are wisely planned and if their results and applications to "action programs" are made clear. Several elements are involved in the judicious planning and execution of plant disease surveys: (a) they should have definite objectives; (b) their objectives should be clearly related to useful applications of the results; (c) their methods should be adapted to the specific objectives; and (d) they should be sufficiently thorough to permit reliable conclusions but no more so, in the interest of economy, than is necessary for such conclusions.

That plant disease surveys should have definite objectives has been stressed by a number of authorities (HAENSELER, 1944; CHUPP, 1945; P. R. MILLER, 1946). HAENSELER has justly criticized what he calls the "shotgun" type of survey in which the surveyor is merely directed to "look around and see what he can see". Such surveys produce such incomplete data that they may hardly be useful. That such surveys have been made probably indicates atavism, in plant pathologists, to the point of view of taxonomic botanists whose forays often have no objective other than to collect any and all interesting plants which may be encountered.

At the same time that each survey should have a specific objective, the surveyor should not be blind to unusual, accidentally encountered disease situations, outside the scope of his survey. The greatest item in the cost of surveying is the expense of travel and subsistence of the surveyor, and the time actually spent in the field may be small in relation to the total travel time. To increase the amount of time spent in actual observation may add little to the total cost of a survey, while providing by-products, in the form of data not originally specified in the survey objective, that contribute substantially to the justification and value of the survey. It goes without saying that such adjunct observations should not be permitted to interfere with the main purpose of the survey. It is sometimes said that surveys should be limited to the more important diseases (e.g., BÖNING, 1936). This is quite illogical; without surveys and loss appraisal how can we know which diseases are more important?

The method, intensity, and scope of a plant disease survey will vary with its objectives. At times it may be desirable to study a limited number of fields very thoroughly, while in other cases it may be more useful to have less precise data from many random samples scattered over a broad area. Sometimes the two methods are combined, as in Dutch elm disease scouting, where a thorough, systematic survey of all elm trees in known infested areas has been supplemented by autogyro scouting along rivers and railroad lines over a great range outside the infested area, to locate other isolated infestations.

The work of the U. S. Bureau of Entomology and Plant Quarantine embraces several types of surveys, with different objectives and procedures (GADDIS, 1947; see also page 277). Most frequent are surveys for usual regulatory purposes, for locating and delimiting unknown infestations and determining the spread of new ones. These furnish the "blue prints" for regulatory action. Unusual or special surveys are to obtain information on specific pests, to determine the need for new or continued quarantines. They employ the method of spot inspections, with study of the ecology of the pests, and are not intended to delimit areas of infestation. Surveys for new pests are conducted to determine the distribution and behavior of recently introduced or little-known pests, and emphasize study of the spread, reproduction, natural control, and economic importance of these. Their chief objective is to determine the potential destructiveness of new pests before these become widespread. The emergency wartime surveys for detecting the introduction, by chance or malice, of new insects and diseases, illustrate general surveys for possible unknown pests. These also have important peacetime uses. Surveys for non-regulatory control purposes are for the purpose of planning regional or national volunteer control programs, such as those directed at control of grasshoppers and chinch bugs. Finally, the Bureau of Entomology and Plant Quarantine conducts surveys to determine pesticide supplies and requirements, so that limited supplies of pesticides can be directed to areas of greatest need. These have critical importance in time of war.

When several surveys are made for the same purposes, in different areas or seasons, it is highly desirable that uniform methods be used so that reliable comparisons and summaries of the survey data can be made.

The degree of thoroughness that is desirable, yet economical, depends on the objective. In some cases data on presence or absence of a disease are sufficient; in others it may be necessary to determine, with greater or less accuracy, the concentration of disease present. Some diseases, such as the cereal rusts, affect great acreages rather uniformly, and here fewer samplings are needed than with diseases that are more dependent on local environmental or agricultural conditions for their occurrence. General-utility surveys are broad, less intensive and less exact than special-interest or special-purpose surveys, such as those designed to aid plant disease research.

A good illustration of a well-planned intensive survey is that of F. R. JONES and LINFORD (1925) for pea diseases in Wisconsin. The survey involved 688 fields, each of which was visited two or three times, and data were taken on location, owner, pea variety, growth stage, date of planting, soil type, cropping history, and occurrence of 13 diseases, aphids, and root nodulation.

As an example of a well organized survey of the extensive type, we have that of VESTAL, on the use of disease-resistant oat varieties in Iowa in 1944. His problem was to obtain a uniform sample, representative of all farms in the State, and actually involved 74 of the 99 counties in Iowa. A tracing was made of the map of each county, numbering all sections along a main road through the county. A minimum of two sections from each county were chosen by selecting section numbers at random, and of these, quarter sections were selected at random. The number of sections selected was proportionate to the total number of sections in the county. Sampling of 149 farms in this fashion showed, with other data, that 13.75% of the land on these farms was planted with oats. This compares with 13.2% of land in oats estimated in the Iowa Assessors Annual Farm Census, based on data from several thousand farms, showing that VESTAL'S sample was reasonably representative. Using this method one man was able to sample slightly more than four counties per day, and a survey of the entire State, by this method, would consume only about 20 days.

P. R. MILLER's (1935) survey of fruit and vegetable losses in market and kitchen, in Knoxville, Tennessee, may be mentioned as an example of a survey involving use of many untrained collaborators. The first step was to determine the channels of flow of fresh produce in Knoxville by interviewing dealers. Data were gathered on the times and places of car unloadings, the time before distribution of the produce, and the quantities distributed to retail dealers. The distributors' losses were determined in two ways. Managers were asked to keep records of their purchases and lay aside spoiled produce for inspection by the surveyor, and the latter also made random samples of produce as it was being sorted in the warehouse. Losses to the ultimate consumer were determined by a house-to-house survey, facilitated by a preliminary appeal to housewives through the press, radio, and garden clubs. Each interested consumer was given a chart illustrating and describing the principal fruit and vegetable diseases, and a record sheet for recording losses, and data were also taken on the housewife's source of produce, frequency of purchase, methods of selection and storage, and other pertinent information. A final estimate of total loss was obtained by combining distributors' and consumers' losses.

The advantage of using lay cooperators in a survey, as MILLER has done, is the large volume of data that can be obtained at limited expense. Its disadvantages are the lower reliability of such data compared with those which are gathered by a trained surveyor, and, in this case, probably some error due to the fact that willing cooperators are likely to be those who are more careful in preventing spoilage of produce. These disadvantages were minimized in MILLER'S survey by efforts to secure uniform data through use of standard data sheets and an identification chart of types of spoilage, and by control samplings made by the surveyor himself, which gave an index of the reliability of the data from cooperators.

PROCEDURE OF SAMPLING: -- At the outset we must distinguish two types of sampling, crop (or commodity) sampling and opinion sampling. The former consists of appraising a part of a crop, before or after harvest, and considering the findings as evidence of the quantity and quality of the whole. Such procedure assumes training in the accurate appraisal of samples. The sample itself may consist of a few plants in a field, a few fields in a county, a few counties in a State, or a few States in a region, or a combination of these.

In the case of opinion sampling, which in agriculture is illustrated by the Crop Reporting Service (page 272), the sample is a part of the human population, and the data obtained consist of the opinions of the people in the sample regarding any question asked them. The reliability of the findings varies with the degree of accuracy with which individuals can appraise the matter in question. In plant pathology we could expect that an opinion poll of wheat farmers who are asked questions regarding smut dockage in the price received for their wheat would be fairly accurate, while the same farmers, lacking training in disease appraisal, might be very poor sources of information on field losses from smut, rust, or root rot.

Assuming some training of lay observers in plant disease appraisal, there is a third type of sampling in which the useful features of opinion and crop sampling are combined. This is illustrated by P. R. MILLER'S (1935) survey of market losses in fruits and vegetables, in which lay correspondents, dealers and housewives, were given sufficient instruction so that they could provide reasonably accurate reports, based on counts and measurements, of the spoilage in perishable produce.

Several methods of opinion sampling are recognized (SABROSKY, 1946) and these have counterparts in crop sampling. Random sampling is illustrated by obtaining information from every n^th^ person named in an alphabetical list or by appraising a crop field at every n^th^ mile indicated on an automobile speedometer. Area sampling involves questioning all people or examining all fields on random areas, and is economical of the surveyor's time. Stratified sampling of opinion consists of getting definite proportions of various types of persons in a sample when the fraction of each type in the total population is known. This is commonly used in public opinion polls which are broken down by sex, profession, race, or political party. An example of stratified crop sampling would be to sample ten wheat fields for each one barley field if it were known that the wheat acreage was ten times the barley acreage. If desired, a greater sample than corresponds to the fraction of the population may be taken for certain items, with the results weighted to correct for the proportion in the population. Thus, if a certain crop disease presents an unusual hazard (e.g., Victoria blight of oats) the surveyor might take a disproportionately large number of oat samples. Finally there is purposive sampling in which all or nearly all of the population having certain narrowly specified characteristics is sampled, as would be the case in sampling all stone fruit nurseries for virus diseases, or in disease appraisal of the fields of all growers of certified seed potatoes in a State.

In studies on comparative yields and other properties of crop varieties or crops subjected to different treatments, much attention has been given to methods of sampling, and many of the principles of sampling that have been developed and used for various agronomic and horticultural purposes have interest and usefulness in plant disease appraisal. While this discussion is from the plant pathological viewpoint, it should be regarded as but one of many applications of general sampling practice.

TIME AND NUMBER OF CROP SAMPLES: -- Of the factors which determine the time, number, size, and type of samples, two are outstanding and diametrically opposed, -- reliability and economy. Neither can be increased except at the expense of the other, and the preferred schedule of sampling must be a compromise which avoids the expense of increasing accuracy beyond the least degree that will give a practical, reasonably satisfactory answer to the problem at hand. This principle of the "minimal reliable sample" is discussed on page 264.

The desirable number of samples to be taken, whether it be quadrats in a field or fields in a region, varies with crop, disease, and environment, and the pathological situation, with the factors influencing disease variability, must be studied in order to determine the most practical sampling procedure. Equal reliability can be obtained from fewer samples if few varieties of a crop are grown, if the disease is one which affects large areas uniformly, and if the survey area shows relative uniformity in soil, climate, and cultural practices. Airborne diseases are usually more uniformly distributed and require fewer samples for equal reliability than soilborne diseases. As contrasting cases, Fusarium wilts, soilborne diseases of irregular distribution in a field and from one field to another, that are frequently controlled by use of resistant varieties, would require far more samples, for equal reliability, than wheat leaf rust in the Great Plains, where the disease frequently is fairly uniform in any given field and over a great region.

When an area is non-uniform it may be subdivided into relatively uniform subareas, each of which is sampled separately. This was done, for example, by MACHACEK (1943) who made use of six soil type zones in sampling wheat root rot in Manitoba. When a principal objective of sampling is to compare disease intensity and loss from one year to another, variability can be reduced and reliability increased by use of standard observation fields each of which is planted with the same crop and variety and otherwise similarly treated from one year to another. This has been the custom in the annual samplings of wheat fields as a basis for leaf rust forecasts.

Other factors being equal it is usually good practice to have the number of samples taken in each of a series of fields proportionate to the acreages of the fields, and to apply the same principle to the number of fields sampled per region. If the disease is uniform in any given field, regardless of size, the same result may be more economically obtained by taking a minimal, constant number of samples from each field and weighting the value attached to each sample according to the size of the field.

The most suitable time for sampling disease intensity is usually the peak of disease attack. This varies widely with different diseases in a single crop, often necessitating several samplings of the same crop if a complete record of disease attack on that crop is desired. With wheat, for example, speckled leaf blotch (Septoria tritici) should usually be sampled when the plants are in the rosette to jointing stages, loose smut (Ustilago tritici) at blossoming time, leaf rust in the post-blossoming to stiff-dough stage before the leaves have died, and stem rust at submaturity of the crop, while bunt may best be sampled in sheaves after harvest, and root rots may require several samplings throughout the entire life of the wheat plant.

This fact accounts for some of the discrepancies or unbalanced emphases on the prevalence and importance of crop diseases, that are based on a single crop inspection. Agronomists and crop scouts tend to concentrate attention on cereal crops as they approach maturity. This often results in an overemphasis on those diseases which are most prominent at this period, overlooking the early-season diseases such as speckled leaf blotch and loose smut of wheat, cereal mosaics, and barley stripe.

In disease intensity appraisal for the purpose of studying the tempo of disease development, several successive samplings of the same plantings are required. This has particular importance in relation to forecasting the destructiveness of diseases such as cereal rusts or potato late blight. More than one sampling will also be required if a given disease reaches its peak of destructiveness on different crop varieties or fields at different times. Sampling for appraising loss from plant diseases obviously coincides in time with the normal harvesting and post-harvest handling practices.

Wherever possible, post-harvest sampling for disease intensity has the advantages that it may be done at any convenient time after the rush of preharvest work, in a uniform and objective manner, in the laboratory where the work is facilitated by ready access to scientific instruments and unhampered by wind or wet weather. By using the soaking method described by POPP (1947), for example, bunt in harvested wheat sheaves can be much more accurately, rapidly, and conveniently counted than in the field before harvest. Loose smut may be more accurately counted in the same operation than in the field after the smut spores have blown away and the short, naked rachises are inconspicuous. Stem rust may be easily appraised after harvest, and there are many other diseases in the same category.

In such cases one precaution is necessary, namely that the harvested sample is fully characteristic of the disease as it occurred in the field. A serious error arises, for example, if the percent of bunt balls in threshed wheat is taken as the percent of field occurrence and loss, since many of the bunt balls are removed from the grain in the harvest operation. HASKELL and BOERNER (1931) have shown that fields with 6.6% smut occurrence and loss produce grain which, after threshing, contains only 2 to 5 bunt balls per 50 grams of grain.

SIZE AND TYPE OF CROP SAMPLES: -- The choice of size of individual samples, like that of the number of samples, must be a compromise between reliability and economy, since any increase of sample size usually increases both its reliability and its cost. The optimal size of sample also varies with crop, disease, environment, number of samples taken, skill and bias of the appraiser, accuracy of the appraisal method, and other factors, which requires a thorough study of the disease situation and its variability before one can determine the optimal size of sample.

Sample size has primary importance in studies of crop yields and much attention has been given to this by agricultural workers. Their findings have many applications in the appraisal of plant diseases. In the Statistical Laboratory of Iowa State College there is an important research program on the study of the effect of size of primary sampling units on statistical efficiency in relation to crop yield determinations. The papers by COCHRAN et al. (1945), HOMEYER and BLACK (1946), and HOUSEMAN et al. (1946) illustrate this study and describe optimal-sized samples of corn, small grains, soybeans, and hemp.

With crops that are closely planted or planted broadcast the approved sample is usually a quadrat, several square feet in area. A standard wire frame that is square, rectangular, U-shaped, or round, is often used to assure that all samples will be of the same size. This is placed in random locations and all plants falling within the frame constitute the sample. The quadrat sizes recommended for yield or disease determinations of various crops include 3 x 3 feet for oats (HOMEYER and BLACK, 1946; COCHRAN et al., 1945), 2 x 2 feet for soybeans (HOUSEMAN et al., 1946), 32 x 32 inches for corn (KIESSELBACH, 1918), 3 x 3 feet for alfalfa and sweet clover (WILLARD, 1931), 3.3 x 3.3 feet for cereal smuts in broadcast fields, and 3 x 3 feet for ergot in rye (U. S. Department of Agriculture).

While the quadrats should be small for labor economy, there is danger of serious error if they are much below such sizes as those mentioned above. COCHRAN et al. (1945) and HOMEYER and BLACK (1946) have found that with oats and wheat 2 x 2- or 2.178 x 2-foot quadrats regularly lead to overestimates of yield due to observer's bias, which is not important in 3 x 3-foot quadrats. This bias results from tendency to include within the quadrat plants at the edges, of doubtful position, and the smaller the quadrat the greater the ratio of periphery to enclosed area.

Statisticians have given considerable attention to quadrat size in India. MAHALANOBIS (1946), working with jute, wheat, and rice, considers that bias error is negligible in plots 40 to 50 sq. ft. in size or larger, although in plots smaller than this yields are overestimated by 3 to 15%. SUKHATMA (1947) goes still farther, citing the finding by PANSE that even a plot of 218 sq. ft. results in overestimation of yield, and favoring plots of 1/80 acre (545 sq. ft.) which have been adopted by the Indian Council for Agricultural Research in its yield surveys. While plots of such size would be practical for gross yield determinations, the small replicated quadrats recommended by American workers would be preferable for most work with diseases of field crops.

Another type of sample in common use with row crops is a measured length of row, in random locations. MACHACEK (1943) used replicated meter-length row segments, ROBERTSON et al. (1942) used 5-foot segments for wheat root rot, and NELSON and LEWIS (1937) have favored samples of 30 consecutive plants in the row in studying celery leaf blight. A similar procedure is common in sampling various crops for seedling disease and in study of diseases of such crops as cotton, corn, and sorghums.

Sometimes other practical considerations dictate the type of sample. With small grains, for instance, strips cut through the centers of plots with a power mower, while giving a greater sampling error than 2.178 x 2-foot quadrats, are preferred because the loss in accuracy is more than compensated for by labor saving in harvesting (HOMEYER and BLACK, 1946). The ideal sample for field crops, in the opinion of SUKHATMA (1947), is a circle containing 218 sq. ft., but such a plot is quite impractical to harvest.

Methods such as the foregoing are much preferable to the loose general directions for sampling which are sometimes given. The "Cereal Disease Field Notebook" of the U. S. Department of Agriculture, though giving specific directions in some cases, in others instructs the observer to make "counts of entire plants in different parts of the field", to "gather a number of leaves from the row or plot at random", or to make "counts of representative areas in the field." As might be expected, the data obtained by different observers, following these loose instructions, vary widely in reliability.

When the sample consists of a collection of certain organs of plants, sampling directions must specify how those organs are to be chosen, whether at random or in some other specified fashion. Cereal leaf rust readings vary with observers, some of whom make collections of leaves of all ages while others select leaves of a certain rank on the plant, e.g., the flag leaf, and still others select the rustiest leaves or the oldest leaves that still remain green. In making readings of the intensity of speckled leaf blotch on wheat the writer has obtained the most consistent results by limiting the sample to the 2nd, 3rd, or 4th leaf from the uppermost one on jointed wheat, thus obtaining a uniform sample of leaves of approximately the same age and duration of exposure to the disease. The particular rank of leaves to be used is determined by preliminary observation of the amount and location of disease present. Methods of sampling to determine varietal reaction to disease or response of plants to disease-control treatments may often be used for the purpose of disease intensity-loss appraisal.

It sometimes happens that of two methods of sampling, of equal reliability, one is more rapid and economical than the other. This is illustrated in a comparison made by TOWNSEND and HEUBERGER (1943) of two methods of determining intensity of early blight in celery. In the "leaf-classification method" all leaves from 10 random plants were picked, graded, and scored, to give the percent of leaf involvement by blight. With the "plot-scoring method" each plot was assigned one of 10 grades of disease infestation and these were converted into percent leaf involvement by multiplying the grades by a constant. The latter method took only 1/24 as much time as the former and gave results that were highly correlated (r = +0.887 at the 1% point) with the more laborious method. This case brings out the important saving in the appraisal expense that can be realized from a comparative study of appraisal methods before adopting any one method.

The certification of seed potatoes involves indexing foundation stocks in the South. The cost of this is so high that the smallest reliable sample must be used. In other steps in potato seed production and inspection the same problem occurs. FOLSOM in 1942 published a table showing the number of tubers that must be examined in stocks containing 2, 3, 4, ...10% disease to give the percent of disease present with a reliability of ± 0.5, 1, 2, 3, 4, or 5% at 30:1 odds. The table indicates that if there is 3% disease present, 2735 tubers must be examined to be sure the reading is significantly between 2% and 4% at these odds, which are considered adequate in this case.

FERNOW in an important contribution in 1944 developed this principle further. He considers that 10:1 odds are sufficient, since an error affects only a few persons and one year's work. FOLSOM has assumed that the question involves whether an observation is either greater or less than the true mean, but in actual practice, FERNOW points out, the question is only whether the observed value is significantly less than the mean. The ideal frequency distribution curves for small samples from stocks with small percentages of disease can be determined by expanding $(p + q)^n$ where p = the proportion of stock healthy, q = the proportion diseased, and n = the number of tubers in the sample. This has been done in Table 4.

Table 4. Minimum and maximum disease percentages likely to be found in samples of indicated size when taken from stocks showing indicated disease percentages. Odds 10:1 against either less or more; 4.5:1 against both. (From FERNOW, 1944).

Size of	Percent disease present in stock								
sample	1	2	3	4	5	6	8	10	15
50	0-2	0-4	0-6	0-8	2-10	2-10	4-14	4-16	8-22
100	0-2	0-4	1-5	2-7	2-8	3-9	5-11	6-14	10-20
200	0-2	1-3.5	1.5-4.5	2.5-6	3-7	4-8	5.5-10.5	7-13	11.5-18.5
400	0.5-1.8	1.2-3	2-4	2.8-5.2	3.5-6.5	4.5-7.5	6.2-9.8	8-12	12.5-17.5
800	0.5-1.5	1.4-2.6	2.2-3.8	3.1-4.9	4-6	4.6-7.4	6.8-9.2	8.5-11.5	13.2-16.8
1600	0.6-1.3	1.5-2.5	2.4-3.6	3.3-4.7	4.2-5.8	5.2-6.8	7.1-8.9	8.9-11.1	13.7-16.3

Whereas FOLSOM, with arbitrary 30:1 odds, concluded that 2735 tubers of a stock with 3% disease must be examined in order to get a value within 1% accuracy, FERNOW'S table, with 10:1 odds, which he considers are justified by the situation, shows that a 400-tuber sample would be adequate, and since in practice it is usually impossible to use samples even of this size, he concludes that we must be satisfied with a 2% error instead of 1%, which, in this case, would be obtained with a 100-tuber sample.

This case has been described because it illustrates the possibilities in predetermining sample size with statistical accuracy, provided the appraiser is familiar with his material and can decide on the degree of error which is tolerable and justified. The method has many other possible applications in disease appraisal.

In crop sampling for disease, just as in sampling for yield or other characteristics, replicated samples are regularly used, the number of replications commonly ranging from 5 to 10. The principles governing the use and number of replications are those commonly found in textbooks on statistical methods, the desired number of replications necessarily increasing with the variability in distribution of the disease. In sampling commercial fields the replications are taken at random, using such techniques as those described below, but in experiments designed to measure disease intensity and loss use can and should be made of replicated planting plans designed to give results most suitable for statistical analysis, in which case the samples are systematically taken from the replicates.

The British committee on disease measurement, after careful study of sampling methods, has issued recommendations on sampling methods for a number of leading plant diseases (W. C. MOORE, 1943; Anon., 1943). Some of these are given here to illustrate well-considered sampling practice.

British sampling recommendations: For virus diseases of potato and sugar beet: If there is less than 1% disease present, estimate 1 diseased plant in a 12-yd. radius (potato) or a 7-yd. radius (beet) as 0-0.1%, and 1 diseased potato plant in a 4-yd. radius or 1 beet in a 2-yd. radius as 0.1-1.0%; if there is more than 1% disease take 5 random samples of 100 plants each on diagonal traverses for general surveying or 10 samples for special purposes (certification). For cereal smuts, take-all, eyespot, and brown root rot causing white heads: If less than 1% disease is present, 1 head in 50 sq. yd. = 0-0.01%, less than 2 heads per sq. yd. = 0.01-1.0%, and 2 or more heads per sq. yd. = 1.0%; for higher disease percentages make counts of 10 random grab samples, each of 20+ headed tillers, on diagonal traverses. For apple scab: Sample 10- to 15-year-old trees of specified varieties, examining 25-50 well-distributed trees per variety; grade visually by walking slowly around the tree, recording the individual grades and the average, but if the first 5 trees show no more than 1% scabbed leaves further grading is unnecessary; a grading scale is furnished (W. C. MOORE, 1943).

PRINCIPLE OF THE MINIMAL RELIABLE SAMPLE: -- In the interest of economy, a sample or sample-group must be as small as possible while still giving results with no more than the greatest allowable tolerance for error. The factors influencing the size of the minimal reliable sample are the allowable error and the causes of error (variability of population sampled, and non-representative sampling due to bias or imperfect techniques). The allowable error should be predetermined; it is influenced by the purpose of sampling and cost considerations. Sampling to obtain data for propaganda purposes, for example, would have a higher allowable error than sampling for regulatory purposes.

Earlier in this chapter reference was made to the considerable error that results when samples of too small size are used, and to the work of FOLSOM and FERNOW in determining the sizes of potato samples corresponding to given percentages of allowable error. It should be borne in mind that sample size alone is no proof of accuracy; if a sample is non-representative, increasing its size makes it worse.

The British survey workers have made a valuable and exemplary contribution to the techniques of plant disease surveying in their study of minimal reliable sample size, including both the number and size of samples to be taken from a single field and the number of fields to be assayed. In studies of potato leafroll, blackleg, storage blight, and onion downy mildew it was found, for example, that appraisal of 10 fields gave disease values closely approaching those obtained by examining up to 157 fields. In adding more and more samples a point is reached at which additional samples do not seriously affect the average, and from this point, which can readily be determined by statistical comparison of different-sized samples, practically optimal sample size can be ascertained.

In a study of soybean yield sampling, HOUSEMAN et al. (1946) illustrate the derivation of the minimal reliable sample. Here the variation of the average sample = $(t_1 + kt_2)\ (A + \frac{B}{k})$ where t_1 is the average time spent in getting to and from the sampling units, exclusive of travel time, t_2 is the time spent in gathering the sample, k is the number of square feet in the sample, A is the variance attributable to fields, B is the variance per sq. ft. within the sample, $(t_1 + kt_2)$ is the total time spent in sampling, and $(A + \frac{B}{k})$ is the total variance between fields. In the soybean study, $\frac{t_1}{t_2}$ equalled 6, and if the value of k that minimizes sampling variance to a satisfactory amount = $\frac{t_1 B}{t_2 A}$, in this case the optimal sample size was 7.1 sq. ft. or approximately 1/6000 acre.

The same principle is followed in forest appraisal, as brought out by LEXEN (1947). Here the coefficient of variation is liberally estimated at 80%. The number of trees to be sampled is obtained from the formula:

$$\frac{(\text{Coefficient of variation})^2}{(\text{Acceptable sampling error})^2}$$

If 2.5% is considered an acceptable error, $\frac{80^2}{2.5^2}$ or 1025 trees should be examined. This is in fairly good agreement with HEPTING'S estimate of 3% error for a 1000-tree sample or 5% for 500 trees in sampling for butt rot cull, and with the sample-size table published by ZILLGITT and GEVORKIANTZ (1948) in which sampling error ranges from 9.6% for a 160-tree sample of 800 trees to 2.1% for a 4000-tree sample of 80,000 trees.

The economy in determining the optimal sample size is brought out in CROWTHER'S (1941) study of disease and other yield factors in cotton. Here it was shown that the results from a single experimental plot were of the same general order as those from a surrounding area of 25,000 acres. The same economy is seen in VESTAL'S (1944) study of Iowa oats plantings, in which a sample of 149 farms showed that 13.85% of the land on these farms was planted with oats, as compared with the figure of 13.2% from the Iowa farm census based on sampling several thousand farms.

MANNER OF OBTAINING RANDOM SAMPLES: -- Plant diseases and their effects are often quite irregularly distributed through a field or from one field to another. Diseases also often show the well-known border effect, with a greater or less disease intensity at the margin of a plot, field, or region. Disease appraisers, unless they have some means of ruling out the personal factor, commonly tend to select samples that are not truly representative, from more heavily diseased areas or the "best" of a field or fields of a region. To avoid this error, ingenious methods of obtaining random samples have been devised, and comparable methods should form part of regular sampling practice.

To avoid border effect in fields, sampling directions frequently mention taking no samples within a specified distance of the field margin, e.g., 10 or more paces or 1/5 the diameter of the field. Nor should all the samples be gathered in one region of the field. This can be avoided by directions to take samples along traverses across the field, preferably two diagonal traverses in opposite directions, completely crossing the field if it is not too large. This method is regularly followed in British surveying. In forest surveying it is sometimes the practice to sample every tree or every nth tree in a compass line. The latter principle is sometimes used in sampling row crops, the observer examining every nth plant in the row or the plants in every nth row, in accordance with the sample size required. In other cases the appraiser walks a specified number of paces, taking his sample at the point marked by his foot at the completion of the nth pace. As an alternative, the distance between samples may be specified in feet and measured. More representative samples are usually obtained if the traverse is across rows, rather than along them.

The British workers often make use of "grab samples" in which the eyes are closed and the sample is the branch or cluster of stems or leaves struck by the hand. If the sample is a quadrat, defined by a wire loop, objective samples may be obtained by throwing the loop a considerable distance from the observer, preferably in a random direction obtained when the observer loses sense of direction by turning around several times with eyes closed. This method is not recommended when two observers are working in close proximity.

In small plot experiments with cereals where 3-row plots are used, it is customary to take the sample from the center row to avoid plot border effect. This is a limitation on the pathologist who makes use of routine yield experiments for his disease measurement tests, since disturbing the center row in these experiments may introduce errors in yield determinations. In such cases it is better that disease measurement experiments be conducted with this as their primary purpose.

The surveyor's ingenuity will often suggest unique, useful methods of eliminating personal bias. In sampling forest trees, for example, LEXEN (1947) used a pocketful of marbles of which one was red, four black, and 45 white. At each tree encountered, he drew out a marble at random; if white, the tree was merely counted, if black the diameter was measured and the height estimated, while if the red marble was drawn the tree was blazed, indicating that its volume and cull would be measured after felling.

In selecting fields for sampling while driving along a highway, an objective method is to use the cropmeter, which measures roadside frontage of the crop(s) being surveyed, with stops for sampling at predetermined intervals of distance indicated by the meter. When the problem is one of selecting, for sampling, farms scattered over a county, a good procedure is to use a map tracing on which all sections of a county are numbered consecutively, and the sample is determined by drawing random numbers, using numbered paper clips or other tokens. The same method is used to determine which quarter-sections of a selected section, or which counties of a State, will be sampled.

Objective instruments are available for sampling some types of harvested produce. Best known of these is the compartment grain trier, a long tube with ten openings at intervals, leading to separate compartments, all of which may be opened and closed simultaneously by twisting a second tube with similarly placed holes, which surrounds the first. With this instrument, in one manual operation, ten samples may be obtained, taken at different depths in the grain bulk. Further objectivity is obtained by using a standard sample mixer, which homogenizes the sample, so that a smaller subsample becomes representative of the larger one. For sampling grain as it runs out of a spout, as in loading ships, a "pelican" is used, a long-handled scoop shaped like a pelican's bill.

As a final example of techniques for obtaining random samples, the following illustrates a very detailed and carefully considered method, used by HOUSEMAN et al. (1946) for sampling soybeans. On a route along well-distributed roads a stop was made each time the cropmeter, measuring soybean frontage, registered two miles. On a line with the car windshield two observers, starting heel to heel, walked a given number of paces in opposite directions parallel to the road, then turned into the field and walked another given number of paces at right angles, into the field. The two numbers, which were different for each observer at each stop, were between 0 and 100 and were each determined by drawing numbered tokens at random from a sack. (It would have been better for the first number in each case to have been between 10 and 110, to avoid border effect). Beginning at the position of the foot on the last pace, an L-shaped sample was taken consisting of 3 feet of row plus 1 foot of each of the first three rows to the left of, and in line with, the third foot of the 3-foot row sample.

In exceptional cases non-random sampling may be desirable. In a survey for rare and new diseases, for example, with emphasis on discovery rather than measurement of prevalence, it would be justifiable to concentrate attention on farms that are uncared for or abandoned, where no effort is made to control disease.

ROADSIDE APPRAISAL WITHOUT FIELD SAMPLING: -- When the presence and amount of a plant disease is conspicuously apparent from a distance, the possibility of surveying from a moving automobile or airplane can be considered, this having an enormous advantage in rapidity and economy. This principle has long been used in appraising crop acreages and other phases of land use. The roadside frontage can be quite accurately measured, originally by counting the evenly-spaced telegraph poles, from a railroad car, later by recording mileages as registered by the automobile speedometer, and now by equipping the car with a cropmeter, an instrument designed for measuring frontages in feet. From our point of view such a method must be considered in the light of several factors: Is the frontage proportionate to the total acreage; is the pathological situation seen from the car representative of the whole countryside; are the observations obscured or invalidated by "border effect"? However, these questions can all be answered by study.

HOUSEMAN et al. (1946) have analyzed the first of these questions. They cite studies by HENDRICKS showing that roadside frontages are proportionate to acreages in the cases of corn, alfalfa, and wheat, but that with some other crops the frontages do not correspond to the acreages because of a tendency to plant certain crops at the roadside and others (e.g., bottomland crops, crops subject to poaching) away from the road. In their own study it was found that in Illinois there was a tendency to plant soybeans away from the road, but the roadside data could be corrected for this by use of an easily-determined constant relating acreage to frontage.

In surveying for plant diseases there is the further question whether certain diseases tend to be more prevalent in fields that border roads than in those away from the roads. The latter is most likely, both because of pride on the part of growers which leads them to attempts at control of diseases in fields that are seen by passers-by, and because the better, more valuable farms, those where control practices would most probably be used, tend to have a higher percentage of frontage along well-travelled roads than do the poorer farms. This source of error, where it exists, could be eliminated by determining the correction factor for disease and frontage by means of a study of this relationship, on foot in sample areas, and then correcting the roadside readings by this factor.

Our best illustration of this method of surveying is the work of EZEKIEL and TAUBENHAUS (1934) and EZEKIEL (1938) in surveying for Texas root rot. This disease occurs in large or small irregularly distributed spots in the field, and is unevenly distributed from one field to another, and with direct sampling it would be necessary to use very large samples because of this irregularity. The spots can easily be observed from a considerable distance.

In their automobile surveys the Texas workers estimated the percent to which fields were occupied by the root rot spots and in five days were able to appraise 770 fields. When the estimates were compared with actual field counts the two methods invariably were in close agreement.

AIRPLANE SURVEYING: -- This method has been much more extensively used in surveying for insect pest infestations than with plant diseases, yet it has a useful place in surveying for those diseases that are conspicuous from the air, such as Texas root rot (Figure 18), dry land foot rot of cereals, cherry yellows, cereal leaf rusts, and dodder.

Figure 18. Aerial photograph of cotton field heavily attacked by Texas root rot, the cause of the dead plants, illustrating the usefulness of aerial survey methods. (Courtesy, A. A. DUNLAP, Texas Agricultural Experiment Station).

Aerial surveying, besides its speed and economy, has the further advantage that it may include aerial photography, in black and white or, better, in color, documenting the survey data with objective photographic records which can be very accurately analyzed by measuring the areas of infestation with a planimeter. In many respects the most striking case of plant disease that the writer has been privileged to see was a general infestation of dry land foot rot in wheat, which showed from the air at harvest time as great black spots, involving 30% of a vast acreage, where the dead wheat, overrun with sooty molds, stood out in sharp contrast to the sunlit golden color of the healthy ripened grain.

The Iowa Statistical Laboratory is using the method of strip-sampling with aerial colored photographs to aid estimation of grain production and quality; a similar practice might well be used for any plant disease that noticeably discolors the crop. The U. S. Department of Agriculture has made successful use of the autogyro in surveying for the Dutch elm disease, where the dead branches of diseased trees are more easily seen than from the ground.

Entomologists have learned the value of airplane surveys, which have been used effectively in surveying for mosquito breeding areas, the hemlock looper, the spruce sawfly and budworm, and the wattle bagworm in Africa. For surveys of forest insects in densely wooded areas with few roads, such as the Gaspé Peninsula, the airplane may be the only effective and practical means of surveying.

A particularly valuable contribution is that of F. E. WHITEHEAD and FENTON (1940) on airplane surveying for greenbug (aphid) injury to cereals in Oklahoma. This insect produces spots of dead grain with bright yellow margins, that are easily seen from the air and distinguishable from other types of spots. The surveying was done at 500-foot altitude, dipping the plane lower in questionable cases. The survey of 47 counties required 24 1/4 hrs. of flying time and cost $163.50 or 8 to 10 cents per mile, which was about half the cost of a comparable survey by car. It was completed 5 1/2 days after the outbreak was first discovered and in 2 1/2 days more all interested persons had been notified and control practices were being undertaken. The forecast of injury, based on the air survey, proved to be "surprisingly accurate" when confirmed later by questionnaires. Besides the advantages of speed and economy, the air survey proved more thorough than a ground survey could have been, because of limited visibility from the ground, the fact that the plane was not limited by roads, and that it was possible to see grain fields and infestations over a broad area, so that the plane was able to follow more efficient routes than an automobile could have done. All of these advantages have their counterparts in plant disease surveying by air.

While most air surveying has been done with conventional types of planes, the light, low-speed models being preferred, the slow autogyro has shown advantages in surveying for the Dutch elm disease, and, in the future, the helicopter, with its complete maneuverability, speed control, and safety at low altitudes, promises to be most useful of all.

No account of airplane surveying would be complete without reference to the use of aircraft, as well as kites and balloons, in sampling the air for the presence of fungus spores, insects, and other airborne particles. This type of work has developed principally in connection with air surveys of spores of cereal rusts and downy mildews, with the findings correlated with concomitant and subsequent disease development, and used in the study of long-distance dissemination of diseases. An extended account of this type of work is given in the symposium "Aerobiology", published by the American Association for the Advancement of Science in 1942.

INTENSIVE VERSUS EXTENSIVE SAMPLING: -- By intensive sampling we mean very thorough examinations of tracts or populations of limited size, in contrast to extensive sampling, over a broad area with less thoroughness. Each has its uses, and a combination of the two is sometimes the best procedure.

Such a combination has been the writer's regular practice in sampling for wheat leaf rust, as a basis for forecasting rust outbreaks. The intensive sampling is a detailed study of rust development of one or a few standard observation fields, with frequent examinations of many leaves, sometimes thousands of leaves per sampling when the rust level is low. During the last week of March in each year this intensive sampling is supplemented by an extensive, statewide sampling, with brief observations of hundreds of fields, to determine whether the results of the intensive sampling have broad territorial application.

In forest appraisal a similar practice has been recommended by LEXEN (1947) called "double sampling". The large sample, which may consist of 2000 trees or more, depending on the skill of the appraiser, permits a preliminary rough estimate of the apparent volume of timber in the forest and may show as high as 35% error. This is corrected by the intensive small sample. In making the large sampling, data are taken on tree height and diameter, with volume of wood being estimated, while in the small sampling, trees taken at random from the large sample are felled, bucked into logs, and the actual gross volume and cull volume are measured. The number of trees in the small sample depends on the amount of defect in the stand; it is greatest in old, defective virgin timber where there is the least agreement between estimated and actual net timber volume.

The advantages of double sampling justify its use rather generally in plant disease surveying. It is particularly desirable in connection with automobile roadside or airplane surveying, both of which are extensive methods, since such surveys must be controlled and validated by intensive study of selected fields.

THE TELEPHONE AS A SURVEY TOOL: -- NEIL STEVENS, to whom we owe many original suggestions on surveying practice, has stressed (1945) the desirability of making greater use of the long distance telephone as an adjunct to surveying which is cheaper than the time and gasoline used in travel. It is a method that deserves more extensive use.

THE IOWA MASTER SAMPLE PLAN: -- The Master Sample Plan is a form of area sampling. Its operation is based on use of large scale aerial photographs involving nearly every county in the United States. Sampling units, such as quarter-sections, are located at random on the maps, and these ultimate units are sampled by questionnaires addressed to dwellers on the units or by interview or personal inspection of the units, or by a combination of these. The size of the sample, i. e., number of units, is large or small according to the needs and purposes of any given survey.

The idea of a Master Sample first occurred to RENSIS LIKERT of the U. S. Bureau of Agricultural Economics in 1943 (KING and JESSEN, 1945). It was decided to work out the project through the Iowa State College Statistical Laboratory because of the sampling experience of the Iowa group. The size of the sample, originally planned to include 5000 farms, was increased to 300,000 farms when the Division of Agricultural Statistics became interested in the Master Sample as a basis for large scale farm surveys. The U. S. Bureau of the Census also was concerned in using the Master Sample in connection with the 1945 Agricultural Census, since it could provide a group of farms suitable for preliminary sampling. Under a cooperative agreement the Master Sample was completed in time to be used in the 1945 Agricultural Census as planned. The three agencies have cooperated in the planning and execution, as a million dollar project, of the further development of the Master Sample. Other governmental agencies and private industries have become interested and made use of the services of the Iowa Laboratory.

The area method of sampling has advantages over other sampling designs because: (a) it is independent of any predetermined knowledge of the characteristics of the population (a weakness of many public opinion polls in which the advance conception of population characteristics is nonrepresentative); (b) it is purely objective, eliminating freedom of choice on the part of the surveyor; and (c) it is usually efficient from the standpoint of maximizing precision on the basis of cost. While the initial cost of designing area sampling is high it has been found justified by the many uses of the Master Sample (KING and JESSEN, 1945; KING *et al.*, 1945; Anon., 1946).

The Master Sample Plan has been put to many and varied uses. In agriculture it has served to determine acreages and crop production, farm land ownership, farm employment, numbers of livestock bought, sold, and on hand, farm receipts and expenditures. Service for industry has included surveys to determine markets for farm and household equipment, magazine readership, and radio program preferences. Two of the most unusual uses of this technique were the collection of data for the World War II European Strategic Bombing survey and the 1946 survey of fairness in Greek election activities. It has also been useful in ascertaining farm and city populations.

On page 278 mention is made of the use of the Master Sample in determining the amounts and causes of livestock morbidity. An exact parallel exists between this problem and that of insect pest and plant disease losses. Thus far the Master Sample has not been used in plant pest surveying, yet it would undoubtedly have much value for this purpose and it is hoped that this valuable new technique will soon be applied to plant disease and insect pest surveying.

Chapter VI

ORGANIZED PLANT DISEASE SURVEYS

It is the purpose of this chapter to describe briefly the plant disease surveys that have been conducted by various State, Federal, and private agencies, in America and abroad, with mention of comparable surveys of insect pests and livestock diseases.

U. S. DEPARTMENT OF AGRICULTURE, PLANT DISEASE SURVEY: -- Prior to 1917 there were scattered attempts at plant disease surveying, one of the earliest of which was the potato late blight survey of 1885 and 1886, conducted on a questionnaire basis by the U. S. Department of Agriculture (N. E. STEVENS, 1934a).

Thanks largely to the interest and efforts of W. A. ORTON, the Plant Disease Survey was organized as an office of the Bureau of Plant Industry, U. S. Department of Agriculture, on July 1, 1917 with G. R. LYMAN, in charge, assisted by R. J. HASKELL. In later years it was directed successively by N. E. STEVENS, H. A. EDSON, and P. R. MILLER. The principal objects of the survey, as originally stated, were "first, to collect information on plant diseases in the United States covering such topics as prevalence, geographical distribution, severity, etc., and, second, to make this information immediately available to all persons interested, especially to those concerned with disease control." Soon after the initiation of the survey, LYMAN (1918) described its organization, value, and objectives, and appealed to pathologists to support and cooperate with the new undertaking.

Plant pathologists and mycologists in the various States have been selected as volunteer cooperators with the Survey. Survey data from the States are routed to the Survey office in Washington where they are coordinated and published in the mimeographed Plant Disease Reporter, which was initiated as the Plant Disease Bulletin in 1917, and received its present title in 1923. In addition to organizing and coordinating miscellaneous State survey activities throughout the country, the small staff of the Survey office has conducted a number of regional or nation-wide special surveys, such as those of the wheat smuts, leaf rust, nematode, and take-all or mosaic, corn root rot and brown spot, potato wart, and alfalfa stem nematode in the earlier years, and the cotton seedling disease and boll rot surveys and the tobacco disease surveys of more recent times.

The regular issues of the Plant Disease Reporter contain a miscellany of reports on various and sundry plant disease occurrences, distributions, losses, forecasts, etc. Supplements have been devoted to more extended treatments of special surveys, check lists, host indexes, cooperative control experiments, epiphytotics, survey techniques, and annual national summaries. The latter have been of two sorts. One contained summaries of all disease data reported during the year, arranged by crops. The other summarized estimates of loss caused by principal diseases of leading crops. Both types of annual reports were discontinued after 1939. This is unfortunate, as both, despite their limitations, were valuable sources of disease intensity and loss data. The annual disease loss reports were based on estimates of loss in the various States, made by the principal Survey collaborators, usually with the assistance of other State specialists. These loss estimates were sometimes little better than guesses, and in numerous cases were demonstrably too low (WOOD, 1935). Yet they represented the only available comprehensive body of data on losses from plant diseases in the United States, and they were undoubtedly more reliable than some other published disease loss estimates. It is hoped that they will again be issued regularly, and it seems assured that in that case their reliability and usefulness would constantly increase as the experience of passing years adds to the accuracy of our loss appraisals.

During World War II it became appreciated that the immediate recognition of crop disease outbreaks, whether fortuitous or by enemy design, was of vital importance to national security, and in 1943, with the approval of the Secretary of War and support from the President's emergency funds, the Plant Disease Survey established the emergency plant disease prevention project, with 24 survey pathologists assigned to territories throughout the United States. Disease identification laboratories to serve these field men were established at Beltsville, Maryland and Stillwater, Oklahoma, with consulting diagnosticians in charge.

These "G-Men of Plant Disease", as P. R. MILLER Has called them, gave particular attention to important food crops and sent weekly reports to the Survey. Much of the information on old and new plant diseases which was disclosed by these surveyors was published in the Plant Disease Reporter during the war years, after which this emergency activity of the Survey was discontinued. Interesting accounts of the more significant discoveries made by these men and of their use in loss-prevention programs have been given by BARSS (1944), P. R. MILLER (1947b), and P. R. MILLER and WOOD (1947).

Another significant advance in the work of the Plant Disease Survey was marked by the Research and Marketing Act of 1946 which allotted to the Survey funds for a Federal-State cooperative regional project on the establishment of facilities for forecasting the development of crop plant diseases, beginning in 1948. This was an outgrowth of the potato late blight warning service developed by MELHUS (1942) during the second world war, and of the national tomato late blight warning service organized in 1947 by the Plant Disease Survey (P. R. MILLER, 1947c; P. R. MILLER, J. I. WOOD, and others, 1947).

The work of the Forecasting Project is now limited to experimental investigation of factors involved in dissemination and severity of the diseases with which it is concerned. For this purpose, a pathologist has been stationed by the Project in each of three regions to begin with, viz. Northeast, Southeast, and North-central. The warning service, which was a part of the Forecasting Project until it was no longer on a tentative experimental basis, is now a function of the Survey proper; it is this service that gathers and relays the current information basic to the forecasts. Key pathologists coordinate disease information in each State and in cooperating Canadian Provinces, sending timely reports on the progress of the diseases to the Survey office in Washington, where they are summarized and redistributed to the key pathologists for such local action as may seem advisable.

Throughout its thirty-year history the Plant Disease Survey has been, and still is, handicapped by lack of funds and of a staff of adequate size for its important task. Considering this handicap it is remarkable how much has been accomplished, under its able and energetic leadership, in assembling plant disease data of current importance and often of lasting value, and in providing these data to the men who could make good use of them in reduction of crop disease losses through research, education, and action programs.

SPECIAL SURVEYS OF THE U. S. AGRICULTURAL EXTENSION DIVISION: -- F. C. MEIER, who became the first Federal extension plant pathologist in 1922, inherited from W. A. ORTON an interest in plant disease surveying, and conducted a number of special surveys in connection with his extension program. It was he who initiated the analysis of wheat terminal-inspection reports which has given us a long-term authoritative record of such diseases as bunt of wheat and ergot of rye.

R. J. HASKELL, who entered the Extension Service after seven years in charge of the Plant Disease Survey, continued the analysis of terminal-inspection reports until this work was taken over by the Chicago office of the Production and Marketing Administration. He also maintained his interest in disease surveys and losses, as shown, for example, by his study with E. G. BOERNER (1931) of the relation between wheat bunt in the field and smuttiness of the threshed grain.

STATE-SPONSORED PLANT DISEASE SURVEYS: -- On numerous occasions in the past, individual States, alone or in cooperation with the Plant Disease Survey or other agencies, have undertaken surveys, some for specific, limited purposes and others of a more general nature. At the present time a number of the State agricultural experiment stations include survey projects in their research programs. In the Oklahoma Station, for example, there is a continuous project entitled "Oklahoma Plant Disease Problems," designed to support work of a survey or exploratory nature, and from year to year, as natural disease outbreaks occur, these are made the subject of special surveys.

Between 1927 and 1929 general statewide surveys of plant diseases were conducted by plant pathologists of Iowa, Utah, Montana, West Virginia, and New York with cooperation and financial assistance from the Plant Disease Survey. Reports of these are found in the Plant Disease Reporter, Supplements 58, 59, 69, 72, and 76 respectively.

The most extensive of the State-sponsored plant disease surveys have been those of the Illinois Natural History Survey. Details of their methods are given in papers by TEHON (1927) and TEHON and STOUT (1930). Each year several surveyors have been in the field, taking very detailed data on the diseases of various major crops. The use of carefully planned standard data sheets has assured the completeness and uniformity of the records. For example, the data sheets used for cereal disease records have included, for each field examined, notes on: crop, disease, county, locality, crop variety, size of field, growth stage of crop, control measures (what, when, and how used), date disease first observed, source of infection, cropping and disease history of the field, association with other diseases, weather, phenology, date of observation, number attached to specimens collected, observer, and degree of infection. Where the disease in question was cereal rust, the latter has included: percent of culms infected and rust intensity in terms of the number of culms in each class of the modified COBB rust scale. With fruit diseases the notes on infection have included: type of injury, percent of trees affected, percent infection in individual trees, percent reduction in area of leaf surface, amount of wood diseased or destroyed, and percent of twigs and of fruits infected, with the latter classified in infection scale classes. The infection data are limited to disease intensity, without the purpose of determining losses sustained. However, in cases in which disease intensity-loss relationships are known or can be determined, these data could be translated into loss estimates.

The thoroughness of the Illinois surveys, the great detail and uniformity of their records, and their long continuance make these surveys unique in plant pathology. Over the years a wealth of valuable records have been accumulated by the Illinois workers, a repository of plant disease survey data that in many respects is unequalled elsewhere. This accumulated information could be of great value in studies of the ecology of plant disease, plant disease losses, secular trends of diseases, and other aspects of plant pathology. This repository bears a relation to plant pathology corresponding to the relation between long-term weather records and the science of meteorology, or between a great herbarium and the science of systematic botany. It would be a distinct service to plant pathology if the Illinois survey records could be subjected to thorough analysis and statistical study, by qualified plant pathologists of different interests and viewpoints, as it is only through such digestion and analysis that large accumulations of survey data can be made fully useful.

While not the product of organized surveys, mention should be made of the disease and fungus check lists and host indexes of plant diseases that have been prepared for a number of States. Those for Texas, Maine, Missouri, and Oklahoma are representative of general lists of this sort, while, in other cases, the lists are more specialized, as with the lists of ascomycetes of Georgia, or of the parasitic fungi on cereals and grasses in Oregon. On a national scale, WEISS of the Plant Disease Survey published in the Plant Disease Reporter between 1940 and 1949, a revision of the "Check List of Diseases of Economic Plants in the United States", which originally appeared in 1926 as U. S. Department of Agriculture, Dept. Bull. 1366. While these check lists do not give much information on prevalence, intensity, or destructiveness of plant diseases, they are valuable sources of data on disease distribution, with many useful applications to the problem of present and potential disease hazards.

No account of State-sponsored surveys would be complete without some mention of the Iowa Master Sample which is used for many other types of surveys than those for plant disease. This has been discussed in detail previously (page 268), and here it is sufficient to recall that this is a means, developed in Iowa but used extensively in other States, for obtaining a representative sampling, of any desired degree of reliability, on a geographic basis. VESTAL'S (1944) survey of the adoption of disease-resistant oat varieties in Iowa is a phytopathological application of this principle of surveying.

CROP REPORTING SERVICE OF THE U. S. BUREAU OF AGRICULTURAL ECONOMICS: -- For more than 100 years there has been national interest in the collection of crop statistics. The report of the Commissioner of Patents for 1845 devoted nearly 1100 pages to statistics and miscellaneous information on agriculture, with much space being given to potato diseases. When the U. S. Department of Agriculture was created in 1862 its purposes were defined to include the collection of agricultural statistics, and immediately there was organized a system of volunteer crop reporters to furnish periodic data on the condition of crops and livestock. Beginning with some 2000 northern farmers as volunteer reporters in 1863, the organization has grown to include over 200,000 correspondents who report in 10,000,000 questionnaires each year.

The Crop Reporting Service has continued to function under a variety of administrations, first of which was the Division of Statistics in the last quarter of the 19th century, which became the Bureau of Statistics in 1903. The program was later under the Bureau of Crop Estimates, and since 1922 it has been conducted by the Bureau of Agricultural Economics, except for an interlude in 1939-1945 when the Crop Reporting Service was first a part of the work of the short-lived Agricultural Marketing Service and later temporarily under the Agricultural Marketing Administration.

Despite its great extent and thorough coverage, and its well-established value for determining crop production, land use, and many other agricultural matters, the Crop Reporting Service has so far produced few reliable data regarding plant diseases. In fact, the scanty disease data from this source which have been published have usually shown such gross error that they have obscured rather than aided in an understanding of plant disease losses. This would be expected, considering that the crop reporters who provide the basic data are generally unacquainted with the nature of crop diseases and, have an almost universal tendency to ascribe to unfavorable weather or soil the reductions in yield that are caused by plant disease. An example of their underestimation is given on page 217.

If it were possible to attain reasonable reliability in plant disease reports of the Crop Reporting Service, this would be a source of survey data of scope and extensity far exceeding any plant disease survey yet attempted. It may be vain to hope that the necessary degree of reliability could ever be obtained in data submitted by untrained farmers. Yet, present-day agricultural education is doing much and can do much more in the future, in familiarizing growers with their production hazards. Some improvement in the reliability of farmers' appraisal of crop damage from disease is bound to accompany this gradual process of education. It could be accelerated by planned efforts in training the survey specialists who coordinate and verify the reports of lay collaborators, so that they, the survey specialists, can give due weight to the disease hazard in their own reports, and aid in securing more reliable disease reports from collaborators. At the end of this book a concrete proposal for such training is given.

REPORTS OF THE FEDERAL CROP INSURANCE CORPORATION: -- The potential value of information on crop losses as a basis for crop hazard insurance was discussed in Chapter I (page 205 ff.) where it was pointed out that the records of indemnification by the Federal Crop Insurance Corporation provide meagre data on annual disease losses as reflected in claims paid. These data have been published in Reports of the Manager of the Federal Crop Insurance Corporation for each year.

As a source of disease loss information these reports are of limited value because: (a) they are intended to include only unpreventable losses (despite some claims paid for losses from wheat smut and cotton "rust") and therefore do not reflect the relative importance of the various diseases of a given crop; (b) they are limited to very few crops and diseases; (c) the data are often limited to a few experimental counties, not giving a representative sample for large areas; (d) in many cases there is no published breakdown to show the distribution of disease indemnities among the several diseases of a crop; (e) diseases are sometimes listed under unrecognizable names as "blight" and "wilt" of wheat and "blight" of flax and tobacco; and, most important of all, (f) taken at face value the claims paid for disease losses are far below the level that would reflect their true importance among the other crop hazards, for reasons indicated on page 206.

The insurance report disease data also appear to lack appraisal uniformity from one State or season to another, so that they cannot be used as reliable indices of relative disease importance. For example, 22% of all claims for wheat insurance in New York State in 1942 were for smut losses, but there were no similar claims in 1940 or 1941. In 1940, 34% of the claims in Indiana and 45% of the claims in Wisconsin were for rust damage, while there were no claims for rust losses in the adjacent States, Ohio, and Minnesota, where rust was presumably comparable in amount to that in the indemnified States. In correspondence from the Manager of the Federal Crop Insurance Corporation it has been stated that the insurance adjusters are inadequately trained in plant pathology, which doubtless accounts for these discrepancies.

On the whole it appears that we cannot turn to the insurance reports for reliable information on crop disease losses, but it is hoped that through future education this defect can be corrected, an accomplishment that would be equally helpful to crop insurance agencies, to farmers whose crops are insured, and to plant pathology.

COMMERCIAL AND OTHER NON-GOVERNMENTAL SURVEYS: -- While most plant disease surveys in the United States have been sponsored by Federal or State governments, there are a few cases of privately supported surveys.

The fruit disease survey made by the Eastern New York Horticulture Society (Anon., 1899) has historic interest as one of the first of such surveys in this country. This survey, led by F. C. STEWART and F. H. BLODGETT, involved sending 250 circular letters to growers in 10 Hudson River counties, followed by inspection trips. The circular letter listed 36 diseases, and growers were asked to indicate those of greatest local importance, with percent crop loss, control measures used, and information on new or unusual diseases. It was found that the questionnaire method alone was unsatisfactory because replies were often careless, diseases were not accurately identified, and there was misleading use of common names of diseases. Good results were obtained, however, when this method was supplemented by the field inspections.

Commercial surveys are well illustrated by those of pea diseases in Wisconsin, made at the request of and supported by the canning industry, and conducted by F. R. JONES and LINFORD (1925) and WALKER and HARE (1943). The first survey involved 688 fields, the second, 4714 fields, and they were made by visiting each field two or three times and taking systematic, well-planned notes on incidence of and losses due to each of several diseases.

It would be to the advantage and profit of processors, marketers, and the industries dealing in seed, pesticides, and pest control equipment to support such surveys more commonly. They can give a foreknowledge of the amount and condition of crops to be harvested, permitting economical processing and marketing, and they can reveal the most strategic points for the concentration and distribution of pest-control products or for the education of growers to the use of commercial materials and equipment in pest control.

TIMBER CRUISING AND FOREST APPRAISAL: -- Forest disease surveys, which are essential and routine parts of forestry, have been so well discussed in books on forest mensuration and forest pathology, such as that of BAXTER (1943), that they can be only mentioned here for the sake of completeness. The subject has also been discussed by WEIR (1918). Two types of surveys are included, limited intensive surveys in connection with forest value appraisal, and extensive surveys such as those to determine the ranges of chestnut blight, pine blister rust, or elm diseases.

PLANT DISEASE SURVEY OF THE CANADIAN DEPARTMENT OF AGRICULTURE: -- For nearly thirty years the Department of Agriculture of Canada has conducted an annual, Dominion-wide plant disease survey. This began as a result of action taken by the Canadian Branch of the American Phytopathological Society at its first annual meeting in 1919. W. P. FRAZER and W. H. RANKIN were appointed to undertake the work. This was done, with the ready permission of the Dominion Botanist, H. T. GÜSSOW, beginning in 1920. Through the years the Survey has continued as a routine part of the work of the Division of Botany, ably led during most of this period by I. L. CONNERS, with many professionally-trained collaborators. The results of these surveys have been published in mimeographed Annual Reports of the Canadian Plant Disease Survey, issued by the Department of Agriculture at Ottawa.

In general form these reports resemble the annual summaries of plant diseases in the United States, formerly issued by the U. S. Plant Disease Survey, with diseases classified according to crops affected, and sub-classed geographically, and with a preliminary summary of the most important pathological events of the year. A unique and valuable feature of each report is the summary of phenological data at three strategic points, beginning in 1936, with blooming dates for many herbaceous and woody plants. This, coupled with an annual summary of the effect of weather on plant diseases, provides extremely valuable source data for studying the ecology of plant diseases.

In addition to the general summaries of plant diseases, which are particularly complete for the cereal crops, some of the reports contain accounts of special survey activities, beginning with DEARNESS' list of anthracnoses in the first issue, and including provincial or local fungus lists, special surveys of diseases of tobacco,, strawberries, flax, sugar beets, soybeans, and peas, reports from the District Potato Inspectors on potato virus diseases and on the vectors of these viruses, and, recently, reports of disease in the rust nurseries and of the determinations of physiologic races of cereal rusts.

As an adjunct to plant disease surveying in Canada, I. H. CROWELL and E. LAVALLÉE have published a "Check List of Diseases of Economic Plants in Canada."

BRITISH WORK IN PLANT DISEASE SURVEYING AND LOSS APPRAISAL: -- The British Ministry of Agriculture and Fisheries initiated a plant disease survey in 1917, publishing in a Miscellaneous Publication series annual "Reports on the Occurrence of Insect and Fungus Pests on Plants in England and Wales." At present the Ministry, through its plant pathology laboratory in Harpenden, also issues "Monthly Summaries of Fungus and Allied Diseases occurring in England and Wales". These are marked "not for Publication" and may not be obtained, on request, by American workers. This is unfortunate from the standpoint of disease intensity-loss study, because the reports contain numerous valuable contributions to the techniques of disease measurement in addition to many useful records of disease occurrence and ecology.

In 1933 the Plant Pathology Committee of the British Mycological Society held a symposium on the measurement of plant disease intensity (BEAUMONT et al., 1933). During the next few years the need for better methods of evaluating disease became increasingly apparent, and in February, 1941, the Committee called a special meeting at which it was decided to attempt to evolve simple, reliable standard methods of recording diseases quantitatively in the field. The subcommittee on plant disease measurement consisted of F. C. BAWDEN, R. W. MARSH, W. C. MOORE, and P. H. GREGORY, with W. BUDDIN acting as secretary.

The work was begun at once. In 1941 questionnaires were distributed and 1200 estimates of plant disease were received. Meanwhile, exploratory work was done on methods for appraising loose smut, take-all, and eyespot of wheat, virus diseases and late blight of potatoes, downy mildew and virus yellows of beets, and apple brown rot and scab.

By 1943 suitable appraisal methods for these diseases had been developed, tested, found practical, and recommended by the committee for general use (Anon., 1943). The British survey methods are discussed elsewhere in this book. They are particularly deserving of study because of the attention given to sizes and types of samples, with an effort toward the smallest samples that will give reasonably reliable results. In this brief account of British survey activities should also be mentioned the work of BEAUMONT at Seale-Hayne Agricultural College, in forecasting potato late blight. This is described in connection with methods of disease forecasting.

DANISH PLANT DISEASE SURVEYING: -- To little Denmark, long a leader in plant pathology, belongs the distinction of having first developed systematic plant disease surveying. Regular annual surveys were begun by ROSTRUP in 1884, with publication of data on the importance of various diseases and pests. This long and complete record, extending well over a half century, is a unique source of data relating disease outbreaks to meteorology.

Monthly surveys and reports of crop diseases and pests in Denmark were begun by KØLPIN RAVN in 1906 with local agricultural organizations and the State cooperating. Data were obtained both by reports from lay collaborators, of which there were 88 in 1919 and 137 in 1937, and by surveys and observations by the central phytopathological staff. Excellent use has been made of various publicity channels, mail, press, radio, and magazines, in promptly disseminating the results of the surveys, and in issuing control warnings, such as those for spraying to control imminent outbreaks of potato late blight. An account of the development of plant pathology in Denmark, including surveying, has been given by GRAM (1938).

GERMAN PLANT DISEASE SURVEYING: -- Plant protection was first organized in Germany in 1889, and from the beginning statistics on outbreaks of plant disease were published. Later as the volume of data became great, there were published annual summaries of diseases in Germany. In 1901 there was prepared a group of 70 tables giving percent injury from diseases and pests of various crop plants.

The German approach to the problem of crop losses was a statistical one. MORSTATT (1929) mentions a pamphlet in 1903 proposing on observation service for uniform records of disease intensity, leaving their analysis and translation into crop loss to the central office which became the Biological Division of the Imperial Gesundheitsamt. Such analysis of large bodies of data, submitted by lay collaborators, as in the U. S. Crop Reporting Service (page 272), is the statistical method in the sense of the German workers, contrasting with the determination of disease intensity and damage by more limited but more exact and thorough studies made by trained personnel, as in the U. S. Plant Disease Survey.

Until 1920, except in 1913-1919, extensive annual reports of insect pests and plant diseases in Germany were issued by the Ministry of the Interior. In that year the responsibility for assembling and publishing these reports was vested in the "Observation and Warning Service" of the Biological Institute, with the purpose of gathering numerical data on yield losses. An innovation was the inclusion of plant pest maps to supplement the text of the reports. In 1927, as a result of a decision made by the German Plant Protection Service, monthly crop pest and disease reports were first issued.

Under the Hitler dictatorship there was pressure to increase agricultural production, involving an intensification of the plant protection information service (BÖNING, 1936; KLEMM, 1937). At that time many thousands of annual reports of major disease occurrence in economic plants were being sent in by lay observers, organized by corps of "Vertrauensmänner", who forwarded the reports to the Biological Institute for analysis and official use. One of the sections of the German "Act for the Protection of Economic Agricultural Plants" of March 5, 1937 was concerned with the organization of plant protection through the Biological Institute in cooperation with local plant protection offices, to be established by the Reich farmer leader (Bauernführer) under the Ministry of Food and Agriculture, and with the plant inspection service (GOETZ, 1937).

The tasks of the statistical section of the service, as stated by KLEMM (1940) included: (a) determination of the distribution of pests and of the areas of their greater and lesser prevalence, (b) determination of the areas of important crop losses and the amounts of loss, and (c) the investigation of the relationships between pests, pest-areas, and environment, to aid in forecasting pest calamities, organizing national pest control, and planning of pest-control research. Whatever service this organization may have been to Germany's effort in World War II, it ended in the demolition of the Biological Institute during the bombing of adjacent military objectives.

RUSSIAN PLANT DISEASE SURVEYING: -- It has been difficult to secure reliable information on Russian science, and we are fortunate that KLEMM (1941) has provided a good account of plant disease survey and appraisal practice in the U.S.S.R.

Plant pathology became formally established in Russia with the founding of YACHEVSKI'S laboratory in 1900, followed by phytopathological sections in the agricultural experiment stations. In the early years annual lists of diseases and insect pests were published. The last year before the Revolution, 1.5 million rubles was spent on plant protection. World War I and the Revolution largely wiped out the experiment stations.

Postwar insect and plant disease outbreaks led to a reorganization and expansion of the plant protection service, with headquarters in Leningrad and many local stations, but the latter were poorly staffed and equipped. By 1930 there were 600 plant protection workers in 109 stations. Booklets of instructions on methods for observing plant diseases were prepared by MURAVEV and SHEVCHENKO (1938), DEMIDOVA (1928), NEVODOVSKII (1925) and STRAKHOV (1925). YACHEVSKI in 1929 published a very detailed analysis of the need for a Russian plant disease appraisal service.

To meet the great problem of plant protection on the many collective farm units, in 1930 the plant protection service was again reorganized as the All-Russian Union for Pest Control (OBV) for action programs, with research delegated to VISRA, the All-Russian Institute for Plant Protection, an affiliate of the Lenin Academy. With this stronger organization OBV developed a far-reaching plant disease observation and warning service with the task of determining: (a) the distribution of plant pests (diseases, insects, weeds), their places of reproduction, and their long-range prognosis; (b) the process of annual development of pests and their short-range prognosis; (c) losses caused by pests; (d) the effectiveness of pest-control measures; and (e) the influences of natural and cultural factors on the reproduction of pests.

By 1934 observation data were being assembled at 267 observation points, from 37,000 correspondents. All data were forwarded to the central office where they were analyzed and 10-day, monthly, and annual reports were issued. Despite their volume, most of the data were unreliable because of the lack of training of the observers, and the organization was defective in placing too great responsibility in the action agency, OBV. Accordingly, in 1934 it was again reorganized, this time putting the responsibility for collecting the primary observation data in the hands of the collective farms and smaller administrative units with central leadership in the offices concerned with production of individual crops. The observation and warning service was assigned to the land administrations in the People's Commissariat for Agriculture (NKS) in each republic. However, the professional work of prognosis, investigation of damage, determination of losses, investigation of the relationship between environment and pest outbreaks, and evaluation of pest control measures was delegated to the Observation Section of the All-Russian Institute, VISRA. The number of observation points was reduced to 123, each with work areas 20 to 30 km. in diameter and staffed with 3 to 5 trained crop pest scientists.

At the observation points detailed studies were made of the increase of pests, their distribution, and their effects on yield as seen in comparisons of protected and unprotected plots. Reports, including local phenology and pest forecasts, were sent to VISRA headquarters where reports were prepared on the development of pests, their overwintering, first appearance, and intensity, long- and short-range prognoses for leading pests, the regional distribution of pests, the results of research and regulation in decreasing the cost of pest-control, and methods and instructions on observation for observers on the collective farms. The tasks of VISRA, inter alia, have included, for all Russia, the determination of methods for appraising crop pests, investigation of the laws governing the increase of pests, and working out methods for pest forecasting. Much of its work has been conducted in a network of substations and six zonal stations.

PLANT DISEASE SURVEYING IN OTHER COUNTRIES: -- The phytopathological services in Italy originated in the Act of 26th June, 1913, for the prevention and control of plant diseases, which became law in 1916 (TRAVERSO, 1923). The machinery of the services included regional phytopathological observatories or stations, of which 23 were formed in 1917, these being partly regulatory and partly concerned with observation, collection of data on plant disease occurrences, and information services. A noteworthy item in the Italian work is its contribution to forecasting outbreaks of grape mildew (page 328).

Reports of systematic, periodic plant disease surveys in other countries have not been encountered, although it is entirely possible that organized surveys may function in certain other nations. Check lists of plant diseases in various countries, such as Sweden and Czechoslovakia, testify to an interest in plant disease surveying even though this may not be a routine practice. The literature also gives evidence of occasional special plant disease surveys abroad, as that of South New Zealand in 1935-1936. The reports of the Minister of Agriculture of Ceylon mention a "Survey Department". Finally, a few special plant disease surveys abroad have been made by foreigners with only temporary participation of the governments of the countries concerned. In this category fall the survey of plant diseases and fungi in Egypt made by MELCHERS in 1927-1928 (1931) and R. H. PORTER'S survey of plant diseases in East China in 1923 (1926).

SURVEYS OF THE BUREAU OF ENTOMOLOGY AND PLANT QUARANTINE: -- The several types of surveys conducted by the U. S. Bureau of Entomology and Plant Quarantine have been mentioned on page 258. These are cooperative with other Federal bureaus, with agencies in the States, including the agricultural colleges with their experiment stations and extension divisions and the State boards of agriculture, and with the pesticide industry, farmers, and other lay groups.

Comparable to the Plant Disease Survey is the Insect Pest Survey which was first organized in 1921 (HYSLOP, 1927). This maintains no field offices or field personnel but is a clearing house for many thousands of reports on insect outbreaks that are submitted weekly, each year, by some 250 collaborators throughout the United States. The survey issues weekly summaries of insect conditions and impending outbreaks during the growing season, and monthly and annual statements furnished to government workers, pesticide manufacturers and other interested persons. It aids other survey activities in pest identification and maintains a file of a half-million individual notes on insect occurrence and destructiveness.

From 1943 to 1945 the Bureau, with the aid of the President's emergency funds, conducted unique Port-of-Entry Surveys designed to detect local establishment of introduced pests around harbors and airports and along the Mexican border (SWAIN et al., 1946). These were parallel to, and cooperative with, the Emergency Plant Disease Prevention project. With personnel of 92, some 63,000 inspection hours were spent along the entire length of the Atlantic, Pacific, and Gulf coasts, and the Mexican border, and special surveys were made of pests in cork imported from Morocco and of the crambid insect, Chilo loffini, in California. Both crop plants and their wild relatives were examined for insects and diseases; and many unusual specimens were found and submitted to specialists for identification. Apart from a number of discoveries of new or little-known but important infestations, much incidental information was gathered, which in itself went far to justify the expenditure of funds.

Most other survey activities of the Bureau, usually cooperative with State agencies, are classified as surveys in the domestic plant quarantine and control field. Information on these is given in the annual "Reports of the Chief of the Bureau of Entomology and Plant Quarantine". Many of these surveys are designed to delimit the areas of infestation, as those of the gypsy moth, browntail moth, Mormon cricket, pea scylla, sweet potato weevil, white-fringed beetle, and potato tuber worm. Surveys for the Dutch elm disease (Ceratostomella ulmi) for this purpose also involve spot inspections, well outside the limits of infestation, and include surveying for the beetle that transmits the disease as well as for the disease itself. In the case of blister rust (Cronartium ribicola) the surveys are aimed at delimiting the areas of occurrence and infestation of both alternate hosts, pine and Ribes.

It is not always possible to distinguish between survey and regulatory inspection work of the Bureau. In the case of phony peach and peach mosaic, for example, the inspection serves all three functions of locating diseased trees to be destroyed, delimiting the areas of infestation, and gathering of information on other stone fruit diseases.

Other surveys have had the purpose of determining whether newly introduced pests have escaped from their limited initial areas of infestation and become established. This has been the case with surveys for the potato rot nematode (Ditylenchus destructor) and with the Hall scale of stone fruits in California.

Another valuable function of the surveys is to determine the likelihood of future outbreaks of pests, permitting a pest warning or forecasting service. This has been a valuable feature of the annual grasshopper, chinchbug, and Mormon cricket surveys. In the case of sugar beet curly top, surveys of the hibernation of the vector of the virus, the beet leafhopper, make it possible to forecast curly top outbreaks before beet planting time, allowing farmers to avoid or control this destructive disease by well-advised crop management.

The annual cereal stem rust survey serves a number of useful purposes: barberry bushes, the alternate hosts of the rust, are located preparatory to their eradication; the annual development of rust in the South and in Mexico, with spread to the North, is observed over a wide area; and each year many identifications are made of the physiologic races of rust that are present, which is a guide to rust control by breeding, and which discloses the future hazards that may result from the occurrence of new races or changes in the proportions of races in the rust population.

In many cases the surveys serve to initiate pest control practices. A survey of the prevalent velvetbean caterpillar in 1946 led to prompt control measures; the screwworm survey, begun in 1943, has greatly aided a program for the treatment of infested livestock; and chinchbug surveys, begun in 1944, direct attention to the areas where control practices are needed. Although control was not practical, the survey of the Sitka spruce beetle in 1946 led to salvage of much timber that would otherwise have been lost.

Special emergency surveys of vegetables, fruits, and cotton have recently been organized, with the primary objective of locating areas of greatest need of pesticides and channelling these to the needy areas. The cotton survey has enlisted the aid of farmers, 4-H members, vocational agricultural teachers and their students, and other State and Federal agencies. Weekly reports are issued to cooperators and the pesticide industry is kept informed about the areas where its products are in greatest demand.

The entomological surveys often make use of ingenious or unusual methods. Insect traps are frequently and widely used in surveying outside the known areas of infestation to locate the activity of such insects as the pear scylla, Japanese beetle, oriental fruit moth, and Mexican fruit fly. Survey inspections of cotton gin trash give valuable information on infestations of the pink bollworm. In 1945 the Bureau developed the soil-wash method of surveying for the golden nematode of potatoes (Heterodera rostochiensis), which has proven to be a useful method for locating this pest.

THE U. S. LIVESTOCK MORBIDITY AND MORTALITY SURVEY: -- In 1944 the National Research Council formed an Agricultural Board which established a Committee on Veterinary Services for Farm Animals under the able chairmanship of R. C. NEWTON, vice-president of the leading meat-packing organization, Swift and Company. The object of the committee was to increase the efficiency of livestock production by reducing losses. The committee soon found that little was known of the economics of livestock morbidity and mortality. As B. T. SIMMS, Chief of the Bureau of Animal Industry and a member of the committee, expressed it: "The simple fact is that no comprehensive information concerning animal losses -- either total losses from death or loss of profits through sickness -- is at present obtainable. If the losses were known, their enormous proportions would probably quickly bring about remedial measures."

The immediate task, then, was to assemble reliable information on the extent of livestock losses. Several interested agencies recommended to the directors of the State agricultural experiment stations that they initiate studies on the economics of morbidity and mortality in livestock. At that time the recently organized Statistical Laboratory at Iowa State College of Agriculture, in cooperation with the Bureau of Agricultural Economics and the Bureau of Census, was attracting national attention by its success in the use of the "Master Sample Plan" (see page 268), for surveying to obtain information on diverse questions. The interest of the Iowa statisticians was enlisted and a direct survey of United States farms was considered. A plan for a one-year project, limited to Iowa, was drawn up by the Statistical Laboratory and approved by the U. S. Department of Agriculture.

The problem of financing the project was solved when Swift and Company provided sufficient money for the one-year undertaking. The survey, based on the reports of livestock farmers on 177 farms in 20 scattered counties, was completed in 1947 and showed that the annual loss in Iowa from morbidity in swine was $14,000,000 and in cattle, $11,000,000. Iowa veterinarians estimated that $13,000,000 of these losses could be prevented with practical preventive measures and $18,000,000 under ideal conditions (Anon., 1948).

These estimates are subject to a high standard error (12-21% of the mean) because of the small sample size, and they have the imperfections to be expected when a survey is based on reports of untrained observers, yet they represent a notable advance in extending knowledge of livestock losses, one that should be a valuable guide in shaping a program of reduction of these losses as techniques improve and the survey expands to involve a greater area and larger period of time. The Iowa livestock survey also illustrates the use of a survey technique that deserves trial in appraising losses from plant diseases and insect pests.

Chapter VII

STATISTICAL AND HISTORICAL METHODS FOR DETERMINING DISEASE INTENSITY-LOSS RELATIONSHIPS

Having determined the intensity of plant disease it is necessary to establish the relationship that exists between disease intensity and the loss produced, the second major step in plant disease appraisal.

Many examples might be cited to illustrate the variation of correlation between disease intensity and commercial loss from different diseases. TEHON and STOUT (1930) found, for instance, that in Illinois, apple scab (Venturia inaequalis) regularly showed a higher intensity, i.e., percent of apples affected, than brown rot of stone fruits, yet the commercial loss in this case was much greater for brown rot. Tomato anthracnose (page 216) is another case in point.

We are only led into error if we conclude that because a disease is abundant a high loss necessarily results, or the reverse of this. Judgment or intuition cannot be trusted; we must learn from investigations the amounts of loss associated with given disease intensities. Such investigations fall into two major categories; statistical or historical methods may be used, as outlined in this chapter, or the experimental approach, described in the next two chapters, may be followed. As a general rule no one method is most generally useful; different methods are most suitable for appraising different diseases, and frequently a combination of several methods is preferable to any one of them.

With some types of disease, such as the virus diseases and Fusarium wilts, which are systemic, it is much easier to correlate disease intensity and loss than with diseases in which infection is local. Usually it is simpler to determine intensity-loss relationships with diseases than with animal pests, since disease intensity is expressed in terms related to plant reaction, while the intensity of insect or other animal attacks ordinarily must be expressed as pest population, i.e., the emphasis is often on the pest rather than on the host.

Less professional training is required to determine plant disease intensity than to translate this into losses. For this reason it is a common practice, as in the German and Russian plant disease survey organizations, for disease intensity data, collected by relatively untrained observers, to be forwarded to a central office for analysis and interpretation by specialists. However, in those cases in which the disease intensity-loss ratio has been worked out and found to be relatively constant, this ratio can be applied by the original observer to his disease intensity data, converting them to loss data.

USES AND LIMITATIONS OF THE STATISTICAL METHOD: -- By the "statistical method" as the term has been commonly used abroad, is meant the assembly and analysis of many individual reports of disease intensity or loss, with the assumption that errors in individual reports will be rendered non-significant by averaging a large volume of reports, which requires the further assumption that overestimates tend to balance underestimates. This is a basic principle in the collection and use of data by the Crop Reporting Service (page 272), which may be regarded as the most outstanding example of the statistical method in agriculture.

The origin of the statistical method in Germany traces back at least a century to SCHLEIDEN (1850) who recommended it to the exclusion of other plant pathological activities: "Instead of writing thick books or even little libraries on the nature and control of plant diseases, we would do better to assemble basic statistical data, to determine, by estimates, the average losses from diseases, so that we may avoid these losses by foresight" (l.c., pp. 474-475). SCHLEIDEN, who believed that plant diseases are inevitable and only result from cultivating crops in unnatural environments, considered that we must determine average losses and then avoid them, on a national scale, by planting a sufficient excess of acreage to compensate for the loss.

In 1909 the pioneer plant pathologist, SORAUER, took up the torch for the statistical method with the proposal that it be applied internationally in an effort to secure reliable data on the cereal rusts. The chief purpose was to analyze the effects of environment on rust development and destructiveness.

SORAUER'S data showed many conflicts, most of which he believed to be explainable; reports of heavy rust with no yield reduction were attributed to lateness of attack or crop varietal resistance. Despite his faith in the method, it led SORAUER to some conclusions which we now know are not valid, for example, the misconception that rust is favored by a reduction in the vitality of the host plant due to any unfavorable environmental factor.

RIEHM (1910) criticized or even ridiculed SORAUER'S statistical findings, without presenting logical reasoning for so doing, and disregarding the fact that a diseased crop of very high potential yield may still yield fairly well despite an important reduction from potential yield. In his rebuttal (in RIEHM, 1910) SORAUER defends the usefulness of his experimentation with pathological statistics. "It is only schoolboy quarreling about what 'statistics' means. I mean the significance of large majorities, and stand firm in my previous position that statistics can become a valuable means of obtaining information for phytopathology."

The statistical approach did become established and highly developed in Germany (MORSTATT, 1929; KLEMM, 1940. See also page 275). Its limitations have become recognized and its results have been interpreted with caution. It has been limited to a few, easily recognized pests and found useful for some purposes but not all. The principal limitation is inadequate training of lay cooperators, and a need for correcting this by more adequate instruction in the schools has been stressed by BÖNING (1936).

The basic weakness of the statistical approach is the assumption that inaccuracies in pest appraisal are reduced to insignificance provided that a sufficiently large collection of data, from many observers, is averaged. The history of science is replete with instances, from GALILEO down, in which large majorities of observers have entertained the same misconception, and that of plant pathology is no exception. The validity of average opinion does not necessarily increase as the size of the sample increases; the reverse may be true, since a popular opinion, whether true or false, becomes adopted by many uncritical or unobservant individuals merely because it is popular. The U. S. Crop Reporting Service is the world's most extensive application of the statistical method in the sense of SORAUER and RIEHM, and while its findings are highly accurate as respects easily observed or measured variants, such as acreages of given crops or crop yields, we have already seen (page 217) how inaccurate these mass opinions may be when they concern less readily observed quantities, the amounts of loss caused by plant diseases in particular.

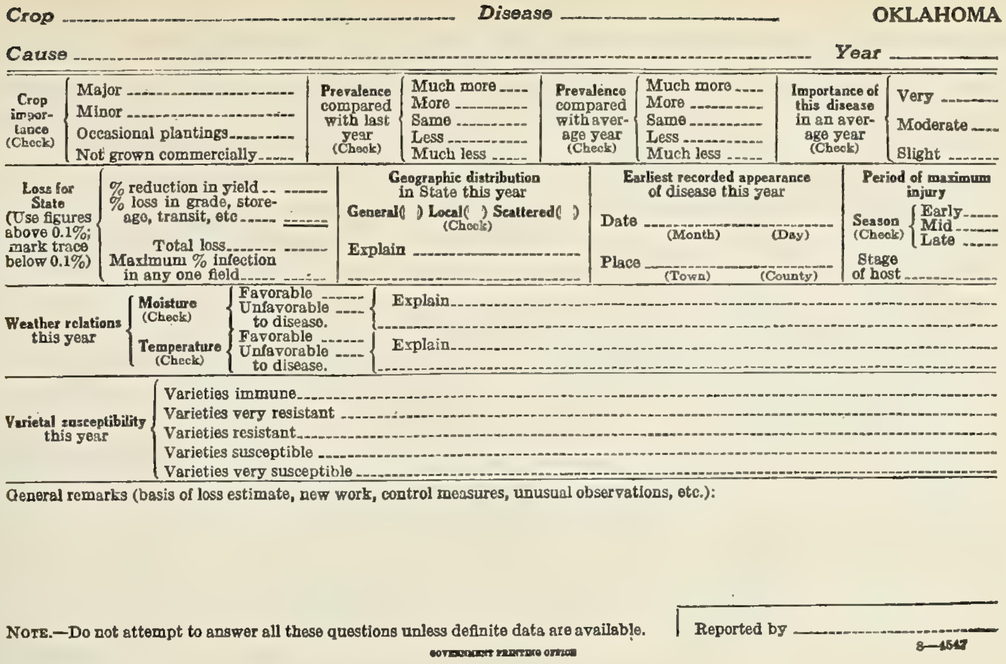
USES AND LIMITATIONS OF QUESTIONNAIRES: -- Plant disease surveying by the use of questionnaires goes back at least to 1804 when ARTHUR YOUNG, then Secretary to the Board of Agriculture in England, used a 12-query questionnaire to determine the relation of environment and cultural practices to cereal rust outbreaks. The data from 35 replies to YOUNG'S questionnaire are given by LITTLE (1883), who used the same method for the same purpose and reported the contents of 84 replies to his 30-query questionnaire.

ERIKSSON and HENNING (1896) have reviewed the history of the use of cereal rust questionnaires prior to that time and presented results of their own use of this method. The pioneering efforts in breeding wheat for rust resistance in Australia were preceded and aided by rust questionnaires sent to wheat growers throughout the province in 1890 and 1891. More recently MELCHERS and JOHNSTON (1939) in Kansas and CHESTER (1939) in Oklahoma used questionnaires in investigating the 1938 wheat leaf rust epiphytotic. CHESTER (1944) has briefly reviewed Russian uses of cereal rust questionnaires.

Also of historical interest is the circular of inquiry regarding losses from potato late blight, sent out to several thousand correspondents by the U. S. Department of Agriculture in 1885 and 1886, discussed by NEIL STEVENS (1934a). Later HARDENBERG (1922) used a long, detailed questionnaire in a survey to determine many factors in potato culture in New York, including diseases. Reference to questionnaire surveys of cotton diseases (EZEKIEL and DUNLAP, 1940), fruit diseases (Anon., 1899), and market disease losses (P. R. MILLER, 1935) serves to show the varied use that has been made of this method of gathering data on plant disease outbreaks and losses.

Disease and insect pest report cards, used commonly in annual plant disease and insect pest surveys, represent another aspect of the questionnaire method. The report card in standard use by the U. S. Plant Disease Survey for annual summary reports from collaborators is shown in Figure 19. Special report cards have also been used at one time or another for limited groups of plant diseases, such as the cereal rusts or market diseases. The report forms used by the British Mycological Society in its plant disease surveys are much simpler (W. C. MOORE, 1943), with spaces for data on location, date, disease, variety, crop, size of field, stage of development of plants, control measures, infection data, and remarks. Analogous report forms are used in the annual Insect Pest Survey. Questionnaires or report cards are the basic tool for surveying by the "statistical method" described in the preceding section.

The principal advantage of the questionnaire or report card is its economy, permitting the gathering of hundreds or thousands of reports from voluntary cooperators at little cost. Against this advantage are two principal limitations or weaknesses. First of these is the lack of training on the part of many correspondents, which may invalidate the data. Correspondents may identify diseases incorrectly, use misleading common names of diseases, overlook important features, or fail to appreciate the significance of pathological situations. In the second place, the returns from questionnaires are rarely random samples. The many individuals who fail to return questionnaires



Crop ____ *Disease* ____ OKLAHOMA

Cause ____ *Year* ____

Crop importance (Check): Major ____ Minor ____ Occasional plantings ____ Not grown commercially ____

Prevalence compared with last year (Check): Much more ____ More ____ Same ____ Less ____ Much less ____

Prevalence compared with average year (Check): Much more ____ More ____ Same ____ Less ____ Much less ____

Importance of this disease in an average year (Check): Very ____ Moderate ____ Slight ____

Loss for State (Use figures above 0.1%; mark trace below 0.1%): % reduction in yield ____ ____ % loss in grade, storage, transit, etc ____ ____ Total loss ____ ____ Maximum % infection in any one field ____ ____

Geographic distribution in State this year: **General**( ) **Local**( ) **Scattered**( ) (Check) Explain ____

Earliest recorded appearance of disease this year: Date ____ (Month) (Day) Place ____ (Town) (County)

Period of maximum injury: Season (Check): Early ____ Mid ____ Late ____ Stage of host ____

Weather relations this year: **Moisture** (Check): Favorable ____ Unfavorable ____ to disease. Explain ____

Temperature (Check): Favorable ____ Unfavorable ____ to disease. Explain ____

Varietal susceptibility this year:
Varieties immune ____
Varieties very resistant ____
Varieties resistant ____
Varieties susceptible ____
Varieties very susceptible ____

General remarks (basis of loss estimate, new work, control measures, unusual observations, etc.):

NOTE.—Do not attempt to answer all these questions unless definite data are available.

Reported by ____

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Figure 19. Report card used by the U. S. Plant Disease Survey. The reverse side of the card bears an outline county map of the State in question, for indicating locations of observations.

properly filled out are likely to be the less interested, less intelligent, less energetic, and less cooperative individuals; if these are farmers the same characteritics are likely to result in a high incidence of disease on their farms, because of neglect of disease-control measures. In this case the questionnaires returned would give a falsely low picture of average disease conditions.

The first of these limitations can be reduced, if not eliminated, by exclusive use of properly trained correspondents, or by educating untrained observers in survey methods and the use of simple, fully-explained or illustrated report forms. Wherever possible, disease should be recorded in quantitative terms, and this is aided by devices such as the cereal rust scale. The education of agriculturists in accurate disease and insect pest appraisal should form a part of the training in agricultural schools. Nonscientists who act as observers can also be advantageously taught the methods of crop inspection in special classes and short courses, aided in this by simple, well-illustrated publications, lantern slides, disease specimens, and supervised field observation. For such observers the questionnaire or report form should be limited to a small number of leading and easily recognized diseases.

There are also ways of overcoming the second limitation, the error due to failures in returning questionnaires. When dealing with lay observers the questionnaires or report forms should be simple, involving only a few, clearcut questions. The cooperators can be encouraged to return the forms by educating them as to the importance and practical value of surveys. Most effective of all is to follow the questionnaire by visits to those localities or individuals from which reports have not been received, a trained surveyor furnishing the missing data. This practice is basic in surveys using the Master Sample Plan (page 268). In other cases the questionnaire data are supplemented, verified, or corrected by a limited amount of field sampling, done by survey specialists.

The shortcomings of the use of questionnaires in general are those of the "statistical method", described above. Alone, the method gives some reliable information and some that is not valid. It is dangerous to depend too heavily on this survey technique alone; it needs to be controlled by some measure of direct observation by trained personnel. Yet, because of its economy and broad scope the questionnaire method is useful and desirable when the data are conservatively interpreted and when the method is supplemented by other more direct appraisal practices.

DATA FROM MARKETING CONTROL RECORDS: -- After agricultural produce leaves the farm it becomes subject to several types of governmental or commercial inspection, the records from which frequently contribute valuable information on the prevalence of plant diseases and the losses caused by them.

Grains for interstate or foreign shipment are inspected at terminal markets by the U. S. Department of Agriculture, with its Extension Division and Production and Marketing Administration cooperating. The results are published in annual mimeographed, unnumbered summaries issued by the Chicago office. Grain is graded according to the U. S. Handbook of Official Grain Standards which recognizes the following disease categories: light smutty wheat, smutty wheat, ergoty wheat, rye, and barley, damaged kernels in corn, and blighted barley, the latter two being caused by any of several organisms.

The grain inspector's reports must be interpreted in the light of the following facts. They include only grain intended for interstate or international shipping; much grain that is transported by truck and grain that is sold to local consumers or used on the farm is not included. It is common practice for growers or grain elevator operators to hold back for local use, or sell to truckers, grain that will not pass the federal grain inspection; the inspector does not see the worst of the crop. In the Oklahoma wheat bunt epiphytotic of 1948 it was estimated that nearly half of the smutty wheat did not pass through the inspector's hands. Furthermore, diseased grain is often cleaned to remove the diseased kernels and fungus sclerotia before it is inspected. The amount of disease shown by the inspection may only be a small fraction of that which was present in the field as has been clearly shown for wheat bunt by HASKELL and BOERNER (1931). Finally, the inspection records do not include the total losses in fields that are so heavily diseased that no crop is harvested or in which the harvested crop is discarded.

For all these reasons, the grain inspection records reveal losses that fall far short of the actual losses sustained. Yet, since they are objective, reliable, and uniform from year to year they have great value, for the few diseases recorded, as indexes of the variation in the annual amount of disease and loss. It is highly indicative of the annual variations in ergot (Claviceps purpurea) of rye, for example, to note that the percent of all carloads of rye in the U. S. which graded "ergoty" was 16.7 in 1942 and 19.1 in 1943, dropping to 9.5 in 1944 and down to only 1.5 in 1945 and 1946. The value of the federal grain inspector's record as an index of annual variations in disease is borne out by its agreement with the disease trends according to U. S. Plant Disease Survey estimates, as brought out previously (page 210 and Figs. 1 and 2).

There are several types of records of post-harvest losses in perishable produce. One of these is the record of claims paid by railroads for fruit and vegetable spoilage (SHEAR, 1918) which is obtainable from the American Railway Association (NEIL STEVENS, 1933). Another source is the data on market losses determined by the U. S. Food Inspection Service. A third is the records of condemnation of produce by the boards of health of leading cities (SHEAR, 1918). RAMSEY et.al. (1947) have called attention to the Chicago law of 1927 which prohibits the dumping of produce without good reason and they have tabulated the produce for which dumping certificates were issued during a number of years.

None of these records is complete. All undervalue the transit or market losses. Claims are not paid by railroads for all losses or partial losses, nor do all cases of spoilage come to the attention of market inspectors or city officials, particularly the great volume of loss that occurs in the home. At times when the demand for produce is great, damaged produce may still be sold, although it represents quantitative and qualitative loss to the consumer.

Cannery records of yields and of damage or rejection of produce have value in indicating relative losses (e.g., H. D. BROWN, 1929; M^c^NEW, 1943j) though they are usually incomplete. The cannery is a good base of operation for loss appraisal, since the surveyor can conveniently determine losses shown by lowered grade of the pack, and by the cull heaps of rejected produce at the cannery, while it is a central point from which the fields producing the crops for canning may be visited to determine the cull produce left at the field or loading point. Entomologists use a gin-trash machine for detecting small amounts of pink bollworm infestation in cotton, and analogous devices might be used in obtaining data on plant diseases. Few studies of this type have been made, but they can be very helpful in loss appraisal and are to be recommended for the future.

In a similar way the warehouse inspection of tobacco furnishes a good record of crop quality in this crop where lowered quality represents an important form of loss. Since the tobacco buyer is the effective judge of quality, the grading, by buyers, of experimental tobacco harvests in loss studies gives the investigator of loss a reliable and impartial measure of quality (M^{C}MURTREY, 1929).

Finally, the production, grading, and cull records of nurseries provide information on losses from such diseases as crown gall (FRACKER, 1918) and root knot. None of these sources of information in itself gives a complete picture of loss, but all are helpful in supplementing or confirming loss data from other sources.

COMPARISON OF YIELDS IN YEARS OF DIFFERENT DISEASE INTENSITY: -- Other factors being equal, the difference between yields in a disease year and in a disease-free year would be a good measure of loss, but, unfortunately, other factors are never equal. Yet we cannot discount this as a source contributing to the total picture of loss, though not decisive in itself.

We can distinguish two types of cases: (a) those in which weather is the primary factor governing the intensity of disease, and (b) those in which the presence or absence of disease is determined primarily by controllable practices, such as spraying, seed treatment, or the use of disease-resistant varieties. It is with the former case that we are chiefly concerned at this point; the latter case is dealt with in later sections on the "historical method" (page 284) and on experimental methods in which disease in a constant environment is permitted or controlled by cultural practices.

Even when acreages, soils, crop varieties, and tillage methods remain relatively constant, crop yields vary greatly from one year to another, this variation being largely due to the interrelated effects of weather and pests. It is difficult to unravel the weather-pest complex and attribute to each factor its proper share in determining yields, yet as our knowledge advances helpful guide lines develop. We know, for example, that the occurrence of certain diseases (cereal rusts, potato late blight) is correlated with weather that is favorable for growth of the crops in question. In such cases a lowered yield during a year of severe disease is a minimal expression of loss due to the disease. In an opposite class fall those diseases which are favored by weather that is unsuitable for the best growth of the crop (many root rots). Here a lowered yield during a year of serious disease must be attributed in small or large part to the direct effect of the weather on the crop; to ascribe it to disease alone would exaggerate the loss due to disease itself.

When disease is catastrophic, obviously wiping out a large fraction of the crop, (e.g., watermelon anthracnose, peach brown rot, cereal stem rust, during certain years) it so overweighs other yield factors that the loss in yield, compared with a disease-free season, can be reliably attributed to the disease. With less spectacular diseases the problem is more difficult.

Finally, the error in this method, that is greatest when one compares only two contrasting seasons, progressively diminishes as the study is extended to include a longer series of seasons, in which the direct effects of weather on crop growth may become cancelled out statistically, increasing the reliability of disease-yield relationships.

This method as applied to cereal rusts has been discussed by NAUMOV (1939) and CHESTER (1944). Historically it was one of the first methods used in estimating rust losses (ERIKSSON and HENNING, 1896) and it is still the basis of the German practice of loss appraisal, relating yield fluctuations to pest fluctuations over a minimum of 10 years (KLEMM, 1940). The method has been used with cereal rusts in America by J. H. MILLER (1935) and WALDRON (1936) and in Russia by BRIZGALOVA (1935).

As examples of this method applied to other types of diseases, we have the loss from powdery mildew of cantaloupe in California determined by comparing yields in years of light and heavy infestation by P. A. MILLER and BARRETT (1931), a similar study of the loss in sugar beets caused by damping-off, reported by MORRIS and AFANASIEV (1945), and a very detailed investigation by CROWTHER (1941) in which the correlations between the effects of weather, soil, and disease (black arm and leaf curl) on cotton yields were determined by comparing these factors during 13 years of observations.

COMPARISON OF ANTICIPATED WITH ACTUAL YIELDS: -- Yields of crops, when the harvest is in, are often but shadows of the bountiful crops anticipated by growers and crop scouts one or several months before harvest. Hail, drought, hot winds, floods, freezes, insect enemies, and diseases -- any or several of these may have had their part in disappointing expectations.

As illustrated in the following example, a comparison of expected with actual yields, making due allowance for the various factors that have depressed the yields, is a means, although a very subjective one, of estimating the relationship between disease and crop loss. In 1921, a year of severe wheat leaf rust in Indiana, GREGORY (in MAINS, 1923) compared the wheat harvest anticipated in May with the actual yield in August, and dividing the difference among the several factors producing reduction in yield, placed the State loss due to leaf rust in the neighborhood of 10%, which agreed with independent estimates of the Soils and Crops Department and the Botany Department.

Since time immemorial this has been the method of farmers in accounting for crop losses. Without an adequate background of understanding of the nature and relative importance of loss factors it may be inaccurate and misleading in the highest degree; the most recent, unusual, or most obvious deleterious factor is usually accused of all or nearly all of the destruction, and less obvious or less well-known factors may not enter into the account at all.

In 1938, in Oklahoma, severe wheat leaf rust was forecast by the writer on April 7, and this developed as predicted. That year preharvest yield expectations ran as high as 77 million bushels.

The actual yield was 59 million. In 1948, the April 1 forecast was for very little rust, and it proved to be the year of lightest rust on record. The official May 1 yield expectation was for 75 million bushels but actually 98 million were harvested. In both years the great discrepancy between estimated and actual yield was "explained" in terms of a wide variety of factors with practically no consideration of rust, which we now know from controlled experiments caused 30% loss in the Oklahoma crop in 1938 and causes 5 to 10% loss in an average year.

In interpreting such data as these it would be unsound reasoning to disregard all of the other seasonal influences on yield, and conclude that the decrease from preharvest estimates in 1938 and the increase in 1948 were attributable exclusively or largely to rust. But is it equally unsound, knowing the effect of rust on yield, to disregard or minimize the role of rust during these years. It would seem that we have, in such figures as these, a clear indication of the magnitude of rust losses. It is not conclusive proof and it does not give us a reliable numerical expression of rust damage, but it is circumstantial evidence that is valuable in confirming loss estimates derived by other, more objective methods.

COMPARISON OF WEATHER RECORDS AND CROP PRICES IN PAST YEARS: -- BARCLAY (1892) in India attempted to determine rust damage in early years by comparing the price of wheat in given years with the record of meteorological conditions known to be conducive to rust. While there were some inconsistencies, there was evidence of a correlation between high prices, poor yields, and weather favoring rust (high humidity in January-March).

The limitations in this method are obvious: prices are regulated by many factors other than crop yields and by many yield factors other than rust; furthermore, our knowledge of the environmental conditions necessarily associated with rust is far from adequate to lead us to the conclusion that a certain year must have been a "rust year" because of its weather. Despite these shortcomings, such a procedure as BARCLAY'S is not entirely without value, as it does provide an inkling, even though it is a very conditional one, of epiphytotics of years long past.

DETERMINATION OF DISEASE IN PAST YEARS FROM EXHIBITION SAMPLES, ETC.: -- Exhibition samples, straw and other plant materials used for packing, and other types of crop residues frequently give useful clues to the occurrence of disease in past years. RUSAKOV (1929d) was able to determine the severity of rust and its presumptive destructiveness in earlier years, for which no field records were available, by examination of sheaves that had been preserved for exhibition purposes. The writer also found an interesting clue to the destructiveness of crown rust (Puccinia coronata) of oats many years past in the abundance of telial pustules present on the straw of a beehive that had been constructed from local materials to illustrate straw hives used in Europe. The student of plant disease appraisal will be rewarded by giving attention to such unusual sources of information.

THE HISTORICAL METHOD: -- By this term we refer to a comparison of yields before and after some fundamental change has occurred in the culture or environment of a crop, markedly affecting its pathology, e.g., the widespread adoption of an effective control measure, or the general and destructive invasion of a crop by a formerly unknown or unimportant disease.

Possibly the best documented case of the historical method is that of decline and recovery of the cane sugar industry in Louisiana, illustrated in Figure 20. Here we see the fall in sugar yield per acre from more than 20 tons to little over 10, as red rot, root rot, and mosaic successively attacked the crop, followed by recovery with introduction of disease-resistant cane varieties, a temporary setback when certain of these became disease-susceptible, and recovery again when more highly resistant varieties were introduced. During the decline, sugar production in Louisiana dropped from 400,000 tons to about 50,000 tons per year. RANDS and DOPP (1938), making liberal allowance for other loss factors, have made it clear that it was primarily this sequence of diseases that resulted in a total loss to the Louisiana sugar industry estimated at $150,000,000. Sugar cane in Brazil passed through a similar cycle (ARRUDA, 1941); between 1923 and 1925 the mosaic disease was associated with a 58% yield decline, and the introduction of mosaic-resistant cane varieties raised production from 477,000 tons in 1925 to 1,965,000 tons in 1932.

The decline of the cane sugar industry has been described by SUMMERS et. al. (1948) in the following words: "In Louisiana toward the end of that period (1916-26) yields of sugarcane had dropped to such pitifully low levels that the banks refused to risk further financing of what they regarded as a permanently collapsed industry. In Brazil a large prize was announced by a State government for the individual who could devise a 'cure' for sugar-cane mosaic, and the temper of the people most concerned in the drama everywhere could be likened to those whose means of subsistence had been snuffed out in a stock market crash with, unfortunately, the same quota of suicides."

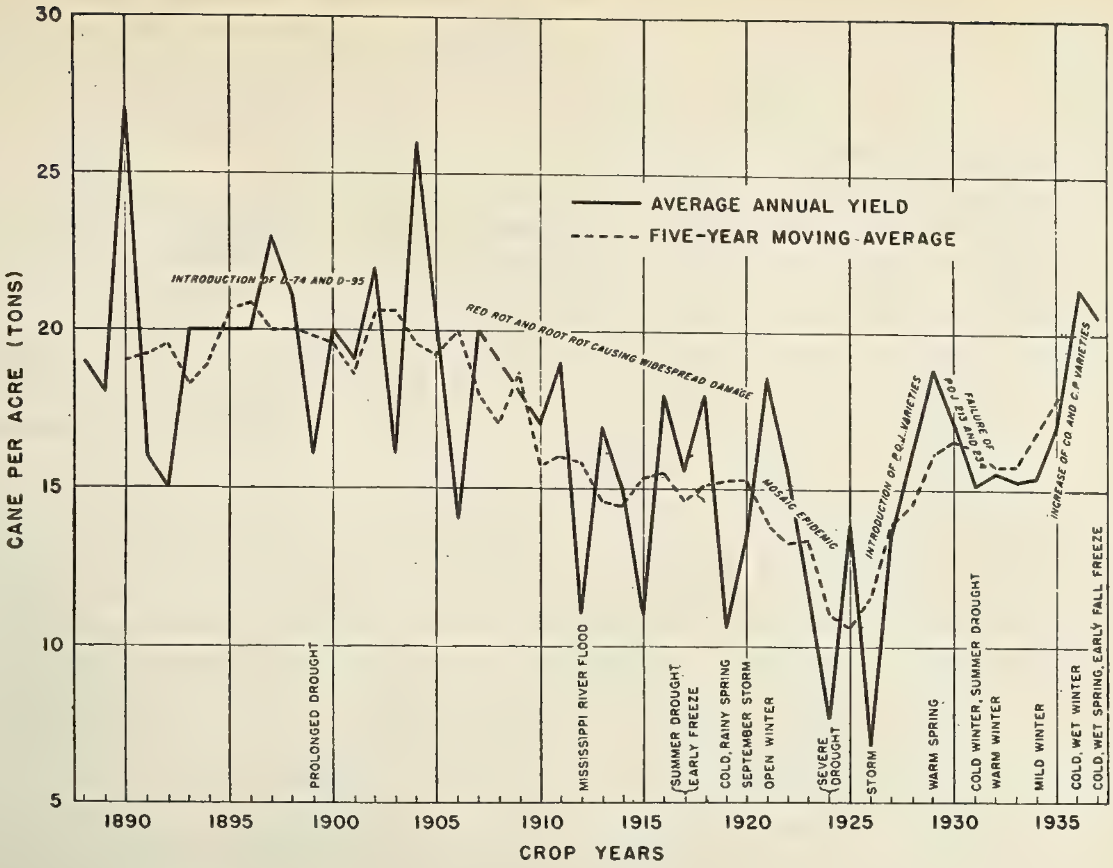

Figure 20. Decline and recovery of sugar cane yields with associated causes. (After RANDS and DOPP, 1938.)

The beet sugar industry in the Pacific Northwest passed through a comparable cycle, owing to the ravages of the curly top disease and its control by disease-resistant beet varieties (CARSNER, 1944). In 1934, 88% of the beet acreage in the Twin Falls, Idaho, area was abandoned, and the harvested acreage yielded only 4.88 tons per acre, whereas in the preceding year, when curly top was not severe, the average yield was 13.78 tons. With the introduction of resistant beet varieties yields rose to former high levels, abandoned factories were reopened, and an industry that had practically failed was reborn. In this case the disease was so pronounced in its effect that other yield factors played negligible parts in the cycle.

Hops culture in Germany passed through a similar cycle (RAGL, 1944). In 1926 downy mildew caused a loss of 30 million marks in Bavaria, the hops yield having dropped from a 1918-26 average of 720 kg. per hectare to 320 kg. At this time 6000 spray rigs were put into operation, raising average production during 1927-35 to 1440 kg.

Important acreage decreases associated with disease outbreaks have occurred in a number of other crops. During 15 years there was a 50% drop in alfalfa production in Kansas, with bacterial wilt the chief factor involved (SALMON, 1930). A 90,000 ton decrease in Utah alfalfa production was conclusively shown to be principally due to the same disease (Anon., 1938). When the California strawberry crop became attacked by yellows (virus) and the growers were forced to turn to poorer but resistant varieties, the yield dropped, during 10 years, from 120,000 to 80,000 chests per year (NEIL STEVENS, 1934b). A half century ago, when the yellows virus became a limiting factor in peach orchards, the number of peach trees in a Michigan county dropped from 654,000 to 43,000 and in a Virginia county from 130,000 to 30,000 trees (M. T. COOK, 1947).

NAUMOV (1939), who developed the concept of the historical approach in studying crop losses from diseases, selected an unfortunate example, the decline in losses from wheat stem rust in North America in the years prior to 1935, which he associated with barberry eradication. The rust epiphytotics of 1935, 1937, and 1938 do not support this explanation, but CRAIGIE'S (1944) data on Canadian wheat yields before and after the introduction of rust-resistant wheat varieties are more convincing. Here rust control has been associated with an annual yield increase of 41,339,000 bushels, valued at $27,242,000. Other spectacular yield changes associated with disease or its control include the reduction to about half of the previous barley yield in Nebraska, primarily due to root rots (LIVINGSTON, 1947), a drop in the Javan potato production from 63,000 tons in 1935 to 40,000 tons in 1940 which "can only be explained as being due to losses caused by Phytophthora attack" (THUNG, 1947), and a decrease, due to bacterial wilt (Pseudomonas solanacearum), in the tobacco crop of the South Atlantic States which between 1935 and 1945 amounted to a 10,000,000 lb. loss annually, and nearly wiped out the flue-cured tobacco industry of this region before it was restored by the wilt-resistant Oxford varieties. (T. E. SMITH, CLAYTON, and MOSS, 1945).

In another connection (page 339) further instances are given of the abandonment of crop culture due to devastating disease attacks. When these are on a sufficiently broad and permanent scale they represent other illustrations of the historical method. A case of the reverse sort is that of cereal culture in the Central Blacklands of Texas. Here, in the past, it has been considered impractical to attempt culture of wheat, oats, or barley. Doubtless this conviction traced back to early, unsuccessful attempts to grow these crops, due to leaf rusts and other diseases. In any event, the introduction of the disease-resistant Austin wheat, Ranger, Rustler, and Verde oats, and Tunis barley are extending small grain production into vast new regions of fertile soils and abundant rainfall.

From these illustrations it is clear that the student of plant disease losses can profit by making use of the historical method. It is too broad to give an accurate measure of acre losses under specified conditions, but it does furnish convincing testimony of the order of magnitude of some plant diseases. It shows that they can be destructive enough to wipe out industries and alter crop geography, and that their control can revive stricken agricultural enterprises and give birth to new ones. In addition, the historical method strikingly extends loss appraisal to involve great agricultural areas, confirming small-scale, precise loss measurement data by depicting them on a broad scale against a dramatic background of human failures and successes.

VOLUME OF PUBLICATION AS A MEASURE OF DISEASE IMPORTANCE: -- In 1939, NEIL STEVENS made the novel proposal that we can secure a comparative picture of the economic importance of diseases of various crops by use of the "disease index", which is calculated by dividing the number of pages of technical publications devoted to diseases of each crop by the value of the crop in millions of dollars. The disease indexes are given for the following crops: fruits, 30+; potatoes, 20+; flax, 14.2; rice, 4.9; barley, 3.5; wheat, 3.4; sorghum, 2.3; oats, 1.8; rye, 1.5; corn, 0.8; buckwheat, 0.0. By the same process it would be possible to determine the disease indexes of individual diseases of any given crop, using a standard, extensive bibliography, such as the Agricultural Index, as the source of data.

Unfortunately this method, however reliable it may have been for STEVENS' purposes, can be very misleading when dealing with individual plant diseases; it is not so much an index of the true relative importance of diseases as it is an index of the relative importance of diseases in the opinions of pathologists and administrators, -- a very different thing. A spectacular disease or one that is easy to work with or one that has scientific attractiveness tends to be overemphasized in the volume of publication, while other truly important diseases are neglected in the literature. A particularly active group of research workers, concentrating on diseases that are important locally but not generally, will contribute a disproportionate volume of printed matter.

Many examples of such misemphasis come to mind. There is the huge volume of literature on crown gall (Agrobacterium tumefaciens), stemming from the challenging nature of this disease and its possible relation to human cancer, which is entirely out of proportion to the economic importance of the disease. Because of the intensive work of Texas and Arizona scientists, cotton root rot, which is only locally important considering the cotton belt as a whole, is represented by a greater volume of publication than the more universal and destructive bacterial blight and Fusarium wilt diseases of cotton. Brown rot of stone fruits is probably much more destructive than the stone fruit virus diseases, yet it is poorly represented in the literature in comparison with these. The same may be said for soft rot (Erwinia carotovora) as compared with other diseases of vegetables. The volume of publication on bunt of wheat and that on the wheat root rots are in reverse order to the economic importance of these diseases. Finally, the great scientific importance of tobacco mosaic has resulted in a volume of publication that is quite out of line with the rank of this disease as an economic factor.

Although the volume of publication sometimes is a poor index of what diseases are doing, it is a very good index of what scientists are doing. This is brought out in a second paper by NEIL STEVENS (1940b) in which he uses a survey of papers abstracted in the Review of Applied Mycology between 1922 and 1938 to shed light on the amount and nature of work being done on disease control.

The writer made a similar study of the space in Phytopathology devoted to the several aspects of plant disease research, the results of which are shown in Figure 21. This is based on a paragraph-by-paragraph tabulation of the new data in the 1914, 1924, 1934, and 1944 volumes,

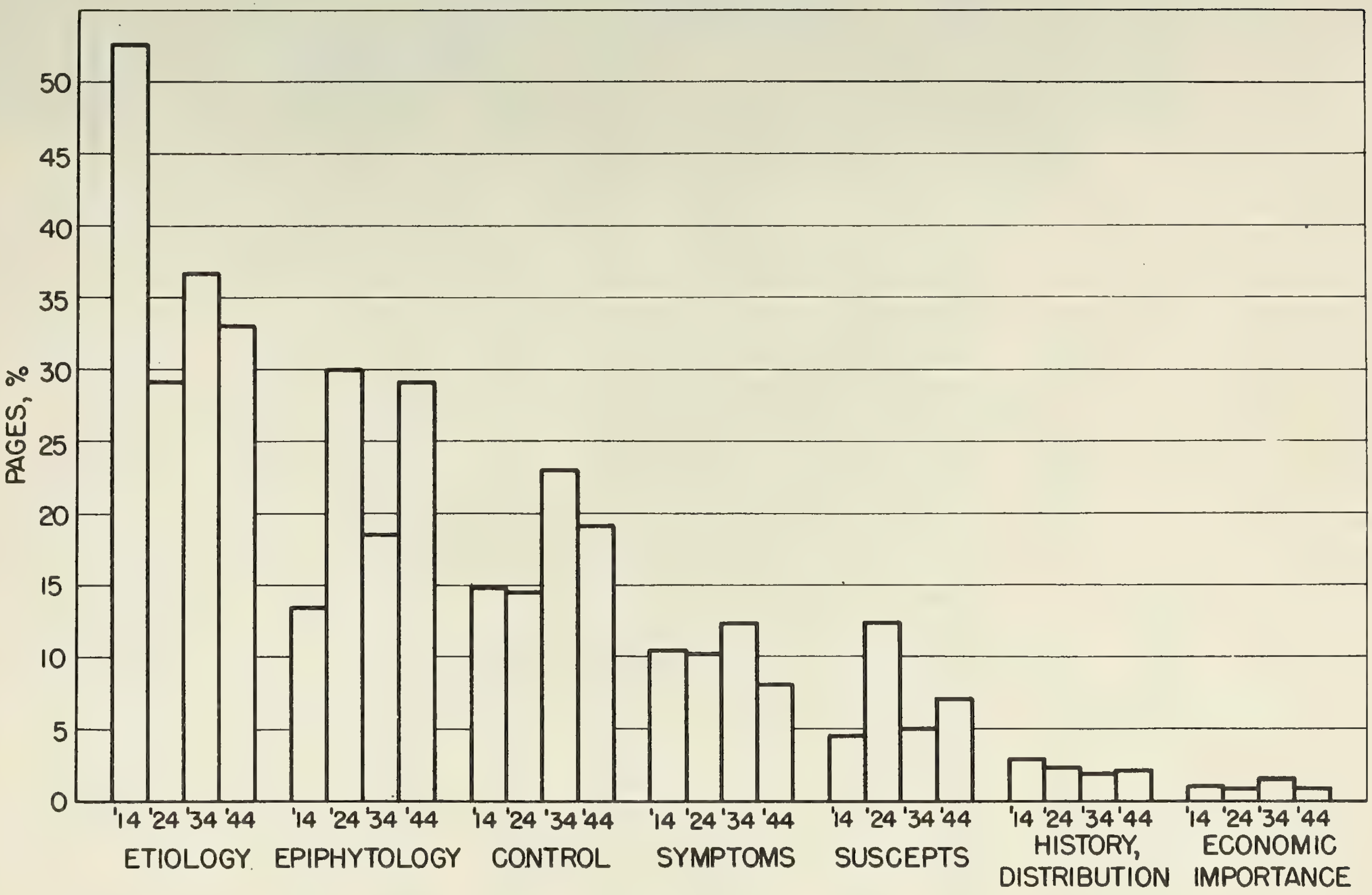

Figure 21. Percentage of pages of new data in "Phytopathology" devoted to indicated subjects in 1914, 1924, 1934, and 1944.

omitting introductory material, summaries, biographies, announcements, book reviews, abstracts, photographs, and necrologies.

There are a number of interesting conclusions that might be drawn from these data, chief of which, from the present point of view, is the almost insignificant emphasis on the economic importance of plant diseases, compared with the great emphasis on etiology. Actually only 21.6% of the papers had anything at all to say about economic importance, and in these papers the space devoted to this subject averaged only 1/3 page. The average amount of space devoted to economic importance, considering all papers, was 3 lines. In many cases, in otherwise significant papers, the economic importance of the disease worked with was dismissed with a single adjective.

The space devoted to economic importance was further subdivided into (a) general statements and (b) measurements of disease loss. Very nearly all of the space fell into the first class, but there was a healthy indication of shift from generalizations to accurate measurements of loss in 1944 as compared with earlier years.

The fair degree of uniformity of the four bars above each rubric in the figure indicates that the sample was an adequate one for its purpose. It is assumed that the journal, Phytopathology, itself is a fair sample of American plant disease publication, since it is the official organ of the science in this country.

If the sample is valid, the data reveal a deplorable indifference to the economic importance of plant diseases, the main justification for the existence of their science, on the part of plant disease scientists, an indifference which, it is hoped, may in time be overcome.

NON-PROFESSIONAL PUBLICATIONS AS SOURCES OF LOSS DATA: -- While many scientists may be loath to accept as scientific evidence data from newspapers, popular magazines, or other lay publications, there are times when such data, if not conclusive in themselves, support and confirm data from more orthodox sources. NEIL STEVENS (1945) has emphasized that while they must be handled with caution, poor records are better than none.

An excellent example of this is found in another of his papers (1944). From a study of the pH of water of cranberry bogs in the Berlin, Wisconsin, area, STEVENS came to the conclusion that a decline of this culture was associated with increasing alkalinity of flooding waters. While this conclusion was reached by direct experimental evidence of several sorts, it was confirmed by a search through files of the local newspaper and study of all articles relating to cranberry culture in early years. The first canal bringing alkaline water to the bogs was dug in 1873, and the newspaper articles gave clear indications of the good crops preceding, but not following, the use of the new source of water. They reported the large number of pickers employed in 1872 in the particular bogs in question, and the number of barrels of cranberries picked, and even confirmed this by reporting the numbers of pickers voting in a straw vote in the presidential campaign of Grant and Greeley.

McCALLAN'S INDEX OF DISEASE IMPORTANCE: -- McCALLAN (1946) expressed the importance of each of 36 leading diseases by an index which is the product of the logarithm of the farm value of the crop multiplied by the logarithm of the estimated percentage of crop loss due to disease, taken from the annual loss estimates in the Plant Disease Reporter. When McCALLAN compared the present status of use of fungicides, by crop and disease, with these indices of disease importance, with consideration of the possibility of fungicidal control of the disease in each case, he was able to designate certain outstanding diseases for which better fungicides are needed.

The use of logarithms is helpful in this procedure, since it avoids the obvious error of considering that losses of equal dollar amount are equally important, regardless of the national value of the crop. It would be unreasonable, he points out, to consider .5% loss in a $1,500,000,000 wheat crop as equal in importance to the total loss of a $7,000,000 cranberry crop or 50% loss of a $15,000,000 cantaloupe crop.

McCALLAN'S index is tentative and has its limitations, as he recognized. It is based on the loss estimates of the Plant Disease Reporter which have sometimes been widely in error. These estimates are considered to be of losses after existing control measures have been used, but in many cases a high estimated loss may be due more to failure to have applied known effective control measures, in which case education, rather than the development of new fungicides, is indicated. Nevertheless, McCALLAN'S index is a very reasonable approach to the problem of determining the relative importance of plant diseases.

DISEASE-CONTROL EXPENDITURES AS A MEASURE OF DISEASE IMPORTANCE: -- It would appear that the amount of money spent in controlling a plant disease is an index of importance, making the usually valid assumption that the losses, were the disease uncontrolled, would exceed the cost of control. The validity of this assumption has been questioned by WHETZEL and others in connection with the expenditures for barberry eradication to control cereal stem rust and with those for various plant quarantines.

In some cases these amounts are very substantial. Between 1916 and 1944 the Federal government spent $40,000,000 for investigating, scouting, and control of pine blister rust. Eradication of citrus canker (Pseudomonas citri) cost the government $13,000,000 between 1915 and 1944, to which must be added the value of 19,000,000 citrus trees that had to be destroyed. The government has spent $21,000,000 on the Dutch elm disease (M^C^CUBBIN, 1946). Expenditure for forest insect and disease control for the decade 1936-45 amounted to $58,000,000 (WYCKOFF, HARTLEY, and ORR, 1947). In addition there have been substantial control costs to the State governments, as Pennsylvania's $25,000 per year for the past 25 years in quarantine and eradication of the potato wart disease (Synchytrium endobioticum).

To these costs must be added the direct expense of control to growers. While it is difficult to determine this for individual diseases, the total amounts of disease-control chemicals annually sold in the United States give us an over-all index of the magnitude of disease-control expense, which we can assume is less than the cost of diseases when not controlled, since growers are careful to keep their expense of production below production income. As examples of the cost of fungicides alone, exclusive of the equipment and labor for applying them, we find that there are annually sold in the United States for disease prevention 150,000,000 lbs. of sulfur, 100,000,000 lbs. of copper sulfate, and, for preventing wood decay, 200,000,000 gal. of creosote and 5,000,000 lbs. of the zinc chlorides.

An even more serious fault in attempting to determine loss from control expenditures is the great inequality between the amounts spent on different diseases of similar importance. By far the greatest expenditures are on diseases that are controlled by government-supported quarantine and eradication programs, and for some of these the loss is not so much present as potential. Next in order of expenditures come those diseases which are controlled by chemical means. Control-cost figures give no index of the importance of diseases that may be very destructive but because of their nature or their lack of appeal to public interests have not yet been the subject of major expenditures.

In thinking of this aspect of loss appraisal one has the impression that the cart is before the horse. We are entertaining the assumption that because much money is being spent on a disease, that disease necessarily is quite important, while logic indicates that it should be the other way around, that expenditure for disease control should follow and conform to prior determination of the hazard.

Disease control expenditures do not give us comparative information on the destructiveness of different diseases. Of two diseases of equal importance one may be combatted in a program involving many millions of dollars while the other, for various reasons, is not the subject of any substantial financial outlay. But disease control expenditures are an absolute, if not a relative, measure of disease importance, for, in general, we can conclude that a disease is a major economic factor when large amounts of money continue to be spent in fighting it, although the converse of this is not true.

THE NEED FOR LITERATURE SEARCHES; THE INDEXING PROBLEM: -- In preparation for writing this book a search was made through all volumes of such periodicals as Phytopathology and the Review of Applied Mycology in an attempt to locate papers and data bearing on the several aspects of plant disease appraisal. The key words used in going through the indexes of these journals were: appraisal, crop losses, crop yields, damage, disease, estimation, insurance, intensity, losses, measurement, methods, plant diseases....., reduction, techniques, and yields. Few useful references were found by this method, and it soon became apparent that the general lack of attention to the economic aspects of plant disease is also expressed in a failure adequately to index this phase of plant pathology.

As a result it has been necessary, in this study, to depend on locating pertinent references by memory, chance, and systematically leafing through many irrelevant articles to secure the references needed. For this reason no pretense to complete coverage of the literature on disease appraisal can be made.

Considering the importance of the whole subject of disease appraisal it would be most helpful to future work if those charged with the indexing of plant disease journals would give attention to indexing the economic aspects with the same thoroughness with which the etiological aspects are indexed.

As can be seen from the bibliography at the end of this work, many references that are relevant to disease appraisal are found in journals that are not primarily devoted to plant pathology, including the literature of agronomy, horticulture, agricultural economics, entomology, and crop insurance. This has further complicated the problem of adequate coverage of the literature and has determined the present approach to the subject, which is intended to be illustrative rather than comprehensive.

Chapter VIII

EXPERIMENTAL METHODS FOR DETERMINING DISEASE INTENSITY-LOSS RELATIONSHIPS

There are many experimental methods that may be used in determining the effects of disease on plant yields, all of which are variations of three basic approaches: (a) producing disease or the simulation of disease and comparison of such plants with healthy control plants, (b) preventing disease and comparison with naturally infected control plants, and (c) finding diseased and healthy plants and comparing their yields. The choice of method depends to considerable extent on the nature of the disease. There is no one "best" method; each has its advantages and disadvantages. Often more than one method is used, in order to obtain confirmatory results by different techniques and to rule out the limitations of any one method.

Loss appraisal experiments have much in common with agronomic or horticultural yield tests, and the principles governing the work are similar. Both are quantitative procedures and are commonly conducted using similar planting and treatment designs, with statistical analysis of the results. It is well known in agronomic work that if a vigorous crop variety is planted adjacent to a less vigorous one, an exaggerated yield difference will be obtained, due to competition, the less vigorous plants being suppressed by the more vigorous ones. This effect is eliminated by various devices, such as triple-row planting of each crop variety with harvesting of the middle row for yield measurement. The same principle applies to loss measurement, since with adjacent diseased and healthy rows the former will be suppressed by the latter, exaggerating the loss from disease.

GREENHOUSE INFECTION EXPERIMENTS: -- This method consists essentially in infecting certain plants with disease under greenhouse conditions, leaving others uninfected or protecting them from infection, and comparing yields. Discussions of the use, advantages, and disadvantages of the greenhouse method are found in the works of NAUMOV (1939) and CHESTER (1944).

There are numerous advantages to the greenhouse method as compared with field methods of disease loss appraisal. In the greenhouse, loss determinations can be made under known, controlled conditions of light, air humidity, and soil moisture. The soil composition can be held uniform. The experiments can be protected from natural hazards which commonly interfere with field experiments, such as other diseases than the one under study, insect pests, rodents, birds, and unfavorable weather. In the greenhouse, attention can be focused on single elements of disease complexes, making it possible to analyze the role of each individual factor in the complex. Or, if desired, it is possible in the greenhouse to use definite combinations of factors, of controlled composition, as GREANEY and MACHACEK (1935) did in studying the effects of the foot rot fungus, Helminthosporium sativum, on wheat growth, with and without the presence of the harmless soil fungus Cephalothecium roseum.

Greenhouse work also gives the investigator much better control over the conditions of infection than he has in field experiments. He can use pure lines or individual physiologic races of pathogens in contrast to the mixed populations of pathogens in the field. He can inoculate plants at any desired developmental stage and produce any desired intensity of infection, or, as is preferable, he can produce a graded series of times and degrees of infection. Finally, there are some problems in loss appraisal which can be done most suitably or exclusively in the greenhouse, such as the measurement of losses in crops that are normally grown under glass, the study of the effects of noxious gases on plants, or the measurement of losses caused by diseases that are not yet widespread in nature, when it is unsafe to liberate them through field experiments.

Against these advantages must be listed the disadvantages of the greenhouse method. For crops that are normally grown in the field the greenhouse is a very abnormal environment. The outdoor conditions of light, moisture, wind, slope, exposure, and fluctuations of weather have no counterpart in the greenhouse, and as a result the field-grown plant is quite different (e.g., in the strength of its fibro-vascular system), the populations of disease organisms and hazard complexes differ, and, as a result, the course of disease, its tempo, is quite different in the field.

From these considerations one might expect that disease intensity-loss relationships will be different in greenhouse and field tests, and one might justifiably ask whether it is valid to use greenhouse data as a basis for estimating field losses.

A number of investigators have compared the results of greenhouse and field loss measurement tests. In some cases substantial disagreement has been found. PETURSON and NEWTON (1939) have pointed out that field experiments on cereal rusts often show a greater loss than greenhouse tests, because in the field rust damage is aggravated by water shortage, which does not affect greenhouse plants. GASSNER and STRAIB (1936) consider the opposite true, that greenhouse experiments indicate more loss than actually occurs in the field. In a comparison of different methods for appraising loss from wheat leaf rust, the writer (CHESTER, 1946b, Fig. 2) found no material difference in the disease-loss relationships as determined by greenhouse and field methods. H. C. MURPHY (1935) also obtained similar determinations of loss from crown rust of oats in greenhouse and field experiments.

The study of the effect of leaf rust on wheat by MAINS (1930) is a good illustration of the use of this method. Numerous others have used it in studying cereal rust losses, including BEVER (1937), JOHNSTON (1931), PAL (1936), and RUSAKOV (1929c). The greenhouse method has been used in studying losses from tomato virus diseases by HEUBERGER and NORTON (1933), JONES and BURNETT (1935), and NORTON (1914), with downy mildew of onions by YARWOOD (1943), and in determining the effects of SO_2 fumes on barley and alfalfa by KATZ and LEDINGHAM (1939).

In using the greenhouse infection method any of the standard inoculation techniques are used: spraying or dusting plants with inoculum or applying it with a spatula, infesting the soil, or transmitting viruses by insects or mechanical means. The healthy control plants are uninoculated, and, if the disease is one that spreads naturally under greenhouse conditions, it may be necessary to protect them with fungicides or other means. Because of the uniform greenhouse environment, reliable results can be obtained with fewer plants in the greenhouse than in the field.

In summary, it appears that the greenhouse infection method is one of the more useful and reliable methods of determining disease intensity-loss relationships. Although its results frequently agree with those secured by field methods, this is not always the case, which indicates the desirability of supplementing greenhouse experiments with field tests in many instances. The greenhouse method has particular advantage in analyzing the loss from hazard complexes, and in some cases, such as the study of losses from crops normally grown in the greenhouse or of atmospheric injuries, it is the best method available.

FIELD PLOT OR BED INFECTION EXPERIMENTS: -- In using this method, disease is introduced into plants that are growing under normal cultural conditions, and the yields from the diseased plants are compared with those from comparable plots of uninoculated, healthy plants.

The chief advantage of the method lies in the normal growing conditions under which the experiment is conducted. The disadvantages are the converse of the factors listed as advantages of the greenhouse method, i.e., lack of control of numerous environmental and pathological factors. Outstanding among these is the natural occurrence of disease in the plots intended as healthy controls. Disease produced in the field by artificial inoculation is not always comparable to natural outbreaks. If the season is unfavorable for the disease the inoculation may only result in a short-lived, atypical attack.

There are several ways of dealing with these disadvantages. Disease may be prevented in the healthy control plots by treating these with fungicides, as was done by M. NEWTON et al. (1945) in studying the loss from barley rust. GASSNER and STRAIB (1936), who consider this the best of all methods of loss determination for cereal rusts, recommend having the inoculated plots widely separated from and on the leeward side of the healthy ones, with a neutral crop between, to prevent the disease from spreading to the healthy plots. This practice has the disadvantage of difficulty in having the two in strictly uniform environments.

In field tests of this sort it may not be possible to control the time, degree, and tempo of disease attack and, therefore, to study intermediate situations between two extremes. This is not always a limitation, however.

Virus diseases, for example, are of the "all or nothing" type, and here the time of infection is the important variable. This can easily be controlled and varied in field infection experiments, and tests of this sort have been used to advantage in investigating the losses caused by tobacco mosaic (McMURTREY, 1928, 1929; WOLF and MOSS, 1933; E. M. JOHNSON and VALLEAU, 1941) and tomato mosaic (HEUBERGER and NORTON, 1933).

In field infection tests, standard pathological and field experimental methods are employed. An approved plot design is generally used, to permit statistical analysis of the results. Inoculation of the plants is by any standard method, such as spraying or dusting the plots with bacteria or spores, introducing inoculum into the soil (root rot and wilt diseases), infecting plants before transplanting in the field (tomato and sweetpotato wilt), setting out infected plants at intervals in the plot to serve as sources of natural disease spread (cereal rusts), or inoculating individual plants by mechanical means (tobacco mosaic).

The study of GREANEY and MACHACEK (1934) on losses from cereal root rots is a good example of the method of field inoculation, illustrating the use of replicated plots, several techniques of soil infestation, and a well-devised system of grading disease intensity and correlating this with yields.

Besides the several studies referred to above, the field infection method has proven useful in investigating losses from sugar cane root rot (EDGERTON et al., 1937), tomato root knot nematodes (FICHT, 1939), flax rust (FLOR, 1941), potato virus diseases (FOLSOM, 1927; K. M. SMITH and MARKHAM, 1945), and sugar beet yellows (WATSON et al., 1946).

FIELD OR GREENHOUSE PLANTINGS WITH INOCULATED SEED: -- This method differs from the preceding two only in the fact that disease is produced by inoculating seed prior to planting, rather than inoculating the growing plants. It has found greatest usefulness with those diseases that are typically or exclusively seedborne.

The seed inoculation method has been successfully used in studying losses from bunt of wheat by FLOR et al. (1932), LEUKEL (1937), and KIESSELBACH and LYNESS (1939). The seed have been inoculated by dusting them with smut spores, and yields from plants produced by such seed have been compared with those from healthy plants. Different degrees of disease are obtained by varying the dosage of spores or by mixing inoculated seed with clean seed in different proportions. A similar procedure was followed by SEMENIUK and ROSS (1942) in their study of losses from loose smut in barley.

PLANTINGS FROM SELECTED DISEASED AND HEALTHY PROPAGATION MATERIALS: -- This method differs from the last only in the fact that the seed or parts used in vegetative propagation are not inoculated but are selected for presence or absence of disease. The method has been so extensively used in the study of losses from potato virus diseases that these are considered separately.

Potato Virus Diseases. -- The basic principle of this method with potato virus diseases is simplicity itself: to plant selected virus-diseased tubers and virus-free tubers and compare yields. Some 45 papers devoted to this subject have been consulted and these reveal a great variation in the details of conducting tests based on this principle.

To begin with, there have been various ways of selecting the diseased and healthy seed tubers. Most primitive, yet in a sense most convincing in demonstrating to growers the value of virus-free seed potatoes, is simply to take a random sample of tubers from a field that is heavily infested with virus diseases and a sample of high quality seed tubers, e.g., certified seed, and compare yields from plantings of the two. Here the "healthy" seed will contain some virus-infected tubers and the "diseased" seed may contain some relatively healthy tubers. Yet it is with such seed lots that the grower is practically concerned and the loss revealed to him by such a test more nearly expresses the virus hazard than comparison with the homogeneous diseased and healthy seed lots that are scientifically more desirable.

A similar purpose has been served by determining yields, year after year, of potatoes grown from stocks that have been rogued each year to remove virus infected plants as compared with yields from unrogued stocks. Here the "diseased" seedstocks are not 100% infected nor are the "healthy" stocks 100% healthy, but the situation is a practical one.

In much of the early work in measuring the losses from virus diseases in potatoes, the plants to furnish the seed tubers, both diseased and healthy, were selected in the field, the diseased plants having occurred naturally or having resulted from deliberate planting of diseased stock for this or other purposes.

This procedure brings the condition of the seedstocks under somewhat better control, since each parent plant producing the seed tubers has been inspected. It is not all that can be desired, however, for some plants that are rated "healthy" will usually be in early stages of infection, and the tubers from such apparently healthy plants produce diseased plants in the experiment the following year. Also, even a well-trained inspector sometime has difficulty in correctly classifying potato plants according to virus infection, especially when two or more viruses are present in the field. The "diseased" seed tubers, in this case, may not be homogeneous.

A more reliable technique is to plant relatively or absolutely disease-free tubers and inoculate some of the healthy plants produced with pure cultures of known viruses, leaving others uninoculated, and roguing out any plants showing natural infection. The tubers from the inoculated and uninoculated plants are harvested separately and used for planting the yield-loss experiment the following season.

A further refinement of the technique is to eye-index each tuber to be used in the loss test, as in the experiments of GARDNER and KENDRICK (1924, 1928). An eye from each tuber is planted in the greenhouse in sufficient time before the field planting to permit the experimenter to inspect the plant developing from the eye and determine virus infection. Each eye is identified with the tuber from which it was taken, and only those tubers with eyes that produce plants of the desired condition with respect to virus infection are used in the field experiment.

During recent years it has become apparent that practically all potatoes of numerous commercial varieties harbor the X-virus, latent mosaic virus, or "healthy potato virus", and that this virus, without producing noticeable symptoms, subtly reduces yields by 10% or more. This implies that in virtually all but recent studies the loss comparisons have not been between healthy plants and those with a single virus disease, but between plants with X-virus and plants with a second virus plus X-virus (K. M. SMITH and MARKHAM, 1945).

Two methods of avoiding this source of error and obtaining truly healthy plants have been used. E. S. SCHULTZ has developed a strain of potato that is immune from the X-virus, seedling 41956, and has used this strain (SCHULTZ and BONDE, 1944), with and without infection with other viruses, to determine the yield-depressing effects of the latter. BALD (1944) has solved the problem by developing and maintaining clones of potatoes free from the X-virus (FX), and using these in his tests. CLINCH and McKAY (1947) verified the condition of freedom from the X-virus in their similar clones by inoculating juice from each plant into *Datura* seedlings, in which the X-virus causes easily observed symptoms, though these are lacking in potato.

When a virus-infected tuber is planted, the plant that develops is subject to the effects of the virus throughout its entire life, in contrast to the healthy plant that becomes infected at some time during the growing season. It naturally follows that the loss produced by the virus is greater in the former case than in the latter, particularly if infection in the field occurs late in the growing season. In practice we are concerned with losses from both types of infection. The method of setting up experiments to measure the losses differs, in the first case consisting in planting infected tubers, which has been done in most of the work on potato virus losses, while the second case involves field inoculation experiments.

As brought out on page 229, the amount of loss varies with the strain of virus used, and the methods of measuring loss from potato viruses include consideration of this point, as is seen in the work of SCOTT (1941), BALD (1943*b*), E. S. SHCULTZ and BONDE (1944), and CLINCH and McKAY (1947).

In the early work on potato virus losses, the experiments were commonly on a small scale, involving comparisons of a few dozen hills and without replications (*e.g.*, FOLSOM, 1920). A field design, if used, was usually a simple matter of planting adjacent rows with diseased and healthy tubers respectively (WHIPPLE, 1919; T. WHITEHEAD, 1924). Later, as the importance of analysis of experiments to determine statistical significance became recognized, the potato virus loss measurements have been based on replicated plantings in approved designs, as illustrated in the papers of BALD (1943*b*) and LECLERG *et al.* (1944).

Since, in actual practice, we do not deal with comparisons between totally diseased and totally healthy stands, but rather with varying percentages of diseased plants distributed at random among healthy ones, a number of the students of potato virus losses have designed their experiments with this point in mind. The percentage of diseased seed pieces was predetermined by mixing healthy and diseased ones in different proportions to produce a series of disease percents ranging between 0 and 100% in the experiments of BONDE and E. S. SCHULTZ (1940) and of LECLERG *et al.* (1944, 1946). Experiments set up in this fashion show that loss is not directly proportionate to disease percent, since healthy plants adjacent to diseased ones compensate for the loss in the diseased plants to some extent.

In deliberate efforts to avoid the phenomenon of compensation, P. A. YOUNG and MORRIS (1930) planted diseased and healthy tubers in alternating groups of four similar consecutive pieces, widely spaced to diminish the compensation effect, while McKAY and DYKSTRA (1932) accomplished the same end by planting in the same fashion at normal spacing, but harvesting, for yield measurement, only the center two hills of each group of four.

In complete contrast with this arrangement, KIRKPATRICK and BLODGETT (1943) planted diseased and healthy tubers in all possible arrangements of three consecutive hills in an effort to study the effect of compensation on virus losses. This is a more realistic approach to the problem, since compensation is a major factor affecting losses under normal field conditions. A more detailed account of this work, with citation of related papers, is given in the discussion of compensation on page 320.

Numerous other difficulties have beset the path of the student of losses from potato virus diseases, most of which have been overcome. A common shortcoming in the earlier studies has been the indefiniteness with which viruses have been identified, the term "mosaic", for example, referring to any of several diseases. This has been largely cleared up through the work of E. S. SCHULTZ and others.

Besides the X-virus, discussed above, other mild or symptomless viruses have sometimes affected the plants thought to be healthy, leading to incorrectly low loss measurements. This source of error is gradually lessening by use of virus-immune stocks, seedling stocks that have been protected from all viruses, indexed stocks, and better methods of virus identification.

A number of investigators have been unable to secure totally healthy stocks to compare with diseased ones and the comparisons have been between stocks with small and large percentages of disease. One way of dealing with this problem is to determine the yields of potato stocks with various amounts of virus disease, derive a formula for regression of yield on disease percent, and extrapolate to the 0% and 100% levels. Such a practice is illustrated in the work of KIRKPATRICK and BLODGETT (1943).

A constant problem in this type of study is the fact that potatoes tend to be infected with not one but several viruses simultaneously. This is desirable, in loss studies, in cases in which a definite mixture of viruses constitutes what, for practical purposes, is a single pathological condition or loss factor. This is true, for example, of rugose mosaic (X + Y viruses) or mild mosaic (X + A viruses). The problem appears, however, when the planting becomes a miscellaneous mixture of viruses, due to natural infections or use of uncontrolled seed stocks. This has been a fault in a number of the earlier studies, but is less so in more recent ones, in which practices mentioned previously have served to keep the stocks homogeneous.

Since potatoes are vegetatively propagated, they exist as clones. Their virus diseases being transmitted regularly through vegetative propagation, any two clones tend to differ from each other in two respects: (a) in their virus content and (b) genetically. If the yield of a clone that is generally infected with a given virus is compared with the yield of another clone that is relatively virus-free, the difference in yield may be influenced both by the difference in virus content and by genetic differences in the clones. This may introduce an error into loss determinations that can be avoided by using tubers of a single clone divided into two aliquots, one of which is infected with a given virus by inoculating the plants producing the infected tubers.

Potatoes are affected with certain troubles resembling viruses but apparently due to genetic defects, such as some forms of "giant hill" and "wilding". The foregoing remarks on determining losses from virus diseases in general apply to these genetic troubles, which are tuber-borne in the same fashion as viruses.

Other Diseases. -- The method of planting selected diseased propagation materials for comparison with healthy plants has also been used effectively in studying losses from other typically seedborne diseases, including loose smut of wheat (COMPTON and CALDWELL, 1946), barley stripe (SUNESON, 1946), sugar cane mosaic (EDGERTON et al., 1937), sugar beet mosaic (GASKILL, 1940), and potato scab and Rhizoctonia (COONS, 1918).

In the case of barley stripe, diseased and healthy seed were obtained from field plots some of which had been inoculated with the disease the previous year. With potato it was a simple matter of separating the diseased from the healthy tubers and planting under comparable conditions. Since beets for seed purposes are grown as biennial crops, the method here is to select diseased and healthy plants toward the close of the first season and plant these separately to compare seed yields in the second season. The case of sugar cane mosaic is very similar to that of potato viruses as already discussed.

COMPARISON OF YIELDS OF ROGUED AND UNROGUED PLANTINGS: -- Roguing, or removal of diseased plants, was mentioned as an adjunct to the method of selecting diseased and healthy progagation materials. We are concerned here with current-season roguing where this is the principal means of securing diseased and disease-free plots for comparison.

In studying losses from potato virus diseases, roguing the previous season to secure virus-free seed stocks has frequently been practiced, but only one reference has been found to current-season roguing for this purpose. This is in a paper by E. S. SCHULTZ and FOLSOM (1923), who planted strains of potatoes carrying given percentages of mild mosaic, rogued out the mosaic plants from a part of each planting. and then compared yields from the rogued and unrogued portions. Here a serious error is introduced by compensation in plants adjacent to the rogued-out hills, unless a similar spacing is used in the diseased plots.

The measurement of losses from bean mosaic, as studied by WALKER and JOLIVETTE (1943) consisted in planting commercial lots of bean seed and roguing out the diseased plants to secure healthy plots for comparison with diseased ones.

With the same disease, HORSFALL (in HARRISON, 1935) has carried this technique a step farther by using a practice which we may designate reverse roguing, one that is very effective in dealing with plantings in which 50% of the plants, more or less, are diseased. The partially diseased plantings are divided into multiples of two similar subplots. In one of each pair of subplots the diseased plants are rogued out and in the other the healthy plants are removed, an attempt being made to secure uniform stands of diseased and healthy plants respectively.

This technique has particular value when an excessive seeding rate is used and the roguing and additional thinning leave the diseased and healthy plantings with similar stands of a desired degree of uniform spacing.

This appears to be an ideal method of studying the effects of non-fatal damping-off on subsequent development and yields of plants, and has been so used, with good results, by STEVENSON (1947) in measuring losses from seedling diseases of castor beans.

THE CULTURAL METHOD: -- This involves a comparison of yields of relatively diseased and healthy crops, the disease occurring naturally, with the degrees of disease being due to differences in cultural conditions, such as different methods of soil management. Studies by this method are subject to serious error due to the fact that the cultural differences have direct effects on yield levels in addition to their indirect effects in increasing or decreasing disease. Yet in some cases this source of error can be minimized, and in any case data obtained by this method are useful in confirming the results of more accurate experimental procedures.

With different types of disease the error due to the direct effect of fertilizers on yield varies considerably. Working with the response of common root rot of wheat to phosphate fertilization, RUSSELL and SALLANS (1940) in a number of cases obtained significant or highly significant correlations between increasing disease and decreasing yield. The phosphate by itself increased yields to an extent great enough to offset the increase in disease associated with the fertilization. With the takeall root rot of wheat, fertilization increased the yield more than enough to offset the effects of the disease in the experiments of DOUGHTY et al. (1939). Complete fertilizer greatly reduced the amount of seedling disease and increased the yields of sugar beets, according to MORRIS and AFANSIEV (1945) but it is not evident to what extent the fertilizer alone was responsible for the increase in yields.

CHESTER (1946a) made an analysis of the loss caused by Fusarium wilt of cotton in relation to fertilization, based on the extensive data of V. H. YOUNG and his associates. This showed that when the disease was aggravated by soil deficiency, especially of potassium, the yield reduction was approximately twice that due to wilt alone, up to 25% wilt, while at higher wilt percentages most of the loss could be attributed to wilt alone. In this case the role of soil deficiency in reducing yields was determined approximately by subtracting the effect of disease alone from the effect of disease and soil deficiency combined. In case the disease data are from experiments in which loss is due to disease and soil deficiency combined, it should be possible to determine the effect of disease alone, in an approximate fashion, by subtracting the loss due to soil deficiency, acting alone in the absence of disease, from the loss due to deficiency and disease combined. This would be one way to rule out the error due to the direct effect of soil treatment, although no study using this method has come to hand.

A second method of escaping the error due to cultural treatment would be to assemble a sufficiently large quantity of data, based on a variety of treatments, to permit deriving the correlation between disease and loss regardless of treatment. This would be valid only if there was not a strong unilateral relation between treatment and disease intensity.

A similar approach has been based on the production of different amounts of disease by various cropping systems. Here there is also the danger that the cropping system itself has a strong direct effect on yield, but this is likely to be less than in the case of fertilizer experiments, since a major influence of crop rotations is on the disease, diminishing the inoculum potential of the soil, rather than directly on the plant and its yields.

AFANASIEV and MORRIS (1943) studied the amount of seedling disease and the yields in sugar beets grown in a variety of crop rotations, and their data show a fairly good regression of decreasing yield on increasing disease when all rotations are combined. Similar findings for cotton root rot have been reported by DUNLAP et al. (1940). Both investigations reveal the value of this method of appraising loss due to soilborne diseases. HOLBERT et al. (1919) have extended the use of the method to losses from wheat scab.

Finally, the cultural practice associated with different levels of dryland foot rot of wheat was date of planting in the work of ROBERTSON et al. (1942). Their study brings out strikingly the limitation of the cultural method except as an adjunct to other techniques of loss determination. It showed that with plantings up to September 15, in Colorado, planting data influenced yield due to its effect on disease, while in later plantings the seeding date influenced yield independently of disease.

THE INDIVIDUAL METHOD: -- This procedure consists in selecting from a planting a given number of diseased plants and a like number of healthy plants, and comparing yields.

The method has certain advantages. It may be applied in any non-experimental planting where any ratio of healthy and diseased plants may be found. This gives the method particular value when the observer has not laid out experiments for measuring loss, but accidentally encounters a planting containing disease, in which it appears desirable to know the amount of loss. There is also an advantage in using this method to measure losses from diseases which cannot readily be produced experimentally under conditions resembling natural occurrence, such as corn smut or Texas root rot, and diseases which require many years to develop to the stage in which the observer is interested, as in wood decays or long-standing cases of virus disease in trees. This is a basic method in forest disease appraisal.

Even when a disease can be produced experimentally, the selection of individual plants with different stages or conditions of disease may give the observer a greater variety of categories of disease from natural occurrence than would result from the more uniform conditions of an infection experiment. Advantage has been taken of this fact in using the individual method to study loss in relation to duration of infection (virus yellows of cherry), relative position of healthy and diseased plants in the row (potato viruses), and type, position, and developmental stage of lesions (corn smut).

This method is indicated when the object is to make a thorough and time-consuming analysis that must be limited, for practical reasons, to very few plants, in which case the individuals to be analyzed are selected with great care, as in the experiments of STONE (1936) on the growth, chemical composition, and efficiency of normal and mosaic-diseased potato plants.

Instead of comparing whole plants, their organs may be compared by the individual method. An example is found in the study of losses from pigeon pea anthracnose by TUCKER (1927) in which healthy and diseased pods were sorted out, shelled, and the yields of marketable peas compared.

When healthy and diseased plants occur spontaneously the occurrence of diseased plants (a) may be due to chance or factors quite unrelated to yield, or (b) may be associated with genetic or environmental factors which themselves influence yield while determining the occurrence of disease at the same time. As examples, the question of which trees in an otherwise uniform orchard become virus-infected and which ones remain healthy is largely or entirely a matter of chance, in which the disease is the only yield factor distinguishing the affected trees, as a group, from the healthy ones. On the other hand, certain root and foliage diseases tend to be concentrated in low spots in the field because of the higher soil moisture and poorer air drainage in such spots. If the yields of diseased plants in the low spots are compared with those of healthy plants on higher ground, yield differences will not be due to disease alone, but also to the direct effects on yield of the distinct soil, moisture, and aeration conditions in the low areas, contrasted with the higher ones. Similarly, one plant may be diseased and another healthy because they differ genetically. But if there is a difference in genetic constitution, shown in a difference in disease susceptibility, there also may be genetic difference in yielding ability in the absence of disease, and a difference in yield will then be due, not to disease alone, but to disease and inherent yielding ability combined. It follows that the individual method will be most useful and reliable in appraising diseases in which infection differences are due principally to chance and not to differences in environment or genetic constitution of the plants.

In using the individual method it is common to compare healthy plants surrounded by diseased ones with diseased plants surrounded by healthy ones. This is just the opposite of infection experiments in which a deliberate effort is usually made to compare yields of plants surrounded by others of the same pathological condition. An objection to the individual method has been raised by FOLSOM (1927) who pointed out that the effect of a disease on yield is exaggerated when a diseased plant is grown in competition with healthy ones. This is true, yet it represents a natural situation; in nature, except in cases of 100% infestation, diseased plants normally are in competition with healthy ones, and loss so measured corresponds most closely to the loss actually experienced in practice. It is often desirable, however, to measure absolute loss under conditions of freedom from competition with healthy plants. It follows that there are uses and values in both types of tests, and that the individual method is not objectionable because it is used to measure loss under conditions of natural competition, but on the contrary its value is enhanced by this fact. Special studies on disease and compensation, using the individual method, are discussed in connection with compensation on page 320.

The individual method has found use in determining the losses caused by virus diseases of potato, cowpea, soybean, sugar cane, stone fruits, and citrus, cereal root rots and rusts, Texas root rot in cotton, Fusarium wilt of potato, and corn smut.

The latter case deserves particular mention since in dealing with corn smut we find the individual method highly developed and almost exclusively used. The basic practice is to select healthy and naturally smutted corn stalks and compare yields. To secure most comparable results it is customary to select the plants by pairs, the diseased and healthy member of each pair being in the same hill, adjacent plants one foot apart, or up to three hills apart, in the practice of different workers. The smutted stalks have usually been subdivided into classes depending on the position, size, and number of smut boils per stalk.

The same principle of using paired diseased and healthy plants extends to other types of disease, as in studies of losses from cereal root rots and of virus yellows of cherry. The use of paired plants is an attempt to secure diseased and healthy individuals that are fully comparable except for the condition of disease. Sometimes a conscious effort is made to select plants that appear to the observer to be comparable. KOTILA (1923) mentions his effort to secure mosaic diseased and healthy potato plants with the same number of stems and of equal vigor. This is a questionable practice; it is highly subjective, since the observer usually does not know the extent to which the disease has made the plants non-comparable, i. e., has reduced the number of stems or decreased the vigor of the plants. A safer procedure would be to select the healthy plants to compare with diseased ones by some arbitrary formula, as was done in most of the corn smut studies, although one must not disregard the necessity for selecting plants that are comparable in respects that are quite independent of the disease (plants in similar soil, trees of similar age, etc.).

For convenience it is a common practice to indicate selected plants by stakes, at the time when the disease is best apparent, to aid in locating them at harvest time.

The study of loss from common root rot of wheat made by SALLANS and LEDINGHAM (1943) is a good example of use of the individual method. A series of paired diseased and healthy samples, each consisting of a square yard area with the two members of the pair not more than 4 to 5 feet apart, were used for disease appraisal and yield measurement. Disease was scored according to lesions on the crown and subcrown internodes, and the yield data included both gross yield and kernel weight.

THE TOPOGRAPHICAL METHOD: -- This is a variant of the individual method in which the samples, instead of being single plants or very small plant groups, are more extensive populations differing in disease intensity because of environmental factors associated with differences in terrain or because of differences in exposure to disease inoculum, although comparable in other respects, such as variety, time of sowing, and cultural practices.

Studies by this method are particularly subject to the criticism that variations in terrain bring about differences in yields quite apart from the effects of disease. The method has been used in Russia (NAUMOV, 1939) in studies of cereal rusts, where it is felt that the method is promising but needs more methodological study.

A special case is that in which the amount of disease is not due to configurations of the land but to distance from a source of infection, conditioned by exposure to wind-blown inoculum. This method was used by RUSAKOV (1926) in studying losses from crown rust of oats, where the differences in disease were associated with distance from a protective forest strip and bushes of the rust's alternate host, the buckthorn.

COMPARISON OF FIELDS WITH DIFFERENT AMOUNTS OF NATURAL INFECTION: -- This is an extension of the individual method, comparing fields rather than individual plants in a single field. As with the individual method, different amounts of disease in different fields result from variations in soil, exposure, and microclimate, and, in this case, also from differences in crop variety, cultural practices, and macroclimate. Here, too, the method is most valuable with those diseases which occur by chance or are not unilaterally associated with ecological factors that in themselves strongly affect yield.

This extensive method lacks the accuracy of more intensive ones, but its reliability may be strengthened by several means. One is the use of so many fields that their differences, other than disease, tend to cancel out one another, leaving the disease statistically as the most important yield factor. Using this method, HORSFALL (1930) examined 195 fields of meadow crops in 35 counties, WIANT and STARR (1936) studied 125 fields of alfalfa, and WALKER and HARE'S (1943) survey for pea diseases involved 654 fields, many of them being examined twice.

A second method of increasing accuracy, which is just the opposite of the first, was used by EZEKIEL and TAUBENHAUS (1931, 1932, 1934) who made a 12-year study of yields from two adjacent cotton fields, one of which was infested with Texas root rot, but which were otherwise very similar and comparable.

The general procedure in studies of this kind is to classify each field according to disease intensity, secure a record of the yields actually obtained, and determine the regression of yield on disease intensity.

MACHACEK'S (1943) determination of the loss from wheat root rot in Manitoba is a good illustration of this method, with the only variation that instead of taking acre yields for entire wheat fields his yield measurements as well as disease intensity records were based on samples of one meter of row taken at harvest time. The three-year study involved 60 fields, 10 in each of six soil type zones, with 10 samples per field. From the data obtained it is possible to plot a regression showing that for every increment of 10% of root rot there was approximately 3% crop loss.

The lack of accuracy in this method is compensated for in considerable degree by its extensive nature, giving the observer a picture of loss over a broad area instead of in a few experimental plots. The method has value in numerous cases and particularly in confirming and extending the results of more intensive studies.

COMPARISON OF YIELDS OF DISEASE-RESISTANT AND -SUSCEPTIBLE CROP VARIETIES: -- On first consideration an excellent method of determining loss from disease would appear to be a comparison of yields of varieties that are resistant to the disease with yields of susceptible varieties and expressing the difference in yield as percent of crop loss from the disease. Reference has already been made to this approach in connection with the historical method of determining loss from disease (p. 284), where it was seen that the introduction of disease-resistant varieties of certain crops, such as wheat, sugar beets, and sugar cane, so improved the yields by reducing the loss from disease that the economics of growing the crop was radically altered.

This method may involve comparisons between yields of resistant and susceptible varieties in small, uniform, replicated plots, or it may deal with large acreages or even great regions, or the two may be combined as in CRAIGIE'S (1944) analysis of wheat losses from stem rust in western Canada. If small plots are used there is the advantage that the work in loss determination may be carried on at the same time and using the same materials as routine variety tests, such as are conducted at every agricultural experiment station. In these tests it is customary to plant assortments of resistant and susceptible varieties under conditions that favor accurate yield determinations, which are regularly taken. For the additional purpose of loss determination it is a simple matter to appraise the disease intensities on these varieties and to analyze the yield data in relation to disease intensity.

The most serious source of error in this type of test lies in the fact that different varieties of any crop tend to differ in innate yielding ability in the absence of disease. If, in the presence of disease, a resistant variety outyields a susceptible one, the yield difference due to disease alone is increased or decreased by the inherent difference in yielding ability. Quite a number of the crop varieties recommended for disease resistance are inferior to the older, susceptible varieties in innate yielding ability, as is commonly seen in cases in which the susceptible variety outyields the resistant one unless disease is present, when the reverse occurs. A good example is Ladak alfalfa, which yields more than the common varieties only in the presence of the bacterial wilt disease. In such a case the disease loss determined from the difference in yield of resistant and susceptible varieties would be underestimated. There are also cases of the opposite sort, that would lead to overestimates of loss. When a disease is catastrophic in character, however, as with sugar beet curly top, Granville wilt of tobacco, or powdery mildew of cucumbers, the loss from the disease so overshadows all other yield factors that the difference in yield between resistant and susceptible varieties approximates the true loss caused by the disease.

Fortunately there are several good methods of minimizing the error due to other yield factors in tests of this sort. These methods are described in the following subsections. Another source of error is less easy to overcome; namely, the fact that resistant varieties usually are not wholly immune from the effects of disease, but suffer some loss, as has been well brought out for wheat leaf rust by MAINS (1930). This has the effect of lowering the observed loss from disease below its true level. When totally resistant varieties are not available, perhaps the best way of dealing with this source of error is to measure the small amount of disease loss in resistant varieties by comparing their yields in the presence and absence of disease, and then use the findings to correct the loss values derived from comparing yields of these resistant varieties with yields of susceptible ones, in the presence of disease.

Correction For Other Yield Factors By Use Of Large Numbers Of Varieties. -- In using variety test data for determining the effect of disease on yield, the error due to other yield factors than disease reaction in the varieties may sometimes be eliminated by using a large number of varieties, with the assumption that there is no constant correlation between disease reaction and some other factor of importance in influencing yields. This assumption is not always warranted; in the case of corn smut, for example, in many varieties there is a correlation between smut resistance and low vigor. In such a case little difference might be seen between the yields of smut-free but less vigorous varieties and smutted but more vigorous ones. Yet in some instances this appears to be a valid approach to the problem of determining loss from disease.

An illustration of this procedure is seen in the work of GOULDEN and ELDERS (1926), who compared 146 wheat varieties, found a negative correlation between yield and attack by leaf and stem rusts, and were able to express this relationship by regressions showing the loss in yield due to increments of rust from 4.5% to 94.5%. The work was somewhat handicapped by the fact that the two rusts occurred together on the same plants. SALMON and LAUDE (1932) worked out a similar problem in the same manner, using 25 wheat varieties that differed in reactions to leaf rust and speckled leaf blotch. When the wheat varieties were arranged in descending order of yield, they were found to be in ascending order of disease, and this was particularly true when the two diseases were combined into a single infection index.

CHESTER (1946a) has analyzed a large body of data on cotton wilt and yields, amassed by V. H. YOUNG and his associates. In this case other yield factors than wilt reaction evidently cancelled out one another when many varieties were classified by wilt percent, so that the latter showed a well-fitting linear relationship with yield, each 5% of wilt resulting in a 3% yield reduction (l. c., Fig. 1).

Correction For Other Yield Factors By Using Varieties That Are Similar In Other Respects Than Disease Reaction. -- Loss due to a disease may be reliably determined if we compare the yields of two varieties that differ, for practical purposes, only in reaction to the disease. This was the procedure followed by WALDRON (1928) in comparing yields, under conditions of rust exposure, of the susceptible variety Marquis and the comparable but resistant variety 1656.85. Various rust intensities on Marquis wheat were obtained in different localities, and the regression of yield on rust was approximately a straight line, from which it was possible to calculate the approximate loss from rust in each of four regions of North Dakota, and for the State as a whole.

Correction For Other Yield Factors By Comparing Varieties In the Presence And Absence Of Disease. -- If varieties that are resistant and susceptible to a disease have equal yields in the absence of disease but unequal yields, in favor of the resistant variety, on exposure to disease, this inequality may be taken as a measure of the loss caused by the disease.

Somewhat more subject to error, but nevertheless to be considered as of some value, is to use resistant and susceptible varieties that differ in yielding ability to a given, constant degree, under disease-free conditions, comparing their yields when exposed to disease. If, for example, variety X regularly outyields resistant variety Y by 10% when the two are not exposed to disease, while variety Y outyields X when the latter is diseased, we may regard the difference in yields, corrected for the inherent difference in yielding capacity, as a measure of loss caused by the disease.

This procedure is subject to the theoretical objection that the equality or difference in yielding ability under disease-free conditions may not exist under the particular environment that favors disease. To illustrate, a resistant and a susceptible variety might yield equally well under the dry conditions that inhibit a certain disease, yet one of these, let us say the disease-susceptible one, might differ from the resistant one in being able to make more efficient use of abundant moisture. When the two are exposed to disease, the yield of the susceptible variety, relative to the resistant one, is subject to two contrary influences: decrease because of the disease and increase because of greater efficiency in water utilization. It could even happen that the two influences would offset each other, in which case the resistant and susceptible varieties would yield equally well whether or not disease was present, and one would be led to the false conclusion, from this procedure alone, that the disease has no yield-depressing effect.

This theoretical objection could be validated or rejected by the simple expedient of using a chemical method of disease control under the conditions favoring disease, to determine whether and to what extent there actually may be a difference in relative behavior, reflected in yields, of the two varieties under the two environments, one favoring and the other inhibiting the disease.

Two examples of the use of this method may be cited. WELLHAUSEN (1942) reported that the leaf blight resistant corn, Hybrid 939, which outyielded the very susceptible Ohio W-17 by 2.5 bu. per acre during five years of minor disease, also outyielded the Ohio W-17 by 2.5 bu. per acre during a year of severe leaf blight (Helminthosporium), which was interpreted as indicating that this disease has little effect in lowering yields. In contrast, H. C. MURPHY and BURNETT (1943) compared the average yields of three oats varieties that were resistant to crown rust with those of three susceptible varieties; the resistant varieties outyielded the susceptible ones by 7 to 10% during three years when there was little or no rust, by 27% during a year of severe rust, and by 61% during a year of very severe rust, which is indicative of the serious losses caused by this disease. In neither of the two cases cited were data submitted to show whether the difference in yield response under the presumably moister conditions of the disease years was the same as that observed in the disease-free years, apart from the disease effect itself. Inclusion of sprayed plots of the susceptible varieties in the experiments would have answered this question.

COMPARISON OF YIELDS OF RESISTANT AND SUSCEPTIBLE SELECTIONS FROM A SINGLE CROP VARIETY: -- It not infrequently happens that in an apparently otherwise uniform crop variety there will be found individual plants that differ strikingly in their reactions to a given disease. The writer found, for example, that while Westar wheat in general is susceptible to race 21 of leaf rust, a small percentage of plants that are otherwise typical for Westar were highly resistant to this race. Comparison of the yields of such resistant and susceptible lines when exposed to disease gives a measure of loss that is relatively exempt from criticism, since, apart from disease reaction, the lines are strictly comparable. Yet, even here the objection may be raised that the resistant and susceptible lines may differ physiologically in other respects than disease reaction, though alike morphologically. This objection could be answered by simple experimentation.

The advantages and limitations of this method, as used in measuring losses from cereal rusts, have been discussed by NAUMOV (1939) and CHESTER (1944). An illustration of use of the method is seen in the work of S. F. ARMSTRONG (1922) with stripe rust of wheat. He found that the variety Jap contained morphologically similar strains that differed in rust susceptibility, and a comparison of these brought out a yield reduction of 48.8% caused by this disease under specified conditions.

COMPARISON OF YIELDS OF RESISTANT AND SUSCEPTIBLE SEGREGATES FROM HYBRIDIZATION: -- This method, which is very similar to the preceding one, is based on the assumption that a group of disease-resistant lines from a resistant x susceptible cross will differ from a group of susceptible lines from the same cross principally in disease resistance alone; the larger the numbers of such lines used, the greater will be the probability that this is true, and that there will be a high correlation between disease differences and yield differences. An objection to the method is the theoretical possibility of genetic correlations of such a nature that disease reaction and some other factor of yield importance do not segregate independently; there is no evidence, however, that this has been a fault in the majority of experiments of this type.

Genetic segregates have been used in studying losses from the cereal rusts in the United States (IMMER and STEVENSON, 1928; WALDRON, 1936; JOHNSTON, 1937, 1938) and in Russia (LUKYANENKO, 1934; SHEVCHENKO, RUSAKOV, PANCHENKO, and PRONICHEV, cited by NAUMOV, 1939, in his discussion of this method). The method is well illustrated in IMMER and STEVENSON'S biometrical study of factors affecting yield in oats, making use of 280 selections from two crosses, with the relation of rust to yield seen in partial correlations. LUKYANENKO grouped 197 wheat lines from six crosses between resistant and susceptible parents into three classes, showing 0-5%, 25-40%, and 65-100% leaf rust intensity respectively. The least infected group exceeded the most heavily infected group in grain yield by 26.7%, with high statistical significance, and the group of intermediate rust susceptibility was also intermediate in yield.

Chapter IX

EXPERIMENTAL METHODS FOR DETERMINING DISEASE INTENSITY-LOSS RELATIONSHIPS (Contd.)

COMPARISON OF YIELDS OF A SUSCEPTIBLE VARIETY WITH AND WITHOUT PROTECTION WITH PESTICIDES: -- This major method of determining the amounts of loss caused by plant diseases basically involves a comparison of yields of two plots of the same disease-susceptible variety, exposed to disease, in which the plants of one plot have been protected from infection by a pesticide. Entomologists have made extensive use of experiments of this sort, using insecticides to protect plots. Standard field plot techniques, with an approved plot design, replications, consideration of border effect, and analysis of the significance of the data obtained are integral elements of this method of disease appraisal.

Pesticide experiments are most commonly conducted for the purpose of developing practical disease control practices. The data from such tests, though not conducted with loss appraisal in mind, frequently may be used for this purpose provided they include accurate information both on disease intensity, in check and treated plots, and on yields of both. Unfortunately, however, the data from many pesticide experiments aimed at disease control cannot be used for the purpose of loss appraisal because of the lack of records of either disease intensity or yields.

For convenience, the following discussion is divided into sections on seed treatment experiments, spraying and dusting trials, and soil treatment, with consideration of the possible effect of pesticides on yields apart from their action in controlling disease.

Seed Treatment Tests. -- Determining disease loss by comparing yields from disinfected versus untreated seed has found its greatest usefulness in studying the losses caused by seedling disease or damping-off, although it may also be used with such typically seedborne or tuberborne diseases as the cereal smuts or potato scab and Rhizoctonia. In the latter cases, however, loss from disease has been more commonly measured by other methods, such as the comparison of yields from plantings of diseased and disease-free seed or tubers.

Consideration of loss from seedling disease at once leads us to the relationship between stands and yields, a question that will be discussed at a later point (page 318). It has long been customary to avoid the losses from seedling disease by using an excessive seeding rate, such that many plants can be sacrificed without loss of a satisfactory stand. In the culture of cotton, before the adoption of seed treatment, it was customary to plant ten times as many seed as were expected to produce plants that would grow to maturity. Many of the untreated seed rotted in the soil, others produced seedlings that damped-off, and the survivors were thinned or "chopped" to a tolerable stand. The height of misunderstanding of this situation is seen in a statement of a former cotton-state governor, who edified his constituents by telling them that the 90% excess seed planted have the purpose of fertilizing the surviving 10%.

If it is true that this practice of overplanting and thinning the survivors does result in a normally-spaced and healthy stand, the loss from damping-off is simply the cost of the excess seed and of thinning. There are several common situations where this is not true, however. Damping-off from untreated seed is sometimes so severe that no useable stand is obtained. Here the loss includes the total cost of seed and seeding, use of the land when it is accomplishing no useful purpose, and the additional losses from replanting at a later, less favorable date, with production of a late crop, harvested when low late-season prices prevail. Even if a tolerable stand is obtained it is usually an uneven one; some plants are widely spaced and others are close together, resulting in some decrease in possible yield due to crowding and incomplete ultilization of the soil. Finally, even if an overplanted crop has withstood the ravages of damping-off enough to produce an even stand of plants that grow to maturity, it is now becoming clear that many of the survivors are subnormal; they never entirely recover from non-fatal root and stem injuries initiated in the seedling stage. This last point is illustrated in one of M^C^NEW'S (1943e) tests of pea seed treatment, in which there was only 1% difference in stand from treated and untreated seed, yet the treated seed produced plants that outyielded those from untreated seed by 9%.

The seed treatment method poses certain problems in assessing disease intensity. The treated plots are seldom 100% healthy and the untreated ones may produce fairly good stands. Such differences in stand as do result are often not conspicuous, and the differences can be brought out only by replicated countings. These give little indication of the non-fatal injuries that may affect the plants. The differences in emergence may be miminized if the stands are thinned, the healthier stands being thinned more heavily than the diseased ones, and if it is the customary practice with the crop concerned, the plots must be thinned to give results that can be applied to agricultural practice. Yield losses from damping-off are most evident when the experimenter "plants for a stand" and does not thin, but this is not consistent with usual cultural practice with such crops as cotton, corn and sugar beets.

In much of the seed treatment work the aim has been to determine the value of treatments and not to measure loss. Data from such experiments can sometimes be used in deriving loss even though this was not an objective of the experiments. Usually a number of different treatments have been used, and a comparison of yields of untreated versus the "best" treatment comes closest to a measure of loss, even though the "best" treatment does not produce perfect stands of entirely healthy plants. With sufficient data the theoretical yield of a perfectly healthy stand can be determined by extrapolation.

The following example, based on the sugar beet seed treatment data of AFANASIEV and MORRIS (1942), illustrates the method. The yield data for 3 seed treatments x 3 replications x 16 fertilizer treatments x 2 years were grouped into disease classes, averaged, and yield was plotted against percent of seedling disease to give the scatter diagram and regression shown in Figure 22. This regression shows that for every increment of 5% disease there was a loss of approximately 0.6 tons per acre or 3.5% loss of the potential crop, if free from seedling disease, which last, 17 tons per acre, was obtained by extrapolating the regression line to the zero disease point.

The seed treatment method is sometimes used in combination with other methods of loss appraisal; it may be combined with the method of comparing yields from diseased and disease-free seed as in LEUKEL'S (1937) work with bunt of wheat, or with roguing or reverse-roguing practices. In making use of seed treatment data for studying loss it is often necessary to consider environmental variables, such as temperature, moisture, and soil fertility, which can markedly affect the disease-loss ratio.

<u>Sulfur Dusting Of Cereals</u>. -- The most outstanding example of measuring disease losses by comparison of protected with unprotected plots has been in connection with losses from the cereal rusts as shown by sulfur dusting experiments. The use of fungicides against rusts goes back a half century to the work of BOLLEY, KELLERMAN, PAMMEL, GALLOWAY, and HITCHCOCK and CARLETON in the United States, COBB in Australia, and ERIKSSON and HENNING in Sweden. These early scientists were interested in rust control rather than loss measurement, but their work paved the way for what was to follow. Beginning in 1926 trials with sulfur dusting showed this to be a valuable aid in measuring loss from the leaf and stem rusts and powdery mildew of cereals, and this led to a series of important studies by CALDWELL, MAINS, JOHNSTON, and many others, in the United States, Russia, and Australia, and especially by GREANEY and his associates in Canada.

It was these experiments that first brought out clear-cut and irrefutable evidence that the losses caused by some of these diseases, notably leaf rust of wheat and powdery mildew of wheat and barley, were very much greater than had been recognized earlier, and that the existing estimates of the losses caused by these diseases were far too low. The literature on this subject has been reviewed, with citation of the important papers, by CHESTER (1946b), and, with special reference to Russian work, by NAUMOV (1939) and CHESTER (1944).

While the sulfur dusting method has many advantages, it also has possible limitations. It can be applied only to those diseases that are controllable with sulfur, e.g., it would not be suitable for bacterial leaf diseases of cereals. Control, when it is obtained, may not be complete, i. e., the comparison is between more and less diseased plants rather than between diseased and healthy ones. It frequently happens that two diseases both controllable by sulfur may occur together, in which case the findings relate to the loss from two or more diseases combined, and not to an individual disease. These last two limitations, fortunately, can be overcome by such devices as extrapolation to obtain theoretical yields of totally healthy plants, and by using crop varieties that are resistant to other diseases than the one under study.

A very important theoretical objection to this method is that the sulfur may have some direct effect influencing yield (fertilization, toxicity) apart from its indirect effect in controlling disease, and this possible objection is considered in a separate section below.

The methods of sulfur dusting experiments with cereals vary considerably in detail. Accounts of these methods, at some length, are to be found in the works of GREANEY (1933b, 1934) and CHESTER (1946b).

Although some of the earlier workers and the Russians have used flowers of sulfur as a cereal fungicide, the later and better investigations have involved use of the finer sulfurs that are manufactured expressly for plant dusting. PHIPPS (1938) in Australia used sulfur sprays. Depending on plot size, various types of dusting equipment have been used, including hand dusters, horse- or tractor-drawn or self-propelled ground dusters, and dusting airplanes.

A problem in this type of work is preventing the drift of the fungicide from the treated to the untreated plots. In small plot tests this has been diminished to unimportance by using dustproof screens to separate the plots during the dusting operation. With larger plots, the problem of

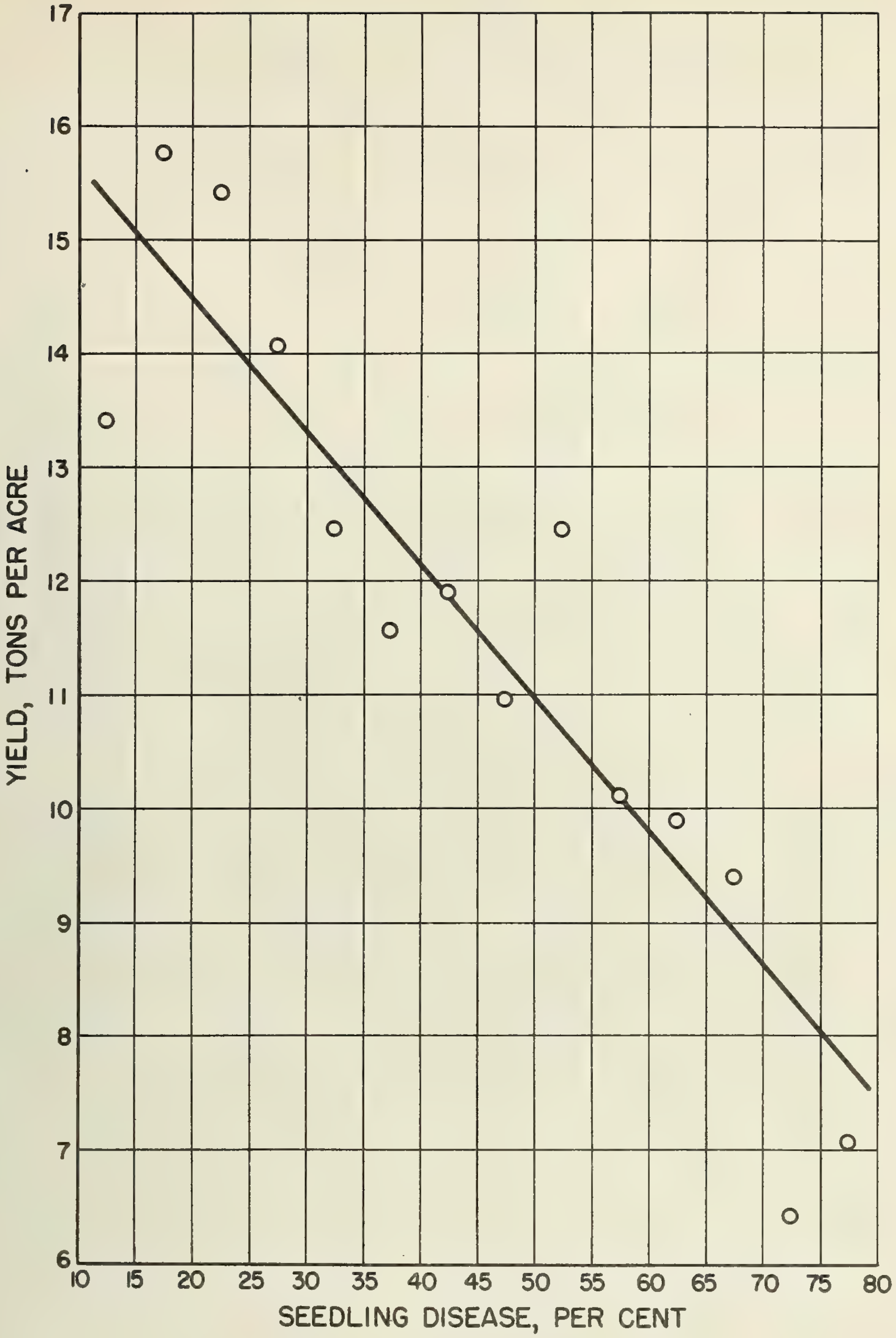

Figure 22. Regression of sugar beet yields on seedling disease. (From data of AFANASIEV and MORRIS, 1942.)

drifting dust is reduced by applying the dust during periods of calm air, locating the plots of untreated plants on the windward side of the treated ones, with reference to the direction of prevailing winds, and separating treated and untreated plots with strips of neutral plants. If the neutral plants are of a tall-growing species, they will also serve as dust screens.

The time, rate, and frequency of dusting have varied widely with different workers and different purposes of their experiments. For studying loss, an objective is to secure plants that are as nearly disease-free as possible, and this calls for earlier and more frequent dustings than would be desirable for an economical degree of practical disease control. There is a common tendency to begin dusting after disease is well established, and this inevitably results in "healthy" plants that are somewhat diseased. Much of the work on cereal dusting has been aimed at control of stem rust rather than leaf rust, which develops earlier in the season. As a result, the dusting schedules have begun later than is desirable for determining losses from both diseases. For controlling cereal rust in loss studies, a thorough schedule would be to begin dusting as soon as the first rust pustules can be found, even though the crop is still in the rosette stage, keeping the new growth protected by sulfur applications at 5 to 7 day intervals until maturity of the crop; this requires many more applications than would be justified for practical rust control. The usual rate is 15-45 lbs. per acre per application, with preference for the higher rates in loss studies. Dusting is most effective if applied before rains, and more frequent applications may be necessary during periods of protracted rains.

The cereal rusts are particularly favorable diseases for this method of loss appaisal because there already exist well-tested, standarized methods for scaling rust intensity, and for designing cereal field experiments, taking yields, measuring qualitative as well as quantitative aspects of loss, and analyzing the data for statistical significance. Replicated field plots for this work range in size from triple rod rows to strips of 1/40 acre or much more if dusting is by airplane. Good examples of the methodology are found in the works of BROADFOOT (1931), CALDWELL et al. (1934), GOULDEN and GREANEY (1930), GREANEY (1933b, 1934), GREANEY et al. (1941), JOHNSTON (1931), MAINS (1930), H. C. MURPHY (1935), M. NEWTON et al. (1945), and PETURSON and M. NEWTON (1939). GREANEY'S papers illustrate how the results of sulfur dusting experiments may be extended to appraisal of loss from cereal rusts over large territories.

The sulfur dusting method may be used to advantage in combination with other methods of determining losses, particularly the use of disease-resistant varieties to eliminate complication with other diseases than the one under study and to measure the direct effect of sulfur on plant growth, and the use of artificial disease inoculation methods to secure the heaviest possible infection on the undusted plants.

Spraying And Dusting Other Crops. -- In general the same principles apply here as were brought out in the preceding section. Spraying has an advantage over dusting in the fact that there is less drift to adjacent plots with sprays, which reduces the problem of eliminating fungicide deposits on untreated plots. The principal limitation of the method is the well-known direct effect of fungicides on yield, apart from disease control, discussed in the next subsection.

In work of this kind it is necessary to conduct controlled experiments. It is not sufficient, for example, to determine loss by comparing the yields obtained by growers who spray with those of growers who do not, since the grower who takes the trouble to spray usually follows other desirable practices, such as fertilization of soil, that independently increase yields.

The results from small-plot experiments sometimes indicate less loss than actually occurs, i.e., less difference in yield between sprayed and unsprayed plots, because the former, being near the latter, are subject to a higher inoculum potential than when large fields or orchards are sprayed or dusted, with no infected plants nearby. This source of error can be controlled, however, by relating yield reductions to degree of disease intensity, which is likely to be greater in treated small plots than in large treated areas.

When several types of treatment are used in the same experiment, the truest measure of loss is expected to be the difference between the "best" treatment and untreated control plants, but judgment must be exercised here since the "best" treatment, the one resulting in highest yields, may be stimulating to the crop in some other way than by controlling disease. Even the "best" treatments frequently do not give 100% disease control, and therefore measure relative but not absolute loss, a problem that can be overcome by analysis of the yield data in terms of degrees of disease intensity. Another principle that has been brought out by spray experiments is that the amount of loss, in absolute or relative terms, is greater for a vigorous, strong crop than for a crop that is growing poorly for any reason, as shown by BEAUMONT and LARGE (1944) for potatoes.

A particular advantage of this method lies in the fact that there exists a large body of data, from many sources, on the effects of spraying and dusting of various crops. Although many of these data have little value in loss appraisal because they give no useful information on disease intensities, there are many other bodies of data that were obtained from the viewpoint of testing disease control measures, yet are sufficiently complete to be equally useful in loss appraisal since they meet the triple requirement of providing information on disease intensities, stage of development of the crop when exposed to given amounts of disease, and yields.

A few representative bodies of data on disease control by spraying and dusting have been analyzed in the present study, to illustrate the value of such data, but no attempt has been made to sift through the voluminous literature on spraying and dusting of fruits, vegetables, and other crops to glean information on the amounts of loss revealed by these tests. This remains a task for the future that may best be done by those with special interests in individual crops and diseases.

In a number of cases spraying or dusting experiments have been conducted with the specific objective of determining the losses caused by given intensities of disease at stated growth stages, often with analysis of the qualitative as well as the quantitative features of loss. Particularly good examples of this are M^cNEW'S (1943a, f-j) studies on losses from tomato diseases. The spraying and dusting experiments to control celery leaf blights, made by NELSON (1939), NELSON and LEWIS (1937), TOWNSEND (1942), TOWNSEND and HEUBERGER (1943), and WILSON (1944), illustrate bodies of data that were not obtained with the intention of using them for loss appraisal, but are nevertheless so well documented that they are suitable for this purpose. In the celery work a particularly praiseworthy effort has been made to state disease intensity in concrete, standardized terms. It would entail little extra work, would increase the value of reports from the standpoint of disease control, and would make an important contribution to the knowledge of disease losses if, in the future, investigators conducting spray or dust trials would report disease intensity data in comparable, standardized terms.

The technique of determining loss percentages by spray tests and applying these to appraisal of loss over a broad area is illustrated in the investigations on potato late blight by P. A. MURPHY (1921), who showed that on Prince Edward Island, late blight caused a loss of more than five million dollars in field and market, the value of the crop being determined with due allowance for freight rates.

Throughout this discussion the problem has been to determine the amounts of loss caused by diseases when there is some reason to believe that important losses do occur. Spray trials may also serve in discovering unsuspected losses. Entomologists have pointed the way to this in tests of the newer insecticides on crops that normally are not sprayed or dusted. PEPPER (1947) has reported that alfalfa yields have been increased 50% or more by a single application of an insecticide. This suggests the value of exploratory fungicide trials on other forage crops and cereals where there is at least a possibility that serious, unsuspected losses from leaf and stem diseases may be revealed.

Effects Of Fungicides On Crops Other Than In Controlling Disease. -- The particular attention that has been given to measurement of losses from cereal rusts by sulfur dusting experiments quite naturally raised the question whether the sulfur has any direct effect on the cereal plant, such as to affect yields favorably or adversely, in addition to its effect in controlling rust. KIGHTLINGER and WHETZEL (1926) found sulfur injurious to cereal yields only if used in excess, and other workers agree that there is no significant direct effect of sulfur on cereal yields. This point is discussed at length, with citations of pertinent literature by NAUMOV (1939) and CHESTER (1946b). The results of three experimental methods bear this out. GREANEY (1934; et al., 1941) found that yields of rust-susceptible varieties were unaffected by sulfur dusting in the absence of rust. PHIPPS (1938), BUTLER (1940), CALDWELL et al. (1934), and BROADFOOT (1931) all showed that sulfur dusting of rust-resistant wheat varieties did not affect their yields. Finally, GREANEY, BUTLER, and BROADFOOT all applied heavy dosages of sulfur to the soil but could detect no effect on wheat yields. These soil applications were at much heavier rates than the soil would receive from crop dusting operations; GREANEY applied sulfur to the soil at the rate of 750 lbs. per acre and BROADFOOT used up to 1920 lbs. per acre without result. It would seem from these results that the sulfur dusting method for measuring losses from the cereal rusts is a reliable one.

Turning to other crops and other fungicides the story is somewhat different. There is abundant evidence of the direct effects of fungicides on crop yields, apart from disease control. Bordeaux mixture, when applied to certain crops that require more copper than is available, results in marked yield increases even though no disease is being controlled by the spraying. On the other side of the ledger, the yield-depressing effects of sulfur on melon crops and tomatoes growing at high temperatures are well known. In Florida the shift from Bordeaux mixture to Dithane sprays for potato late blight has shown yield increases quite out of proportion to disease control. It is not always clear, in such cases, whether the difference is due to elimination of a yield-depressing effect of the one fungicide or to a yield-stimulating effect of the second. It is quite possible that some of the newer organic fungicides may have growth-promoting qualities in addition to their value in disease control. Whatever the mechanism, these effects are common, and it is obvious that comparison of yields of sprayed and unsprayed plots will not give a reliable measure of loss if the fungicide used has such direct effects on yield.

Yet this cannot be taken as a blanket indictment of the spraying-dusting method of loss appraisal. There are cases in which it can be demonstrated that the fungicide has no direct yield effect, as in sulfur dusting of the cereals. In other cases the direct effect of the fungicide can be measured and used as a correction factor in loss studies. The experimental verification of this point is a simple one; it can and should be a part of all spraying or dusting experiments to measure disease loss; it consists merely in supplementing the ordinary fungicide trial in the presence of disease with a trial in the absence of disease, comparing yields of sprayed plots with those of disease-free unsprayed ones. The latter can be secured by using a disease-resistant crop variety or conducting the tests in a season or under experimental conditions in which there is no natural occurrence of disease on the unsprayed check plots.

Use Of A Graded Series Of Spray Concentrations. -- Comparing yields of healthy sprayed versus heavily diseased unsprayed plots gives a measure of maximum loss but no indication of the increment of loss per unit increment of disease. This last is desirable, because it is unsafe to interpolate values for intermediate degrees of disease, given only two, respectively low and high, points, since with some diseases there is not a linear relation between units of disease intensity and units of loss.

The spraying or dusting method allows the production of a series of times and degrees of disease intensity, of any desired number of stages, by varying the rate, time, frequency, and concentration of fungicide application. The value of this is brought out admirably in YARWOOD'S (1945) study of copper sulfate as an eradicant spray for powdery mildews.

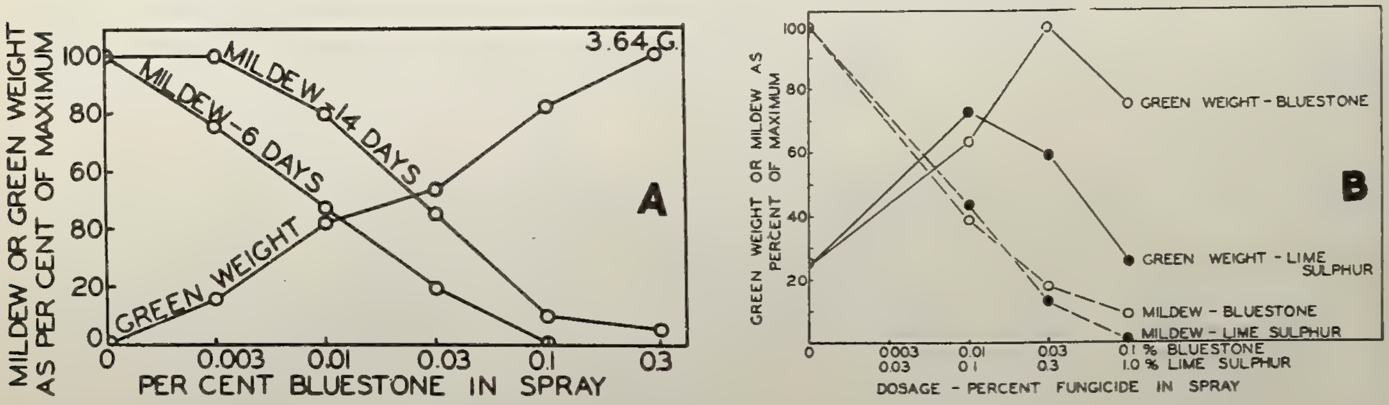

Figure 23. A: Relation of concentration of bluestone spray to eradication of bean powdery mildew and to the green weight of the same plants. B: Relation of concentration of bluestone and lime-sulfur sprays to powdery mildew control and green weight with cantaloupes. (After YARWOOD, 1945)

Figure 23 A (l. c., Fig. 6) shows an almost linear relationship between decreasing mildew and increasing green weight of bean plants as the copper sulfate content of the spray increases by logarithmic steps. Here, if we knew only the values for disease and yield for the highest spray concentration and the unsprayed controls we could interpolate intermediate points without too great inaccuracy. But that this is not always true is brought out for cantaloupes in Fig. 23 B (l. c., Fig. 7). If this experiment had been conducted using only the 0.3% lime sulfur spray, the loss caused by the mildew would have been seriously underestimated, and if the 1.0% lime sulfur spray alone had been used one would conclude that mildew causes no loss, since with this spray concentration the advantage of disease control was almost exactly counterbalanced by the disadvantage of spray injury. Copper sulfate spray at 0.03% concentration alone would have given a fairly accurate measure of loss from the disease, but at 0.1% concentration alone the loss would have been set far too low, since the injurious effect of the strong copper sulfate offset the advantage from disease control to a considerable extent.

Soil Disinfestation Tests. -- The same principles apply to soil disinfestation as to spraying and dusting of crops as a means of loss appraisal. Few soil treatment studies have been made with this objective, but there have been many aimed at control of plant parasitic nematodes and, in a few cases, fungi, the data from which can be used in loss determinations wherever both disease intensities and yields are reported. An example is seen in the work of G. M. ARMSTRONG

(1946) who treated soil with five dosage rates of the disinfestant "D-D", thereby decreasing the root knot index on tomatoes from 3.23 to 0.93 accompanied by a yield increase from 45.4 to 60.7 lbs. of tomatoes per six plots.

As with the spraying and dusting tests there is always the possibility, in this type of experiment, that the disinfestants may have direct or indirect effects on yield apart from controlling the pest concerned. Soil disinfestation radically changes the composition of the soil microbios, both quantitatively and qualitatively altering the populations of harmful and beneficial microorganisms. Cases are known in which soil disinfestation has substantially increased yields without destroying known plant pests, and there are other cases in which the treatments decrease yields through toxicity to plants or destruction of beneficial microorganisms.

The elimination of this source of error is similar to that in the case of spraying or dusting; namely, to determine the effect of the soil treatment on healthy crops and interpret or correct the loss measurements accordingly. Little is known of the extent of damage from many kinds of root diseases, some of which may be causing unexpectedly high losses. It appears that more extensive use of the soil disinfestation method would be a very promising approach to this problem.

THE EFFECT OF ARTIFICIAL MUTILATION ON YIELD; RELATION OF THIS TO DISEASES: -- The effects of removing or injuring leaves of plants hold interest for investigators in many fields. Plant pathologists who would like to know the effects of leaf destruction by rusts and leaf spot diseases see in this a convenient and exact method of studying the losses produced by these diseases, and we find that leaf mutilation experiments have shed considerable light on these losses, especially for the leaf rusts of cereals. Entomologists, too, who are concerned with the damage from leaf chewing insects have found artificial defoliation experiments helpful in appraising this damage.

Agronomists and animal husbandmen are concerned with the effect of loss of leaves on pastures, in an attempt to determine the practical compromise in grazing practice that will give the greatest yield of fodder with the least injury to the plant, especially in the case of cereal pastures where the same crops are used both for grazing and for grain production. Horticulturists are interested in the relationship between leaf surface and number, size, and quality of fruits and nuts, and have conducted important studies on the optimal leaf-fruit ratios, to determine the fruit-thinning practices that will give the greatest financial return.

Plant physiologists also find need for artificial defoliation experiments in their basic studies of the effects of photosynthesis on the chemical composition and development of plants. Ecologists and physiologists both are interested in knowing the harmful or possible beneficial results of loss of leaves from plants which have developed abundant foliage during a cool, moist season, and then are exposed to hot, dry, windy weather in which transpiration is high and the loss of water from plant and soil varies directly with leaf expanse. Plant breeders find it an advantage to learn the laws that govern the relationship between leaf area and yield so that in their plant selection practice they may select the most efficient plants and will know how much reliance to put on leaf area as a criterion of selection.

For the most empirical reasons of all, commercial interests have a stake in the understanding of defoliation and mutilation of plants, the outstanding examples being in connection with hail insurance and chemical defoliation. Excellent experiments by DUNGAN, ELDREDGE, KLAGES, HAWTHORN, KALTON, and KIESSELBACH and LYNESS, using injuries resembling the effects of hail on corn, small grains, onions, soybeans, and flax, have laid the scientific groundwork for determining equitable amounts of indemnity for insured hail damage.

Much less scientific in its approach and basis is the commercial exploitation of the chemical defoliation of plants. The advocates of chemical defoliation enumerate in glowing terms the many advantages that result from removing the "useless, detrimental" leaves of plants as the crop approaches maturity, ranging from facilitating mechanical harvesting to the heightened morale of cotton pickers who are not plagued by mosquitos in the leafless fields and can spend their time picking instead of scratching. These accounts maintain that late season defoliation results in no reduction of yielding ability of the plants, which is not true, although it is probably true that in many cases the advantages of chemical defoliation outweigh its yield-depressing effect, and more than compensate for reduced yield by better quality of the crop, easier harvesting, and other economic advantages.

The studies and interests run the gamut from basic science through applied science to technology. They are found in a wide diversity of publications from academic journals to trade literature and in numerous fields, but all have in common an interest in the relationship between reduced leaf surface and yields. All are embraced in this discussion, for it is frequently the case that the student of loss appraisal will find data, principles, and conclusions which, though derived for an entirely different purpose, nevertheless bear directly on the problem at hand, -- the extent to which loss of leaves, whether due to disease or other agencies, decreases yields.

Some of the questions involved are these. Are the effects of artificial mutilation comparable to those of disease, so that we may place reliance on such defoliation as a measure of disease loss? To what extent is loss of leaves harmful, considering crop, time and degree of defoliation, environment, and cultural practices? Is defoliation ever harmless or beneficial? How can we account for differences in the effects of defoliation at different growth stages of the crop? How is partial defoliation related to the physiological efficiency of the leaves? What effect does it have on the growth of perennials in the present and future years? An attempt will be made to throw light on these questions, following an account of the methods of experimental mutilation and of measuring leaf areas.

Methods Of Artificial Mutilation. -- The manner of reducing leaf surface has been varied in different investigations. As a general principle, the best method is the one that most closely imitates the type of natural injury under study, but other factors, such as convenience or economy, may influence the methods. Simplest is to remove entire leaves, all that are on a plant or only some of them. This imitates the effects of defoliation diseases and insects, such as grasshoppers, which partially or completely strip the leaves from plants. In China, farmers jerk off sorghum leaves for use as fodder and fuel, and the same method was used by LI and LIU (1935) in studying the effects of this practice on yield.

Next in simplicity, particularly with cereals and grasses, is to clip off distal segments of the leaves, removing 1/4, 1/2, or some other fraction of the leaf. This resembles the effects of leaf injuries caused by drought and by numerous types of disease, in which the leaf dies back from the tip. A variant of this method is to clip grass pasture with a lawn mower, adjusting the cutter bar at some given distance above the ground. This is probably as close an imitation of the effects of pasturing as can be carried out conveniently.

SHCHEGLOVA and CHERNISHEVA (1933) in Russia used the procedure of punching out small areas of tissue leaving round holes in the leaves. With this method it is somewhat inconvenient to determine the percentage of leaf tissue removed, but there would be an advantage in using this practice in imitating injury from those pests which produce circular holes in leaves, such as the shot-hole leaf diseases of stone fruits or the work of leaf-cutting bees and some of the leaf beetles.

In an effort to imitate natural injuries it is not enough merely to simulate the appearance of the injury; the time, duration, and recurrence of the injury must be considered. Some injuries are sudden, others protracted through the season with constant, increasing, or diminishing intensity, and still others come as successive waves of injury. An attempt to imitate this timing is necessary. Instead of cutting cereal leaves transversely, in loss studies, some workers have removed longitudinal leaf sections. This perpetuates the injury, since cereal leaves grow from the base and with longitudinal cutting the fraction of a leaf removed will remain constant with later growth of the leaf remnant. Contrary to criticism by LUBISHCHEV (1940), longitudinal leaf excision does parallel some forms of natural injury, such as stripe disease. DUNGAN'S (1929) method of removing 4-inch sections of corn leaves on alternating sides of the midrib appears to have no counterpart in nature.

Somewhat more complicated and ingenious forms of mutilation, in addition to simple removal of leaves or leaf segments, have been used in efforts to imitate the injury from hail. This is well illustrated in the experiments of DUNGAN (1928, 1929, 1930, 1932) and KIESSELBACH and LYNESS (1945) with corn, KLAGES (1933) with flax, and KALTON and ELDREDGE (1947) with soybeans. The types of injury included breaking the midribs of leaves, splitting them or shredding them with a rasp without removing tissue, cutting off young plants, pounding ears and stalks or bruising with a lath and board, and flailing plants with specified numbers of lashes with a specially devised wire flail of the "cat-o'-nine-tails" type.

Horticulturists interested in leaf-fruit relationships in apples, pears, peaches, grapes, and nuts have made use of HALLER and MAGNESS' technique of removing from a twig a ring of bark and phloem tissues or girdling the twig with wire in order to confine the products of photosynthesis from the leaves distal to the ringing operation, making them available only to the fruits or nuts on the same twig portion. In this way a certain number of fruits receive foodstuffs only from a given number of leaves, and this leaf-fruit ratio has either been left as in nature, increased by removing some of the fruits, or decreased by removing some of the leaves.

The interest of entomologists in losses from insect defoliation is brought out in such studies as those of MINOTT and GUILD (1925), GRAHAM (1931), SUMMERS and BURGESS (1933), BAKER (1941), and WALLACE (1945). This work suggests the possibility that plant pathologists might apply the entomological findings to appraisal of loss caused by diseases with effects comparable to those of leaf-feeding insects, or even deliberately make use of insect injury as a form of mutilation in disease loss investigations. The entomologists have not only worked with natural insect attacks but have also simulated them, with an attempt to duplicate the manner of action of the insects, as in the work of WHITE (1946), who attempted to defoliate wheat in the same fashion as grasshoppers do.

Chemical defoliation is more comparable to loss of leaves from frost than to most other natural hazards, because of its suddenness and completeness. Calcium cyanamid is commonly used for this purpose, at the rate of 30 to 40 lbs. per acre, applied when the plants are moist, by airplane or any ordinary ground dusting equipment. The leaves begin dropping off in 24 to 48 hours and the dusted plants have lost all leaves 5 to 15 days after the application.

In a few cases other parts of the plant than the leaves have been mutilated or removed in loss studies, as with stem injuries and the removal of terminal buds in connection with injuries in imitation of hail damage. H. M. BROWN (1944) simulated the effect of loose smut by removing wheat heads at heading time, which produced approximately the same loss as an equal percentage of smutty heads.

Methods Of Measuring Leaf And Fruit Areas And Fruit Volumes. -- Accurate study of the relationships between leaf area, defoliation, and yield often requires some method of measuring leaf area. Numerous methods have been used for this, and the choice of method is dictated by leaf shape and its constancy, convenience, rapidity, and degree of accuracy required.

Most elementary is to measure the leaf area with a planimeter. This is inconvenient, however, because of the thickness, softness, and wilting of detached leaves. This disadvantage can be obviated by first reproducing the leaf outline on paper, using blueprints (LOTT and LEMERT, 1932; GUSTAFSON and STOLDT, 1936) or charting the outlines on paper. STANILAND (1946) has described a drawing apparatus for projecting on paper scale replicas of leaves in situ.

To save the time required by planimeter measurements, some workers have followed the practice of outlining leaves on paper of uniform thickness and cutting out and weighing these. A conversion value is obtained by weighing paper of a known area, and the weights can then be fairly accurately converted into units of area by a simple calculation.

Still more rapid though somewhat less accurate, is to estimate the areas, using estimation aids. One way is to prepare a set of standards of leaves of different sizes, which may be leaf tracings or blueprints, measure these with a planimeter, and estimate the areas of leaves by comparing them with these standards (e.g., BALD, 1943a). Another method is to prepare a set of celluloid patterns, shaped like leaves and of a graded series of sizes, measure these accurately, cover a leaf with the one most closely corresponding to its size, and estimate its overrun (SCHUSTER, 1933). A variant of this is to cover the leaf with a glass grid, ruled in squares of standard size, estimating the area from the number of squares occupied by the leaf (VYVYAN and EVANS, 1932).

Other workers prefer to use methods based on measurement of one or both diameters of leaves. With leaves of fairly constant shape, measurement of one diameter may suffice. CARUTHERS (1929) found this true of leaves of Ribes and prepared a scale, resembling a logarithmic ruler, on which area can be read off directly, knowing leaf width. He found the method accurate within 5% error. With tomato leaves, A. M. PORTER (1932) found a highly significant curvilinear relationship between leaf area and length ($r = .968 \pm .0018$), so that leaf area could be calculated from length using an equation that fitted the curve, or more readily by reading area directly from the curve.

Multiplying the product of leaf length and width by a constant, DARROW (1930) with strawberry, MARSHALL (1933) with raspberry, and DAVIS (1940) with bean leaves all found this a satisfactory method of obtaining leaf areas. BATEN and MUNCIE (1943; BATEN, 1942) carried this one step farther by preparing nomograms from which areas of bean and sugar beet leaves can be read directly, knowing their length and width. MARSHALL (l. c.) has described a very ingenious mechanical device for this purpose, consisting of two syringes with plungers attached to stiff, indicator wires, their liquid contents being forced into a vertical tube with a calibration scale for leaf area. A leaf to be measured is placed on a platform, the two plungers, at right angles, are pushed in until the wires touch the end and side margins of the leaf, and the area is read directly from the level of liquid forced into the vertical tube. The equipment was calibrated by using planimeter measurements, and had accuracy within 1% for a considerable number of leaves.

If leaf area is well correlated with some other easily measured portion of a plant, it may be most convenient to make use of this correlation. SCHUSTER (1933) found such a useful correlation between twig length and leaf area in working with filbert.

The most highly developed methods for measuring leaf area make use of photometers or photoelectric devices. The "phyllometer" of BOLAS and MELVILLE (1933) is a relatively simple photometric device based on the principle that the larger the leaf the less light will pass to a photometer in which a dial adjuster is turned to the limit of visibility of a black cross against a white background. The dial readings are calibrated with leaves of known size. Leaf measuring devices based on degree of activation of a photoelectric cell have been described, improved, and used by

GERDEL and SALTER (1928), BERGMAN (1933), FREAR (1935), WITHROW (1935), MITCHELL, (1936), KRAMER (1937), HIBBARD et al. (1938), and MILTHORPE (1942). The principle is that the smaller the leaf, the greater the amount of light transmitted and the resultant electric current, which is converted into leaf area after calibration with measured leaves.

BATEN and MARSHALL (1943) have published equations for determining the surface areas of such fruits as apple, pear, and plum, and the volume of fruits may readily be obtained by water displacement.

Interpretation Of The Leaf Area-Yield Ratio. -- The quantitative and qualitative effects on yield of leaf area and its reduction are complex, varying with crop and variety, amount, time, and manner of defoliation, and environment in which the crop is growing. As we might expect, this results in apparent inconsistencies or contradictions when one case is compared with another, yet there are certain principles that apply generally. The subject of defoliation in relation to crop loss has been discussed at some length by CHESTER (1945*a*) and EIDELMAN (1933 *a*, *b*).

It is generally true that any defoliation, at any stage in the development of the crop, with the possible exception of the last few days before crop maturity, produces some reduction in yield. ROEBUCK and BROWN (1923) and R. M. WHITE (1946) have found this true for wheat, HUFFINE (1947) for sorghum, GIBSON *et al*. (1943) for soybeans, CROWTHER (1941) for cotton, and others for a number of other crops.

Defoliation sometimes has little effect on one type of organ or even stimulates its development, but at the expense of other organs and of the growth of the plant as a whole. In the case of soybeans (*l. c.*) moderate defoliation increases the yield of leaves while seed production is reduced, and with onions, defoliation reduces bulb formation without having much effect on seed production (YARWOOD, 1943).

With different degrees of defoliation at any one time, some workers consider that the percent reduction in growth or yield is approximately equal to the percent of defoliation (SUMMERS and BURGESS, 1933, for hardwoods; DUNGAN, 1929, for corn), but in the majority of cases the cause and effect are not proportionate. Ordinarily the percent of loss seen in comparing plants having 100% of their foliage with plants having 90% foliage is less than the percent of loss seen in comparing 90% foliated with 80% foliated plants and, continuing in this fashion, each additional 10% increment in defoliation results in a greater percent of loss than preceding ones. This principle has been observed and expressed in different ways in defoliation experiments with tomato (GUSTAFSON and STOLDT, 1936; A. M. PORTER, 1932), corn (DUNGAN, 1930), apple and pear (MAGNESS *et al*., 1928, 1929, 1931), peach (WEINBERGER and CULLINAN, 1931, 1932), grape (WINKLER, 1930), and filbert (SCHUSTER, 1933).

The relation between leaf area and both quantity and quality of fruit is brought out in WEINBERGER'S data on peach thinning and defoliation, presented here in Table 5, which illustrates the increasing importance and efficiency of the remaining leaves as the degree of defoliation increases.

Table 5. The relation between Late Crawford peach leaf area and fruit size and quality. (After WEINBERGER, 1931).

Leaves per fruit	Leaf area per fruit[a]	Size of fruit[b]	Efficiency of leaves[c]	Dry weight of fruit[d]	Total sugars (%)
75	538	133.7	2.5	17.16	10.84
50	538	124.9	3.5	17.38	11.21
40	286	128.3	4.5	17.38	10.74
30	215	115.8	5.4	16.51	10.38
20	143	117.2	8.2	15.43	9.69
10	72	78.5	10.9	13.49	8.11
5	36	42.5	11.8	10.62	4.63

[a] In sq. inches. [b] In c.c. [c] As c.c. of fruit per 10 sq. inches of leaf area. [d] As % of fresh weight.

The explanation why the first leaves lost are more dispensable, causing less damage to the plant than further equal increments of defoliation, is expressed in terms of the efficiency of the leaves. When a plant has its full complement of leaves, these are functioning at a relatively low efficiency, but as more leaves are lost, those remaining function more and more efficiently and their loss is more detrimental to the plant than that of the first, inefficient leaves that are lost (Table 5). When a plant has other green, photosynthetic tissues than leaves (leaf sheaths, glumes and awns, green stems) the loss of leaves is less serious than in plants lacking these partly compensating tissues (cf. DUNGAN, 1932). EIDELMAN (1933b) has shown that wheat leaves normally are not used at full efficiency, and that removing some of them increases the photosynthetic activity of the remaining ones, although not enough to compensate fully for the cutting.

Defoliation is regularly associated with a decrease in quality of the crop, the cause and effect showing the same disproportionate relationship with increasing degrees of defoliation as was the case with gross yield. Table 5 illustrates this in showing the decrease in sugar, a prime quality factor, with decreasing leaf area per peach. The same thing has been observed in apples and grapes. Apples with a low ratio of leaf to fruit have been found to be insipid, with little aroma, and almost inedible (MAGNESS, 1928).

As the degree of defoliation increases, soybeans contain less oil and have shrivelled seed (KALTON and ELDREDGE, 1947), corn becomes floury and chaffy (DUNGAN, 1928) and has a reduced content of sugar in the stalks (SAYRE et al., 1931), onions show a higher percentage of boilers and culls as compared with the jumbo and medium grades (HAWTHORN, 1943, 1946), and wheat contains less protein and sugars, has a reduced bushel weight, and produces flour of poorer baking quality.

There are also serious secondary effects of defoliation, as in the case of tomatoes where loss of leaves exposes the fruits to sunburn. With a number of crops, defoliation retards the date of maturity with numerous undesirable effects, including loss of the high prices paid for early-harvested crops and increased danger from late-season weather and pests. Also, of a secondary nature, but important to the yield and quality of the crop, is the fact that defoliation leads to a reduction in root development and, in turn, a reduction in mineral and water uptake, which aggravates the direct loss.

Thus far we have been considering degree of defoliation, with time of defoliation a constant or neutral factor. Reversing this procedure brings out important principles governing the effects of defoliation at different growth stages of the plant.

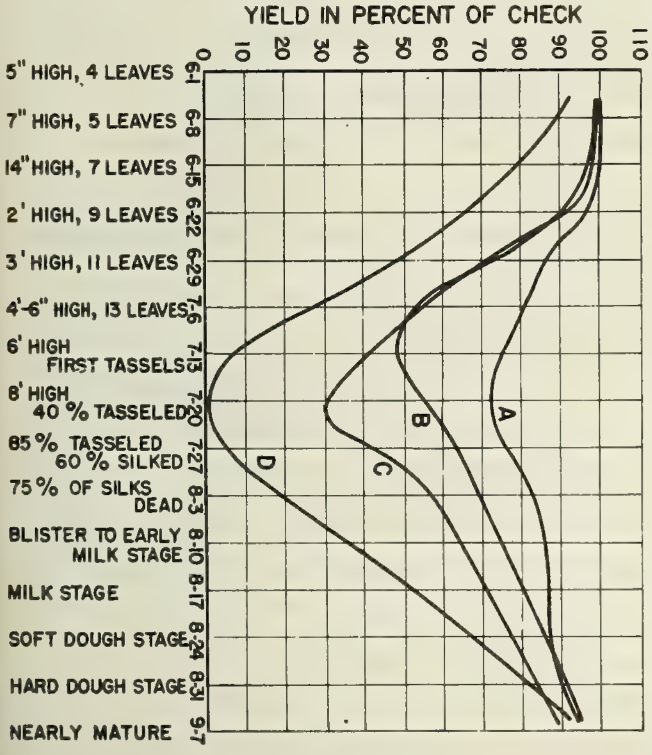

Figure 24. The effect on corn yields of 1/2 (A), 2/3 (C), and total (D) defoliation at different stages in development of the corn plant. Curve B shows the effect of shredding the corn leaves. (After ELDREDGE, 1935).

Consider a uniform planting subdivided into groups of plots, one group being completely defoliated early in the development of the crop and then undisturbed for the remainder of the season, a second group defoliated once at a somewhat later growth stage, and other groups defoliated at successively later dates, extending to maturity of the crop. If now the yields of these plots are measured we regularly find, with such various crops as corn, barley, oats, sorghums, onions, flax, and soybeans, that the loss in yield is greatest when the plants are defoliated in midseason and progressively less with earlier or later defoliation. This is well illustrated for corn in Figure 24.

As the figure shows, comparatively little loss results from complete defoliation when the corn is only 5 inches high, more and more loss results as defoliation is progressively later, until the time at which the corn is 8 feet tall and 40% tasselled, when complete defoliation causes total loss. With defoliation at progressively greater intervals after this growth stage, the yield reduction is less and less, until the effect on yield is minor if the crop is defoliated when it is nearly mature.

The figure also shows a comparable result if defoliation is partial, not total, the effect on yield being less in degree but similar in character as smaller percentages of the leaves are removed. In all cases any indicated amount of defoliation is most injurious at midseason and least very early or very late in the development of the crop.

Results similar to those of ELDREDGE with corn have been reported by HUME and FRANZKE (1929) and KIESSELBACH and LYNESS (1945). The latter workers also observed the "midseason effect" on yields of corn stover and fodder and have published an excellent photograph, reproduced here as Figure 25, showing graphically the relation between time of defoliation and corn ear development.

Figure 25. Effect of complete defoliation, at different growth stages, on typical corn ear development. Left to right, growth stage at time of development: check; plants 2 feet tall; 3 feet tall; 4 feet tall; initial tasseling; fully tasseled; 10 days after silking; early milk; and late milk stage. Acre yields, left to right respectively were: 52.7; 50.1; 43.3; 20.3; 0.0; 0.9; 12.5; 15.4; and 31.6 bushels per acre. (After KIESSELBACH and LYNESS, 1945.)

The time or growth stage at which defoliation is injurious is: for oats and barley, when in the grass stage before the growing point has emerged from the crown (ELDREDGE, 1937); for sorghums, 60 days after planting (HUFFINE, 1947); for flax, in the bud stage (KLAGES, 1933); for soybeans, when the beans are beginning to develop in the pod (KALTON and ELDREDGE, 1947); and for onions, when bulbing begins (HAWTHORN, 1943, 1946).

Some workers have reported merely that the effects of defoliation are greater the younger the plants are when defoliated. This contradiction is only apparent, because in each of these cases the defoliation was begun at or after the time of the midseason effect, without consideration of its effect earlier in the life of the plant. In an early study of DUNGAN'S (1928), for example, corn defoliation began after the plants had tasselled, and as a result he observed only the right-hand half of the curve shown in Figure 24. He observed the entire curve of effect in later work (1931). The same thing is seen in ELDREDGE'S (1937) work with wheat, where defoliation was not begun until the plants were at least six months old and well into the jointing stage, and in the sorghum defoliation experiments of LI and LIU (1935), begun when the crop was in the dough stage.

The most probable explanation of the "midseason effect" is that at this critical stage in development the foliage has not yet served its photosynthetic function, yet it is too late for the plant to develop a new set of leaves to compensate for those lost. With defoliation progressively earlier than this, the plant has more time to replace the lost foliage, which then is able to function fairly well, while with defoliation progressively later than the critical period, the leaves have served their purpose to an increasing extent, and to the same extent are dispensable.

Wheat provides an important source of fall and spring forage, and there is much interest in the amount of grazing that it can yield without serious injury to the grain yield. Experiments in the Southwest show that a considerable portion of the leaves of young wheat plants may be grazed off without much effect on grain production. This loss of leaves is quite early in the morphological development of the wheat plant, and therefore has little effect on grain yield. Winter wheat

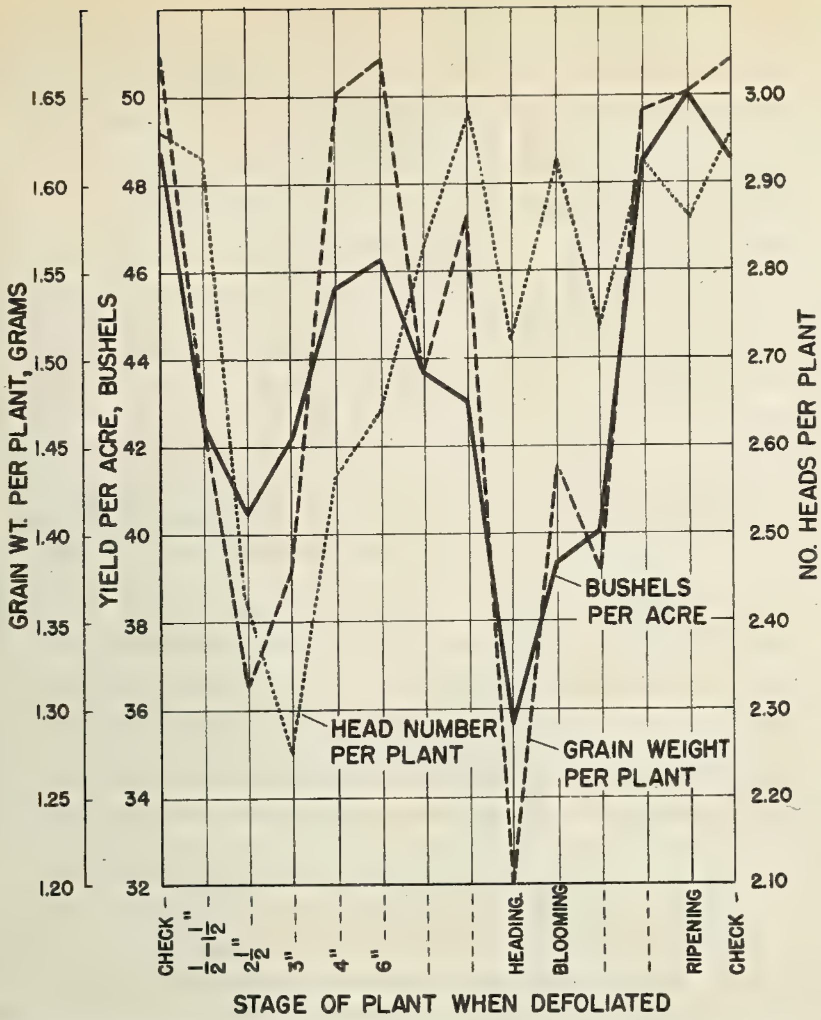

Figure 26. Effect on wheat yields of defoliation at different stages in development of the wheat plant, illustrating a double valley in the yield curve due to anatomical and nutritional effects of defoliation. (After WHITE, 1946.)

plants in the spring may be several months old, to be sure, but the winter dormant period has protracted the life of the plant in a juvenile condition. In this case, also, the leaves removed by grazing are but a small fraction of all leaves on the plant. When wheat pasturing is prolonged in the spring the result is serious or even total loss of grain yield.

Apparently anomalous results have been obtained in R. M. WHITE'S (1946) defoliation experiments with wheat as shown in Figure 26. Here yield, whether expressed as grain per head or bushels per acre, was most depressed by defoliation at the heading stage, but there is a second valley in the yield curve indicating serious yield reduction resulting from defoliation when the plants are 2-1/2 inches high, with less effect of defoliation between these two growth stages. How can this double valley be explained?

It is quite likely that the maximum loss in yield due to defoliation at the heading stage, as in other crops, is due principally to the inability of the plants to fill the grains, since the morphological framework of the plant and its reproductive parts has been fully differentiated by the time the heading stage is reached. The loss in yield associated with defoliation at the 2 1/2-inch stage, on the other hand, appears to result from a failure of the injured plant to differentiate its organs and form the framework of normal plant structure, and this is borne out by the curve showing the number of heads per plant, which has but one deep valley, associated with defoliation at the 2 1/2- to 3-inch stage.

A slight tendency toward a double valley is also seen with defoliation of soybeans in the data of KALTON and ELDREDGE (1947), where yield is somewhat more depressed by defoliation when the plants are 4 to 6 inches tall than when they are 7 to 9 inches tall, with the remainder of the defoliation-yield curve showing only the typical "midseason effect".

Turning to the effect of environment on the leaf area-yield relationship, a number of investigators have shown that loss of leaves is least detrimental under drought conditions, where a moderate degree of defoliation may even increase corn yields (ELDGREDE, 1935). LUDWIG (1927) has reported that late defoliation of cotton results in death of twigs or even whole plants if the soil is moist, but not if it is dry. In South Russia, MOLOTKOVSKY (1945) has gone so far as to recommend mowing potato vines in midsummer, and has presented rather variable data which suggest that yields are frequently increased by this method. This is evidently an atypical case in which the growing season is regularly interrupted by heat and drought, and in which the defoliation has the main purpose of retarding crop maturity until a time of more favorable weather.

LUBIMENKO (1933) has given special attention to this aspect of defoliation. He defines the "coefficient of damage" as "that factor by which it is necessary to multiply the degree of damage to the vegetative organs in order to obtain the actual effect of the damage, i.e., the amount of loss in quantity and quality of the yield." EIDELMAN (1933a), in summarizing the extensive Russian work on artificial defoliation, has computed the coefficient of damage for 100% defoliation of spring wheat as .24-.28 at Kiev and .48-.69 at Leningrad, i.e., the yield reduction for the same degree of injury was much greater at Leningrad. This is interpreted as meaning that under the environmental conditions at Kiev the wheat had a greater capacity for compensating for deficient leaf tissue through increased activity of the remaining tissues.

Under dry conditions leaves may be more efficient, and it has been shown that in dry soils a smaller leaf area is required to produce a bushel of sorghum (SWANSON, 1941) or to produce peaches of a given size and quality (I. D. JONES, 1931). Total yields are greater under moister conditions in these cases, because there is greater leaf area, even though it is less efficient. As regards soil fertility, we have the statement of EIDELMAN and BANKUL (1933) that fertilizers act on defoliated plants in much the same fashion as on normal ones.

The manner of defoliation is a factor in the effect on yield. This is well seen in experiments using various types of injuries in imitation of hail damage. For example, cutting off the outer half of a corn leaf, removing a longitudinal half, removing alternate entire leaves, and removing 4-inch sections on left and right sides of the leaf alternately, all eliminate essentially 50% of the leaf tissue, yet the effects in depressing yield are quite different in the four cases, the first method producing the greatest loss (DUNGAN, 1930).

Different crops and different varieties of the same crop vary in their response to defoliation. For example, EIDELMAN and BANKUL (1933) have reported that the yield of barley is less affected by defoliation than that of wheat, GIBSON et al. (1943) found that defoliation reduced yields of the Tokyo soybean less than those of the Biloxi variety, and WEINBERGER (1931) has shown that it takes more leaf area to produce a given fruit volume in the Crawford peach than in the Elberta.

With perennials the effects of loss of foliage are seen both during the year of defoliation and in the following years. This subject has been studied especially by entomologists with interest in the work of such leaf feeding insects as the gipsy moth and cankerworms, e.g., GRAHAM (1931), BAKER (1941), and WALLACE (1945). A single defoliation may kill evergreen conifers, while hardwoods suffer decreased radial and twig growth and may be killed in three to four years by the action of the complete defoliation, directly, or by secondary pests favored in their work by weakness in the trees. Different species and individual trees of a single species vary in their response to defoliation, depending on their genotype and environment.

The work on ringing fruit and nut trees, referred to above, shows that the normal complement of leaves is usually inadequate to give the best economic returns from the trees. Fruit thinning is now a recognized desirable practice in order to increase the leaf-fruit ratio and thereby secure larger fruits of better quality. Any fruit thinning reduces yields but moderate thinning, to a point where each apple, pear, or peach fruit, for example, is supplied with 30 to 40 leaves, increases the value of the crop, the higher quality more than offsetting the slight reduction in crop volume. Tomatoes are thinned for similar reasons. With tree fruits, thinning also has the advantage of making available more needed foodstuffs as reserve food in the wood for the following year.

The case of late-season chemical defoliation, which is becoming a standard practice with cotton and some other crops, also deserves special mention. Enthusiasts of chemical defoliation indicate that the leaves of crops such as cotton and soybeans are quite useless during the last weeks before maturity. M. V. BAILEY (1947) calls cotton "an excellent example of a plant which retains its foliage long after it is of any value in growing the crop or increasing the yield." Contrary to this notion, LUDWIG (1927) for cotton and KALTON and ELDREDGE (1947) for soybeans have shown that defoliation at any stage decreases yields.

Nevertheless, chemical defoliation has, or is claimed to have, many advantages, most important of which are the facilitating of mechanical harvesting operations and forestalling of unfavorable late-season weather. According to the accounts of M. V. BAILEY (1945, 1947) and GULL and ADAMS (1945, 1946), defoliated cotton produces lint that is relatively free of chlorophyll and mold stain, suffers less from boll rots, may be picked with greater comfort and earlier in the morning, opens its bolls sooner, which dries the lint and improves the lint grade, contains less foreign matter in mechanically harvested lint, facilitates hand picking by making it easier to see the bolls, which doubles the picking rate, starves the late-season overwintering brood of boll weevils, enables growers to harvest in time to comply with the Texas law that requires all cotton plants to be destroyed by September 1 for pink bollworm control, and permits a degree of irrigation that would otherwise be inexpedient because of excess foliage produced. With soybeans, the earlier maturity due to chemical defoliation makes it possible to fit this crop into a desirable rotation plan with wheat, and decreases storm damage to the beans. With tomato it is said to accelerate maturity, facilitate harvesting, and increase yields of ripe and uncracked fruits; from what is known of shading in relation to vitamin formation, defoliation would probably also increase the content of ascorbic acid in tomato fruits. It is used with nursery stock to induce dormancy, aiding fall digging of stock. It is recommended for ramie to aid harvesting and facilitate decortication. With potato the entire plant is killed by chemicals to aid early harvesting when the price is high and to prevent infection of the tubers by the late blight fungus.

Although these claimed advantages of chemical defoliation have not always been subject to critical testing, there seems little doubt that in many cases they may outweigh the disadvantages, including some loss in volume of yield, especially if defoliation is delayed until the plants are nearly mature. The effects of chemical defoliation are so complex and far reaching that it may be that the test of time and practical experience is the best arbiter of the value of this practice.

Since much of the work on artificial defoliation has been done with other objectives than disease loss appraisal, the application of the results to an understanding of disease losses is somewhat theoretical. There appears to be general agreement, however, that the losses caused by leaf clipping are similar to, but somewhat less severe than, those caused by an equal loss of foliage from leaf rust diseases (Anon. 1933, 1934, 1936; RUSAKOV 1929b). CHESTER'S (1946b, Fig. 2) presentation of losses from wheat leaf rust shows that the results of leaf clipping experiments are in good agreement with those revealed by infection and sulfur dusting tests. There appears to be no contrary view that artificial defoliation is not comparable to the effects of disease if we except LUBISHCHEV'S (1940) general denunciation of the method as used by Russian workers, which is based on no original evidence and reveals a lack of understanding of the physiological and pathological principles involved.

If there is any discrepancy between the results of leaf clipping and those of leaf rust, the effects of the disease are somewhat more severe (CALDWELL and COMPTON, 1939; SHEVCHENKO, 1933). This might be expected since leaf disease, besides eliminating leaf tissue, has other harmful effects, such as inducing excessive transpiration and respiration, decreasing the palatability of forage, and, in some cases, the production of toxins which are damaging to the plant or the animal that consumes the plant, or both. The effects of disease are usually progressive, giving the plant less opportunity to recover from the loss of foliage than in mutilation experiments as usually conducted. All this leads us to the conclusion that the results of artificial defoliation experiments give us a conservative measure of the losses caused by disease that destroys an equal amount of tissue. If this is true we are justified in applying some of the principles brought out in artificial defoliation experiments to an interpretation of the effects of plant disease.

Since any degree of artificial defoliation causes some reduction in yield, it follows that any loss of foliage from disease also reduces yields. It also follows that the damaging effect of leaf diseases will be proportionately greater with each succeeding increment of loss of foliage. We may infer that loss of foliage from disease in midseason, at the time when artificial defoliation results in greatest losses, will be most harmful, which leads us to focus most attention on those diseases that defoliate plants which have developed a full complement of leaves but have not yet made extensive use of these leaves in food production and storage. If the "double-valley" phenomenon described on page 313 is significant and common, there is a second danger point in the developmental cycle of plants, when they are in a formative stage, at which time loss of leaves may lower yields seriously by preventing proper formation of the plant structure. This is at an early stage when defoliation diseases such as the Septoria leaf spots of cereals are frequently considered as relatively harmless.

Continuing the parallel, the loss from leaf diseases must include qualitative as well as quantitative yield factors. If the greatest economic return from orchards results when there are 30 leaves per fruit and this must be attained by fruit thinning, it is clear that any defoliation by disease will reduce this ratio, making more radical fruit thinning necessary if fruit quality is to be maintained, and it has been shown that gross yields decrease with degree of thinning. The other forms of qualitative loss from artificial defoliation, discussed above, may be expected to follow defoliation by disease.

If it is objected that the manner of defoliation in mutilation experiments is unnatural, it must be recalled that virtually all of the methods of defoliation that have been used have analogies, in character and degree, among the effects of various diseases, including diseases that kill the distal portions of leaves, others that destroy longitudinal segments of leaves, others that shred leaves, and still others that kill in well-defined leaf spots, simulated by the leaf punching experiments.

Since different crops and different varieties of the same crop suffer to different extents from artificial defoliation we can expect the same principle to apply to defoliation diseases, and this is indeed the case as witnessed by the observed "tolerance" of some crops and varieties to leaf diseases. It has been shown that barley is somewhat more tolerant to artificial defoliation than some other cereals, and the ability of barley to produce a fair yield of grain despite drastic loss of leaf from rust, powdery mildew, bacterial blight, and Septoria leaf spot is a matter of common observation. The post-seasonal effects of artificial defoliation of trees have their exact counterpart in the effects on the succeeding years' development or even death caused by needle-cast diseases and such leaf diseases of angiosperms as cherry leaf spot.

The relative harmlessness of loss of leaf seen in experiments in which leaves are removed under drought conditions or at the end of the growing season, leads us to infer that leaf diseases are also least injurious and possibly even beneficial at such times. It may not be desirable to combat diseases that act in this fashion, but we can hardly expect to use them to induce desired defoliation in view of our lack of control of the development of disease in nature and the highly controllable method of chemical defoliation.

In summary, the method of artificial mutilation to determine losses resulting from defoliation appears to be a sound, reliable, and conservative approach to an understanding of the losses caused by foliage diseases. It challenges some of our traditional concepts of the damage from disease, confirms others, and stimulates the investigation of some of the little known aspects of the economics of plant disease.

COMPARISON AND COMBINATIONS OF METHODS: -- Of the various methods used in appraising loss from diseases each has advantages and limitations. A method which is entirely suitable for one type of disease may not be applicable to another type. Comparison of yields of plants from inoculated or naturally infested seed with those of plants from disease-free seed is an ideal method for exclusively seedborne diseases, but would be quite unsuitable for soilborne or airborne diseases. Like a well-equipped craftsman, the plant pathologist has at his disposal a variety of tools for ascertaining disease loss, calling for judgment in the choice of a tool or method for any given disease problem. The examples given in the preceding sections may serve as a guide to those methods that have been found most useful in determining loss from various types of disease, and in each case the advantages and limitations of the several methods have been pointed out.

Looking through the literature on disease loss appraisal we find numerous cases in which investigators have made good use of combinations of techniques. Those who have been concerned with cereal rusts have carried out parallel experiments involving sulfur dusting of plants, comparisons of disease resistant and susceptible varieties, infection tests, and artificial defoliation, and the results by the several procedures have been in harmony. EZEKIEL and TAUBENHAUS (1934) used three mutally confirmatory methods in appraising the loss from Texas root rot in cotton.

It may be emphasized that such combinations of two or more loss appraisal methods are often desirable. The results obtained by one technique tend to confirm, correct, or qualify those obtained by another. One method may extend the applicability of another, more intensive method. A combination of methods tends to reveal the shortcomings of any one of them, and the reliability of a conclusion that can be verified by each of several experimental or observational processes makes it more defensible for the various uses of accurate information on plant disease losses discussed in Chapter I.

Chapter X

ANALYSIS AND SUMMATION OF DISEASE INTENSITY-LOSS RELATIONSHIPS

STATISTICAL SIGNIFICANCE IN DISEASE LOSS APPRAISAL STUDIES: -- It has been suggested before, and may be emphasized here, that experiments in determining loss from plant diseases are quantitative experiments, requiring the same techniques in experimental design and statistical analysis of the results as are required in other quantitative biological studies where there is more or less uncontrolled variation in repetitions of treatments, materials, and environments. In particular, the statistical methods used with agronomic field work have a parallel in those required for disease loss studies, and the manuals of statistical methods for agricultural experimenters, such as SNEDECOR'S "Statistical Methods Applied to Experiments in Agriculture and Biology" (Ames, Iowa, 1946), are indispensible guides to reliable experimentation in this field.

In loss studies of earlier years, and occasionally in more recent ones, there has been no attempt to determine the statistical significance of results and we have only such general statements as: "Small percentages of wilt infection did not materially affect yields, but where the larger counts of wilted plants occurred the yields were generally lower." This is not very helpful in trying to arrive at an exact picture of loss.

Statements on the significance of losses may also be misleading when statistical significance and economic significance are not distinguished. In a study of the effect of virus diseases on potatoes, for example, the spindle tuber disease did not cause a "significant" reduction of yield unless 32% or more of the plants were affected, nor did leafroll if less than 24% was present. It is quite evident from other work that there is economic significance to lesser amounts of these diseases and that there would undoubtedly have been statistical significance to losses from the lower percents of disease had the tests been more extensive or more uniform.

Many loss studies might be cited in which exemplary use has been made of approved statistical methods. This is particularly true of recent papers from Canada such as that of M. NEWTON, PETURSON, and MEREDITH (1945) on losses from barley leaf rust, and SALLANS' (1948) study of the effect of root rot on wheat yields, as well as the work of BALD (e.g., 1943b) in Australia. Other good examples of the statistical treatment of loss data are mentioned in the following sections.

CORRELATION BETWEEN DISEASE INTENSITY AND YIELDS: -- When extensive data on disease intensity and yields of diseased and healthy crops are available, the relationship between disease and yield may be simply expressed as a coefficient of correlation. This not only brings out the extent to which disease is responsible for yield reductions, but also, by using partial correlations, it is possible to allocate the fractions of total yield reduction due to several injurious factors acting as a complex.

The study of SALLANS (1948) on the interrelations of common root rot and other factors with wheat yields in Saskatchewan is an excellent illustration of this method. His Table 3 gives simple and partial correlations between preseasonal rainfall, June-July rainfall, air temperature, root rot, insect damage, and yield. It was possible to develop a yield formula which accounted for 77.8% of the variance in yield when these factors were considered, with only 22.2% of the yield variance due to error or unaccounted for. The regression of yield on common root rot was -0.583 with a standard error of ± 0.203 bushels per acre for each increase of one unit in the disease rating, indicating a substantial yield decrease from disease. The variance in yield associated with common root rot was second only to the portion related to June-July rainfall, and greater than the variation associated with preseasonal rainfall, air temperature, or insect damage. The average disease rating for the study was 8.81 units, corresponding to a loss of 5.14 ± 1.79 bu. per acre or one third of the yield harvested, with 95% fiducial limits of 1.55 and 8.37 bushels per acre. The lowest limit here is not far from the annual estimates of loss from root rot in Manitoba and Saskatchewan, indicating that the estimates of losses from this demonstrably destructive disease have been ultra-conservative. These details are given to bring out the usefulness of such analysis of data in appraising losses.

Correlation studies comparable to this have been made of loss factors in cotton (CROWTHER, 1941) and oats (IMMER and STEVENSON, 1928), and the use of simple correlations between disease and yield is illustrated in the work of IMMER and CHRISTENSEN (1928, 1931) and HAYES (1926) on corn smut, and ROBERTSON et al. (1942) on wheat foot rot. The literature also contains data for which correlations could be calculated although this has not been done, as in the case of SALMON and LAUDE'S data on wheat yields, leaf rust, and Septoria leaf blotch, and the excellent entomological paper of C. C. HILL et al. (1943) relating the number of Hessian fly puparia per wheat culm to the percent of culms infested, and this to yield reduction. RIHA (1928) has pointed out the economic advantages that would result if correlation coefficients could be established to estimate in advance the yield reduction from important potato diseases.

CORRELATION BETWEEN STANDS AND YIELDS: -- If the principal effect of a disease is to reduce or thin out stands, the loss caused will be a function of the extent to which stands and yields are correlated. If reduction of stand does not seriously reduce yield, because of compensation for missing plants by greater productivity of adjacent ones, the disease may be of little significance. Many of the available data on disease intensity, especially from seed treatment experiments, are reported in terms of stand, not of yield, but if the stand:yield relationship is known, as well as that between disease and stands, it might be possible to determine losses from disease intensity data on the simple basis that if A:B and B:C are known, A:C can be calculated.

The study of the relationship between yields and the density and uniformity of stands serves several useful purposes. Chief of these, from our point of view, is the way in which such study aids in appraising and interpreting the losses caused by those diseases that have as their principal effect the depletion of stands. In evaluating effects of depleted or irregular stands, whether this is due to disease or other causes, it is helpful to have a sound basis for calculating the theoretical yields of perfect stands, and this can be done by making use of the findings of stand-yield studies. In certain types of experiments, plots must be rogued (p. 294), and stand-yield information enables us to estimate the theoretical yields of unrogued plots. To some extent gaps or missing plants in a stand are compensated for by greater productivity of adjacent plants which make use of the soil, water, light, and space vacated by the missing plants, and stand-yield studies give us a measure of this compensation, whether associated with disease or with other hazards. Finally, stand can be determined early in the season, and where this is well correlated with yield, as it is in the case of corn, it becomes an important factor in the early forecasting of yields (Anon., 1947).

Some of the valuable sources of information on stand-yield relationships are found in purely agronomic studies. Although these have not been concerned with disease the findings are highly applicable to disease loss appraisal, and extensive reference is made to them on this account.

Seedling Disease, Stands, And Yields. -- Investigators of the control of seedling diseases by seed treatment have repeatedly observed that significant increases in stands resulting from seed treatments may not be followed by significant yield increases. This is usually due to use of an excessive seeding rate for treated seed, and most old standard seeding rates are excessive if seed is treated, sometimes extravagantly so. The effects of seedling disease are avoided by planting at such a heavy rate that even after considerable seedling mortality a fair to good stand remains. In such cases, if the seedling disease leaves no residual weakness in surviving plants, the loss is chiefly or entirely measured by the seed waste. If seed treatment tests are to be carried through to yield measurements, and if differences in yield, due to the treatment, are to be demonstrated, it is necessary to reduce the seeding rate to one that would produce a minimum satisfactory stand with treated seed and that would give a deficient stand with untreated seed. Differences in the degree of observance of this requirement evidently explain some of the discrepant results of the effect of seed treatment on yield.

In a similar fashion it is usually necessary to "plant for a stand" and avoid thinning the plants to a uniform stand in order to demonstrate the effects of seedling disease on yield. Where thinning the plants has commonly been the practice in the past, as in culture of cotton or sugar beets, the yield losses from seedling disease are sometimes avoided by excessive seeding rates, and are not seen when lightly-thinned diseased stands are compared with heavily thinned healthy stands, both eventually having equal numbers of plants per unit area.

In such cases, however, there may still be a difference in yields even though the stands from diseased and healthy plantings are thinned to equal numbers of plants. This is the result when seedling disease not only eliminates some plants but has a residual injurious effect on others, such as the "soreshin" of cotton which follows Rhizoctonia attacks on seedlings, so that the adult plants are never quite so healthy, although they are as numerous, as plants in a normal planting. In this respect the effects of disease on yields differ from those of other causes of defective stands (birds, rodents, washing or blowing of soil, uneven planting, etc.), so that it is conservative to apply to disease loss appraisal the results of experiments with induced variable stands.

M^c^NEW (1943a, b, c, d, e), who has submitted some of the most useful data on seedling disease, seed treatments, stands, and yields for peas, lima beans, sweet corn, and spinach, has had the experience (1943e), for example, of securing almost equal stands from treated and untreated peas, 97.0 and 95.9% stands respectively, yet the yield from the untreated plantings was 9% (311 lbs./acre) less than that from the treated seed. In most of M^c^NEW'S other tests there was a high correlation between treatments, stands, and yields. PIRONE et al. (1933) observed that with spinach, stand reduction and yield reduction were almost equal numerically, indicating either no compensation for missing plants by the remaining ones or a residual effect of the disease that offset the benefit of compensation.

There is another valuable source of data on seedling disease, stands, and yields in the work on sugar beets by AFANASIEV and MORRIS (1942, 1943), MORRIS and AFANASIEV (1945), and AFANASIEV (1945). Their experiments, in which the amount of seedling disease was controlled by fertilizer treatments, show that for every increment of 5% of disease there was approximately 3.5% reduction in yield. This is indicative of some compensation for missing plants, but the compensation effect may have been greater than could be detected because of the observed contrary yield-reducing residual effect of lasting injury in plants which survived disease attacks in the seedling stage but failed to develop normally.

In these cases in which yield increase, because of compensation, and yield decrease, because of residual effect of seedling disease, obscure one another, it would be possible to separate the two effects and measure each separately by suitable experiments. Compensation could be measured in healthy stands that are reduced by thinning, while the residual effect could be determined by comparing stands of equal density but consisting, respectively, of healthy plants and plants that have survived seedling disease.

Stand Variability And Yields Of Corn. -- The data on variable and depleted stands in corn, all of which are purely agronomic, make this a particularly well-documented example of stand-yield studies and their usefulness to disease loss appraisal. A number of investigators have found a good correlation between stand and yield in this crop, so reliable in fact that the relationship can be used in forecasting corn yields (Anon., 1947), and in calculating the theoretical yields of perfect stands, having only the data from imperfect ones (OLSON, 1928).

This relationship is not a numerically equal one unless the plants of a perfect stand are so widely spaced that each plant has all the space it can profitably use. More commonly they do not have this, and as a result, plants adjacent to a missing hill profit by this and produce yields somewhat above those of plants at normal spacing. If a normal, complete stand is taken as 100%, a 50% but fairly uniform stand will not produce 1/2 as much corn but about 2/3 as much, a 65% stand 4/5 as much, and a 90% stand 97% as much corn as the 100% stand (HUGHES and HENSON, 1930), because of compensation.

This relationship holds for stands in which the 100% stand is not planted at an excessive rate. OSBORN (1925) has shown that under favorable weather conditions corn stands and yields are correlated up to 9,000 or 10,000 plants per acre, but above this density yields fall, rather than rise, with increase in stand. The workers with corn have found that various corn varieties differ in their optimal densities of stand (cf. E. B. BROWN and GARRISON, 1923), and that for a given variety the optimal density varies with seasonal weather, being lowest under dry conditions (E. B. BROWN and GARRISON, 1923; OSBORN, 1925).

The extent of loss from missing plants and compensation by adjacent plants of corn is seen in the experiments of KIESSELBACH (1918) and of BREWBAKER and IMMER (1931). Where a 3-plant hill is considered normal, a 2-plant hill surrounded by normal ones yields 76-85% as much as normal: although the stand is reduced by 33% in this case, the yield is reduced by only 15-24% since the two remaining plants develop more strongly than they would in the normal presence of a third one. Similarly a 1-plant hill surrounded by normal ones has its yield reduced only by 40-74%, and with a single missing hill the reduction is not 100% of the normal yield of one hill, but only 67%.

Looked at from the opposite point of view, that of increased yield in the favored hills, a 3-plant hill adjacent to a 2-plant hill has 2.3% yield increase over normal, if adjacent to a 1-plant hill it is 5-9%, if adjacent to a single missing hill it is 13-15%, and if adjacent to two missing hills the increase in the 3-plant hill is 25-43% over normal yield, in the experiments of KIESSELBACH. Others report similar trends though with different numerical values, doubtless owing to different responses of types of corn and different environments. If weeds are permitted to occupy the positions of missing plants, the advantage of compensation may be largely or entirely lost, as has been observed in wheat (MACHACEK, 1943).

The investigations have shown that corn will tolerate a considerable amount of variability in stand without serious effect on yield, provided the total number of plants per acre remains constant. For example, KIESSELBACH (1922), and KIESSELBACH and WEIHING (1933), varied the number of plants per hill in different ways all of which gave averages of 3 plants per hill, and obtained yields for the uniform 3-plant-hill arrangement (3-3-3-3) of 59.0 bu./acre, for the arrangement 2-4-2-4, 59.2 bu., for the arrangement 1-3-5, 56.0 bu., and for the arrangement 1-2-3-4-5, 58.6 bu.

OSBORN (1925) who also found marked ability of corn to compensate for missing plants, has explained that this compensation takes the form of larger ears, more ears per stalk, and more tillers. A variety with a strong tendency to tiller may produce a stand of approximately 5000 stalks per acre from a 3000 seeding rate.

Effect Of Missing Or Diseased Hills Of Potatoes. -- Turning to the work with potatoes, much of which has been motivated by an interest in losses from virus diseases, we find a similar but more fully documented situation. The work was begun by FITCH and BENNETT (1910), followed by STEWART (1919, 1921), LIVERMORE (1927), and FOLSOM et al. (1931), all of whom found that when there is one missing hill in a row the adjacent plants on each side of the skip together make up about one half of the normal yield of a hill, leaving a loss of 1/2 hill. If the skip consists of two or more consecutive missing hills, all workers except LIVERMORE found that the adjacent plants fail to compensate for any more loss than 1/2 hill, so that a skip of 2 hills would be 1 1/2 hills loss, a 3-hill skip, 2 1/2 hills loss, etc. All investigators agree that the effect of missing hills is much influenced by soil, climate, and potato variety.

It is at once apparent that this compensation effect must be considered in evaluating losses from potato diseases. If adjacent plants compensate, to some extent, for missing hills they probably also compensate for hills of weak and sickly plants, and a comparison of hill yields, above all of yields of adjacent diseased and healthy plants, would exaggerate the loss from disease. The compensation effect will also be influenced by the arrangement of diseased hills among healthy ones, and it will decrease as the disease infestation approaches 100%.

This problem has been analyzed, mathematically and experimentally, in important studies of BLODGETT (1931) and BLODGETT et al. (1931). Healthy plants (H) and diseased plants (D) may be divided into 6 classes according to their arrangement in the row, with respect to the nearest two adjacent plants, as follows: HHH, DHH or HHD, DHD, DDD, DDH or HDD, and HDH. If p is the fractional part of plants diseased and q = 1-p, the frequency of these 6 classes for any given amount of disease is respectively q^3, $2pq^2$, p^2q, p^3, $2p^2q$, and pq^2. The yields of the middle plants in each of the 6 classes can be measured, and summation of the products of yield of each class by class frequency gives the estimated yield of similar potatoes with any given frequency of disease. Use of such a formula enables one to derive the loss from disease with full consideration being given to compensation effect and random arrangement of diseased and healthy plants in the field.

If this is applied to missing plants there will be only 3 classes (DHD, DHH or HHD, and HHH), since there is no yield from any class having D as the middle plant, which is the one measured for yield.

If there is 10% disease in the field the chance of finding a DHD combination is .1 (i.e., 1/10 chance of finding the first D) x .9 (the chance of finding the H after the D) x .1 (the chance of finding the D after the DH), or .9%. Using a similar procedure, BLODGETT (1941, Table 1) has calculated the percentage for each plant combination for 0, 10, 20, ...100% disease infestation.

Field studies with the potato leafroll disease, made by TUTHILL and DECKER (1941) using this method, have shown that healthy plants partly compensate for the losses in adjacent diseased plants, but that there is little or no difference in the low yields of leafroll plants, whether or not the adjacent ones are diseased or healthy. The more extensive field trials of KIRKPATRICK and BLODGETT (1943) showed that a healthy plant with a leafroll plant on one side (DHH or HHD) outyielded HHH by 16.8%, while leafroll plants gained 4.2 and 8.1% from having leafroll plants on one or both sides respectively. The effect of different percentages of leafroll in these experiments, calculated by BLODGETT'S method, is shown in Figure 27. The field studies have confirmed the view of BLODGETT that there is a basis for accurately appraising yield loss, with due consideration of plant arrangement and compensation effects, by determining the yields of the central plants in the 6 arrangement classes. This would seem to apply to nearly all tuber-transmitted potato diseases, to missing hills, and to any row crop where competition occurs between adjacent plants, and it has value either in evaluating loss or in estimating the disease-free yielding capacity of a variety even though fields of this variety have known percentages of disease.

Stands, Yields, And Compensation In Other Crops. -- Barley behaves like corn in having considerable ability to compensate for uneven spacing, with little difference seen in yields from evenly and unevenly spaced plantings (SPRAGUE and FARIS, 1931). Studies on the barley stripe disease, which causes total loss in affected plants (SUNESON, 1946), have shown a 3/4% yield reduction for each 1% of stripe, indicative of 25% compensation for deficient stands. With small-grains, which are not cultivated, there is a tendency for weeds to occupy the positions of missing plants, which prevents compensation for space and increases loss (SALLANS, 1948). The artificial removal of heads of small-grains is associated with a minor degree of compensation (HEUSER and BOEKHOLT in LUBISHCHEV, 1940). This has practical application in connection with head smut diseases such as bunt of wheat, where the yield reduction is slightly less than the smut percent (KIESSELBACH and LYNESS, 1939), although LEUKEL (1937) accounts for this by a more abundant stooling in infected plants rather than by compensation.

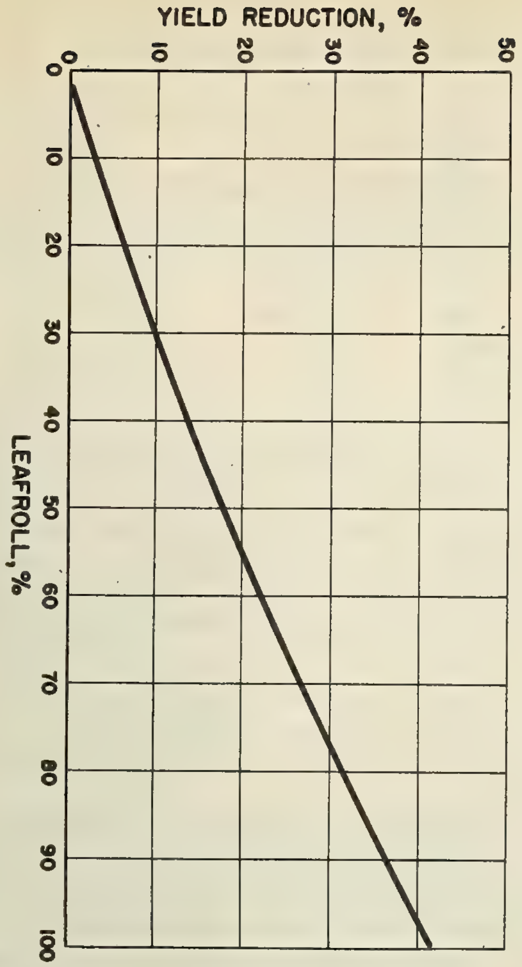

Figure 27. Relation between percent leafroll and yield reduction in three varieties of potatoes during three years. (From data of KIRKPATRICK and BLODGETT, 1943.)

With sugar beets, compensation for stand defects due to seedling disease was discussed on page 318. In contrast, the studies of WATSON et al. (1946) showed no compensation by adjacent beet plants for losses due to virus yellows.

Cotton, resembling corn and potatoes in its row culture, and being a crop in which stand defects are common, is a good crop in which to study the effects of stand variability. WARE and YOUNG (1934), who observed no loss from the killing cotton wilt disease (Fusarium) unless the wilt percent was 10% or even considerably higher, attributed this to compensation by healthy plants adjacent to diseased ones, but CHESTER'S (1946a) analysis of cotton wilt losses indicates that any amount of wilt causes some loss. Each increment of 5% wilt is associated with 3% loss, but this may be due more to the fact that wilt-infected plants produce some cotton than to compensation for this mid- to late-season disease.

A thorough study of the effect of missing row segments on cotton yields has been made by POPE (1947), who found that in single-row plots a three-foot skip is fully compensated for by the adjacent plants, while any skip longer than this causes a loss directly proportionate to the length of the skip, minus three feet. When skips are in a row bordered on each side by normal rows, the skips are largely compensated for by the plants at the ends of the skips and the plants in rows adjacent to the skips. Cotton is able to compensate for missing plants to a fairly high degree, and if a stand is uniformly thin, without long skips, there is little loss in yield as compared with that of denser stands.

The most outstanding cases of compensation for reduced stand are seen in forestry, where initial stands are far too dense to produce merchantable timber, and more or less radical thinning is regularly followed by space compensation by the remaining, marketable trees. The necessary thinning may be by various agencies, including natural hazards, suppression by the dominant trees, and selective harvesting. Disease is an important agency for thinning stands. This may be very harmful in the cases of those diseases of pure stands which destroy trees in patches up to several square miles in area. In other cases, much of the effect of the disease may be beneficial and necessary thinning, so that the loss is far less than indicated by the percent of trees destroyed. MEINECKE (1928) has reported, for example, that in one plot of pine 21% loss of trees from Comandra rust was a wholesome and beneficial thinning of an over-stocked stand, and even in a second plot where 65% of the trees were killed, the net result was to reduce the stand to only 32% below the Forest Service optimum.

FORMULAS OF DISEASE INTENSITY-LOSS RELATIONSHIPS: -- The expression "coefficient of injury (or damage)" has been used by various investigators with different meanings, in their attempts to find single numerical expressions of loss in relation to disease intensity. The "injury coefficient" of GASSNER and STRAIB (1936) is the percent reduction in yield for each week of duration of attack by disease (cereal rust) of a given intensity; for example, that of moderate stripe rust of wheat was 3%, and of severe rust 5%, yield reduction per week of rust infestation. The German workers consider these coefficients as conservative measures of rust damage, and recognize that the coefficients will vary with a given amount of rust in different environments, and in the same environment with differences in the extent to which the rust species interferes with the physiology of the host plant.

KLEMM (1940) has used the same term "injury coefficient" for the expression $Q = \frac{(a-b)\,100}{a}$ where a = yield of healthy plants and b = yield of diseased plants. The loss, $C = \frac{P.Q}{100}$ where P = the number of injured plants. Here Q is simply loss percent and P the percent of the crop affected.

In similar fashion, YACHEVSKI (1929) used a term "coefficient of damage" to express the relation of yield under definite conditions of disease (b) to yield of healthy plants (a), or $\frac{b}{a}$, with a maximum of 1 for a healthy crop, which, if multiplied by 100, would give the percent of a normal crop remaining after disease has taken its toll.

The "coefficient of damage" of LUBIMENKO (1933) is "that factor by which it is necessary to multiply the degree of damage to the vegetative organs in order to obtain the actual effect of the damage, *i.e.*, the amount of loss in quantity and quality of the yield. This was used in artificial defoliation experiments with the form $\frac{\text{percent yield reduction}}{\text{percent leaf reduction}}$, and might equally well be applied to any disease that defoliates plants.

LUBISHCHEV (1940), who criticized LUBIMENKO'S "coefficient of damage" on rather untenable grounds, has introduced the concept of "threshold of injury", to indicate the maximum degree of injury, *e.g.*, percent of leaves removed, that can be borne without loss in yield. This, regarded from the practical viewpoint, is an expression of the greatest amount of injury that is not accompanied by observed yield reduction and is more a measure of our ability to detect losses than of the plant to endure injury without loss. For practical purposes, 5% loss of leaves may be regarded as non-injurious but careful measurements show that any degree of defoliation has its effect, however small, in reducing yields.

Finally a fourth Russian worker, NAUMOV (1939), has given the expression "coefficient of injury" a still different meaning in his formula $R\frac{y}{x}$, where y = actual yield and x = amount of yield of diseased plants expressed as percent of theoretically normal yield. The values range from zero for a healthy crop to infinity for a completely diseased one. This is further developed, in studies of cereal rust damage, into a more complex formula involving tiller height from which NAUMOV indicates that regression of yield on any amount of rust infection can be calculated.

These several types of coefficients can be compared by making use of a concrete illustration. Suppose that a crop, which under disease-free conditions would yield 20 bushels per acre, is subject to a disease that destroys 30% of the leaves during a 5-week attack and reduces the yield to 15 bushels. KLEMM'S coefficient would be 25 (*i.e.*, 25% loss), YACHEVSKI'S would be 75 (*i.e.*, 75% of a normal crop), and NAUMOV'S would be .2 multiplied by some constant, which is not readily comparable to usual loss measures. LUBIMENKO'S coefficient would be 83.3 which relates leaf injury to yield reduction, the latter being expressed as simple percent loss (25%). GASSNER and STRAIB'S injury coefficient would be 5% loss per week of disease attack.

The coefficients of LUBIMENKO and of GASSNER and STRAIB are related to the physiology of injured plants and to the effect of disease in time, respectively, and therefore they have special uses apart from the main problem with which we are concerned, -- relating disease intensity to disease loss. The coefficients of KLEMM and YACHEVSKI are simplest and most understandable, and differ only in the point of view, -- whether attention is focused on the fraction of yield that was lost or the fraction of yield that remains. Neither, however, gives proper attention to disease intensity, as do the disease intensity-loss tables and regressions discussed below.

DISEASE INTENSITY-LOSS TABLES: -- Tables in which the approximate amount of loss is given for each of a series of disease intensities are useful devices for loss appraisal, but except in forest pathology very few of these have been made available. Best known, perhaps, is the table relating wheat stem rust severity at different stages of crop development to loss. This was prepared by the Office of Cereal Crops and Diseases of the U. S. Department of Agriculture and first published by KIRBY and ARCHER in 1927, and is here reproduced as Table 6. NAUMOV (1939) claims that this table does not apply to losses under conditions of wheat culture in Russia. CHESTER (1946*b*, p. 23) has presented a similar table for losses from wheat leaf rust.

LECLERG and his associates (1946) have published a table relating percent of virus-infected potato plants to reduction in yield of No. 1 tubers for five potato varieties and two virus diseases, spindle tuber and leafroll, each at seven intensities. The table shows some variation in loss between varieties and seasons but is nevertheless helpful in gaining an approximate indication of the losses from these diseases.

TIMBER CULL TABLES AND CURVES: -- The higher degree of development of forest disease appraisal than that of diseases of other crops is seen in the many useful tables and curves relating loss (cull) to observable indices of wood decay. Cull tables and graphs are developed by dissecting a large number of trees, correlating the decay found with external symptoms of decay and with

Table 6. Relation between wheat stem rust severity and loss in the crop (from KIRBY and ARCHER, 1927).

State of Development of the Crop						Loss from stem rust
Boot	Flower	Milk	Soft Dough	Hard Dough	Mature	Percent
. .	. .	. .	. .	(tr)	5	0.0
. .	. .	. .	(tr)	(5)	10	0.5
. .	. .	(tr)	(5)	(10)	25	5.
. .	(tr)	(5)	(10)	(25)	40	15.
(tr)	(5)	(10)	(25)	(40)	65	50.
(5)	(10)	(25)	(40)	(65)	100	75.
(10)	(25)	(40)	(65)	(100)	100	100.

size and age of tree, and formulating general relationships with stated, permissible degrees of error. The two examples given here serve to show the nature and value of these devices.

An excellent illustration of a well-devised cull table is given in a recent paper by ZILLGITT and GEVORKIANTZ (1948). The external symptoms are listed and described, including broken or dead limbs or tops, butt-rot, cankers, hidden rot, conks, cracks, crooks or sweeps, holes, ingrown bark, rotten burls, scars and seams. Each of these, where applicable, is divided into subgroups according to position of the defect within the merchantable length of a tree and according to condition or degree (large or small ; slight, moderate, or excessive; active or inactive). Then, for each symptom subgroup is given the percent of cull for 1-, 2-, 2 1/2-, 3-, and 4-log trees. To determine cull is a simple matter of multiplying the gross volume of the tree by the cull percent shown in the table for each defect present or the sum of cull percents in case of more than one defect.

An example of a somewhat different nature is found in HEPTING's (1941) study of the prediction of butt cull following fire. It was found that butt cull was highly correlated with width and age of fire wounds. An equation was developed from tree analysis data relating these three factors, and this is graphically illustrated in the curves of Figure 17 (see page 251), which were derived by multiple regression analysis. Aided by such graphs, cull volume can be estimated, with a practically sufficient degree of accuracy, knowing the age and width of the basal wounds.

As with other aids to loss appraisal, the cull curves and tables developed for a given species, habitat, and pathological situation, apply to stands and conditions of a similar sort but cannot be applied more generally unless it has been demonstrated that the disease-cull relationships have broader application.

REGRESSIONS OF DISEASE INTENSITY ON YIELD: -- Regressions, straight lines or curves depicting the relationship between disease intensity and yield, are among the most useful devices for translating disease into loss, and have been used very sucessfully in studies of the losses caused by numerous types of disease. A regression tells us, for each unit of disease intensity, the percent or amount of loss resulting.

The quantities related by regressions to yield may be any of the various measures of disease and include disease intensity as expressed in scale values, or indices, proportion of plants or plant parts occupied by disease, or time during which the crop has been exposed to disease.

When a regression of disease on yield is available, for any given disease intensity one can read off the amount of loss directly, interpolating between experimentally-determined points. If loss is measured in experiments in which different degrees of disease are compared but there are no completely healthy or totally diseased plants, the regression line can be extended to the zero and 100% disease points permitting one to determine loss values at disease levels beyond the range of those of the experiment, by extrapolation. If time or duration of disease is the quantity related to loss, the regression gives the basis for forecasting loss, as has been done with sugar beet yellows (WATSON et al., 1946).

While regressions are convenient ways of expressing disease loss relationships, they are only as valid as the data from which they are derived. We have seen that disease intensity-loss relations may vary with variety of crop, strain of pathogen, and environment in which disease develops. The regression of disease on yield derived from data that apply only to certain limited conditions, will itself have application only to those conditions. Fortunately, many of the findings of loss appraisal experiments have rather wide application within the range of error that is permissible for loss estimation (cf. pp. 220-221).

The methods of deriving regressions and testing them for significance and for linearity are to be found in standard works on statistical methods. A good illustration of their use is found in GREANEY'S (1933b, 1934) studies of the effects of stem rust on yields of wheat and oats, based on sulfur-dusting experiments. His regressions of yield on percent stem rust are reproduced in Figure 28.

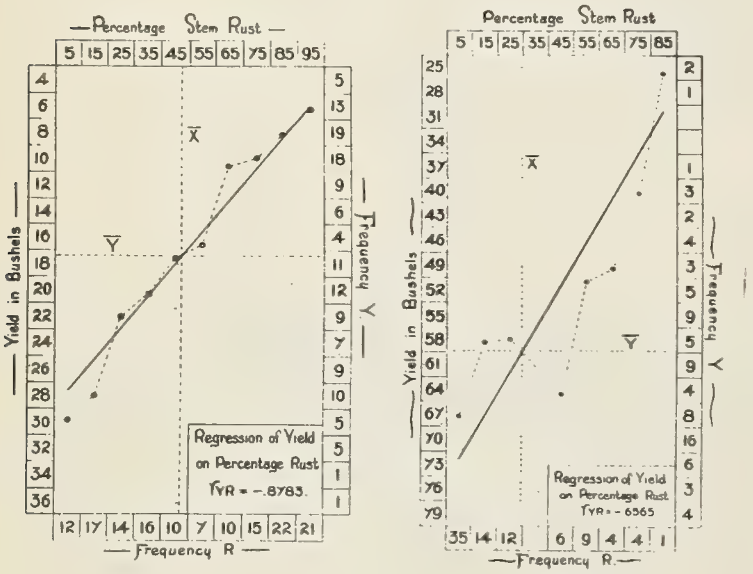

Figure 28. Regression of grain yields on percentage stem rust according to the modified COBB scale. Left: Marquis wheat. Right: Victory oats. From 1930 experiments of F. J. GREANEY (1934).

In this, as in numerous other studies, it has been found that the regression is linear, i.e., an increase from 10 to 20% rust decreases the yield by the same amount as an increase from 70 to 80% rust.

In the study of wheat, the regression showed that each 10% increase in rust resulted in a 2.1 bushel per acre decrease in yield, representing 6.9% of the possible yield, while with oats each 10% of rust lowered the yield by 4.7 bushels, representing 7% of the possible yield. In both cases the correlation coefficients were high (-0.88 and -0.66) with odds for significance much greater than 100:1.

When a study is made of several factors each of which simultaneously affects yield, the partial regressions of yield on each factor can be calculated, making this a useful manner of determining the relative effect of each factor influencing yield. This was the method used, for example, by SALLANS (1948) in distinguishing the effects of preseasonal rainfall, June-July rainfall, air temperature, root rot, insect damage, and yield of wheat. It showed that for each increase of one unit of root rot intensity there was a decrease of 0.583 ± 0.203 bushels per acre of yield, a drain on the crop equalled only by that of deficient rainfall in June and July.

Using regressions one can analyze a series of interwoven factors related to disease and yield, as was done by WIANT and STARR (1936) in work on bacterial wilt of alfalfa. The wilt problem is interpreted through regressions of wilt on stand, wilt on age of field, age of field on stand, and wilt on winter injury lesions. This study shows that not all disease-yield regressions are linear. That of wilt on age of field is practically linear, with an increase of approximately 12% of plants affected each year from the first to the fifth years of stand age, and then becomes horizontal, with little increase in wilt percent from the fifth to eighth years. This change is explained by the death of diseased plants after the fifth year, which eliminates plants at the same rate at which new cases of disease occur. The regression of wilt on winter injury lesions is a curve in which each increment of lesions is associated with a greater increment of wilt than the preceding increment of lesions.

Other studies that illustrate the usefulness of analyzing disease intensity-yield data by use of regressions are those with the cereal rusts by GOULDEN and ELDERS (1926), GREANEY et al. (1941), and WALDRON (1928), with loose smut of barley by SEMENIUK and ROSS (1942), and with cereal root rots by MACHACEK (1943) and SALLANS and LEDINGHAM (1943).

The literature on plant diseases and their effects on yields contains many raw data that would be suitable for analysis by use of regressions, although this has not been done in the published reports. An example is the body of data on potato leafroll and yields published by GRAM (1923). "Healthy" (somewhat diseased) and "diseased" (somewhat healthy) potatoes were planted at each of 12 locations in Denmark during 5 years, the seed tubers for each year being those harvested from the experiment the preceding year, with much variation in disease percent from year to year. On inspection the data appear so heterogeneous as to defy interpretation, nor did GRAM attempt to interpret them from the standpoint of disease loss but only from that of annual disease increase. There is no zero point and no 100% disease point, but instead many comparisons of yields of stocks with greater or less disease intensities, under different environments.

J. H. M^CLAUGHLIN (unpublished) analyzed these data by the regression method and obtained the highly significant coefficient of correlation between disease percent and yield of $\underline{r} = -0.9369$. A linear regression fitted the data best and this showed that for every 1% increase in leafroll there was a decrease of .1599 centners per hectare which approximately equalled a 0.67% yield decrease. This value is in good agreement with independent measurements of loss from leafroll. The analysis by locations and by years showed that the intensity-loss relationships were more constant between locations in any one year than between years at any one location.

M^CLAUGHLIN'S analysis of GRAM'S data is an important technological contribution in showing how data that were not intended for loss study may be useful for this purpose, how apparently heterogeneous data yield to analysis by the regression method, revealing highly significant disease intensity-loss relationships, and how additional conclusions to those drawn by the author, in this case on the epiphytology of the disease, are brought out by approximate analysis.

The success seen in this example indicates the fertile source of disease loss information that lies hidden in many papers comparable to that of GRAM, and suggests the value, to the student of loss appraisal, that lies in a search for such data and their appropriate analysis.

EXTENSION OF LOSS CALCULATIONS TO LARGE REGIONS: -- In summarizing disease loss data for States, Provinces, or countries, either of two practices may be followed. The disease intensities for numerous sub-areas may be averaged, with weighting for the crop acreages of the sub-areas in the fashion described on page 256, and the final mean disease intensity may then be converted into terms of loss. More commonly, when the object is to determine total loss for a region, disease intensities for the sub-areas are converted into terms of loss, in percent or in units of production, and the individual losses are summated or averaged, weighting for the sizes of the crop areas involved, to give a single figure for total loss.

In the annual loss summaries of the Plant Disease Reporter a standard, common practice of loss summation is used. This is described in Supplements 6 (1918), 12 (1920), 83 (1932), and 94 (1936) of the Reporter. In calculating losses it is considered that:

$$\text{Possible production} = \frac{\text{Actual production}}{100\% - \%\text{ loss from disease (s)}}$$

The loss caused by disease is then taken as the product of possible production x percent disease loss. If disease is causing a 50% loss in a crop that actually produced 1000 bushels, the loss is not 500 but 1000 bushels, because the 1000 bushels was only half a crop; a 100% crop would have been 2000 from which 50% disease loss subtracted 1000 bushels, leaving 1000. The fallacy of determining loss by multiplying actual production by percent loss is sometimes encountered; this fallacy is avoided by using the technique followed by the Plant Disease Reporter.

In calculating the mean percent loss for the United States the loss for each State, in production units, is determined as above, and these are totalled and divided by the possible national production in the absence of disease. Examples of these calculations are given in Supplement 83 (1932) of the Plant Disease Reporter. The loss estimates are expressed in percent of crop loss or in production units but never in dollars "because of the complex economic considerations which this would involve". (This point is discussed on page 342).

Essentially the same method of summarizing national losses from disease has been used by the German plant protection service (MORSTATT, 1929, 1937). An example of use of this method in a special survey is seen in H. D. BROWN'S (1929) determination of the loss caused by Septoria leaf spot in the Indiana tomato canning crop. All fields examined were classified as healthy or in two degrees of disease. Actual yields of fields of the three types were ascertained and the differences between yields of diseased and healthy fields gave a measure of loss in tons of tomatoes. Knowing the total inspected acreage, the actual yield of the inspected fields, and their possible yield (total acreage x acre-yield of healthy fields), the loss in percent could be readily calculated, and from this loss percent and the actual State yield BROWN determined the possible State yield and the State loss in tons and dollars.

A comparable practice is illustrated in appraisal of the damage done to the Texas cotton crop by the root rot disease, reported by EZEKIEL (1938). Many cotton fields were scanned from the roadside and the loss percents estimated, These were averaged for each county, weighted for the cotton acreage of the county, and combined to give the State loss in percent and bales.

GREANEY'S estimates of cereal rust losses in Canada (1933a, b, 1936) represent use of the method of summarizing disease intensities and finally converting these into summarized loss estimates. Having determined the regression of yield on percent rust, he was able to translate any given rust intensity into percent loss. Then, having ascertained the average rust intensities in numerous sub-areas from the Canadian plant disease survey data, and the actual production from the Provincial Departments of Agriculture, it was a simple matter to convert disease intensity to loss in percent, bushels, and dollars, on a national scale.

An analogous practice was used by HORSFALL (1930) to estimate losses from meadow crop diseases in New York. It was first determined in the case of Macrosporium leaf spot of red clover, for example, that each 1% of leaf spot infection results in a 0.25% hay loss. Next the mean percent of infection for the State was estimated by summarizing the individual products of acreages x infection percents and dividing by the total acreage. Finally the loss percent corresponding to the mean infection percent was applied to the State yield to give the State loss in tons and dollars.

APPLICATION OF LOSS RATIOS TO DISEASE INTENSITY DATA: -- The foregoing illustrations show how the disease intensity-loss ratios, derived by experiment, can be applied to data on disease intensity to give reliable estimates of loss in terms of percent, production units, or financial loss. By far the greater part of recorded plant disease survey data is in the form of disease intensities. As more intensity-loss ratios are determined, we can go back through the records of disease intensity and convert them into loss estimates. GREANEY'S regressions of cereal yields on stem rust, for example, can be applied not only to current rust attacks but also to rust outbreaks of past years, as far back we as have any reliable information on rust intensity, giving us a record of losses down through the years. The same can be done with the loss ratios that have been derived for cotton wilt, root rots of cereals and cotton, virus diseases of potaotes and sugar beets, and any other disease for which we have such ratios. The planners of agricultural progress think in terms of decades or greater fractions of centuries, and the value to them of having the costs of agricultural hazards on a comparable basis is patent.

We are just at the beginning of this important application of plant disease appraisal. Few disease intensity-loss ratios have yet been derived and many more are needed. Fewer still are the cases in which these ratios have been applied to the disease intensity data of past years. The only two instances of this that have come to hand in the course of the present study are in connection with GREANEY'S work with cereal stem rust and BUTLER'S (1940) application of his wheat leaf rust intensity-loss relationship, derived from sulfur dusting experiments, to earlier New York rust data. The derivation of loss ratios and their use in converting recorded disease intensities to loss estimates is one of the most promising methods that can be suggested for obtaining extensive and reliable loss data with minimum labor and cost.

Chapter XI

FORECASTING PLANT DISEASE OUTBREAKS AND LOSSES

Science is concerned with the discovery of causation of natural events, and when the principles of causation are sufficiently well known, science reaches its goal of permitting the accurate prediction of events on the basis of known antecedent circumstances. The study of disease appraisal is no exception. Any instance of the estimation of disease intensity and conclusion, based on experiment, that this disease intensity will result in that given degree of loss, is a prediction from cause to effect, a legitimate application of the scientific method. In plant disease appraisal, this usage reaches its highest development when a knowledge of disease intensity-loss relationships is combined with an understanding of the progressive changes in disease intensity itself, permitting one to predict accurately that the pathological situation of the moment will be followed by certain developments in disease intensity, and that these, in turn, will result in a given degree of loss.

The subject of plant disease forecasting was mentioned in Chapter I (p. 207) where the economic value of such forecasts was pointed out. Here we are concerned with the methods and accomplishments of disease forecasting.

PLANT DISEASE IN YIELD FORECASTING: -- Forecasting plant disease intensities and their effects is a special branch of the subject of yield forecasting. In the past, the forecasting of crop yields has been largely guesswork by men varying widely in knowledge of crop conditions and in judgment. As a result, yield forecasts are often far from correct, even when made just before crops are harvested. Faulty estimates are almost invariably "explained" in terms of decisive influences of late-season weather which could not have been foreseen, rather than in terms of ignorance of, or misplaced emphasis on, the more truly decisive early-season influences.

Recently attempts have been made to substitute science for intuition in yield forecasting. Two elements have aided in this: the establishment of correlations between early-season crop characteristics and yield, and the use of long-range weather forecasts to take some of the guesswork out of the late-season weather factor. The scientific forecasting of yields is a major project of the Iowa State College Statistics Laboratory, and good progress has been made in increasing the accuracy of the corn yield forecasts by basing early predictions on seasonal development, soil moisture, stand counts, stalk size, ear counts, and measurements of ear size, with correction based on the long range weather forecasts (Statlab Review, Sept., 1947 and May, 1948).

In a similar fashion, CROWTHER (1941) has evolved scientific methods for forecasting cotton yields, based on a study of correlations between yield and leaf nitrogen of seedlings (a reflection of soil fertility and index of potential growth vigor), plant height, internode length, number of blossoms, leaf and stem dry weights and nitrogen content, defoliation, and degree of infection by the black-arm and leaf-curl diseases.

For the most part, attacks by insects and plant diseases have not been considered in yield forecasts except as unpredictable hazards that might explain incorrect forecasts. Their inclusion would go far in contributing to more accurate yield forecasts. It is not entirely that these hazards have been overlooked nor are they entirely unpredictable. This defect is due in an important measure to the fact that plant pathologists and entomologists have not provided the basic information relating environment, disease or insect intensity, and ensuant losses, that would permit the inclusion of these hazards in yield forecasting.

THE BASIS FOR PLANT PEST FORECASTING: -- Contrary to lay opinion, outbreaks of plant pests do not suddenly occur without warning. Forty years ago SORAUER (1908) called attention to this: "In all endemics and epidemics a simultaneous sickening of a great number of individuals indicates a considerable period of preparation leading up to the actual outbreak of the malady..... Each epidemic is, so to speak, the explosion of a charge which has been slowly accumulating for some time." With plant pests as with political movements, ascendancy is a surprise only to those whose eyes have been closed to the progressive development of the pest or ideology, from small to ever larger proportions.

The basis of plant pest forecasting is a careful, thorough study of the survival of pests and the early stages of their seasonal increase. This has been stressed in studies on the forecasting of wheat leaf rust outbreaks (CHESTER, 1946b, p. 151-152). It has been shown that destructive rust outbreaks must be preceded by many generations of rust increase, weeks or months before the disease becomes apparent to the layman. If these early generations occur, subsequent destructive rust is inevitable, and if they are inhibited there is not sufficient time in the remainder of the growing season for rust to increase to damaging extent. The early generations of rust increase are not readily apparent, and it may require long hours of search and counting to chart the course of rust development early in the growing season, but if this is done it permits reliable forecasting of rust long before harvest time, as has been shown by the accurate wheat leaf rust forecasts of the past decade.

Together with observations on the development of plant pests, forecasting requires a knowledge of the effects of environment on their increase, so that long-range weather forecasts may be applied to future pest increase. In the case of wheat leaf rust again, enough is known of the relationships between temperature, moisture, and rust development to give assurance that once a certain date has been passed (April 1, in Oklahoma) the odds are highly against weather that will interfere with rust increase, the course of the disease in late season being chiefly dependent on early-season weather. For purposes of disease forecasting, DOROGIN in Russia (in YACHEVSKI, 1929) considers it necessary to have information on air, soil surface, and subsoil temperatures and humidities, amount and type of precipitation, cloudiness, depth and duration of snow cover, and strength of prevailing winds, and to know the effects of these factors on the disease in question. It is self-evident that the particular types of information on environment that are needed for forecasting will vary from one disease to another.

DISEASE TEMPO AND FORECASTING: -- Forecasting plant disease intensities and losses is materially aided by knowledge of the tempo of disease development, a subject discussed on pages 234-237. Disease tempo is an expression and a resultant of the interplay between reproduction of pathogen, environment, and host plant response. From a study of disease tempo under given conditions, it becomes possible to predict that under similar conditions in the future the intensity of disease will progress in a similar manner, and to predetermine the intensity of the disease at any given future time. Where disease tempo depends on unpredictable future conditions, a knowledge of this fact brings out the limitations of reliable forecasting.

Some diseases progress at a fairly regular rate that is relatively insensitive to normal weather fluctuations. In such cases the tempo is expressed by the regression of disease intensity on time, and the forecast of disease intensity at any given time in the future can be read directly from the regression line. The table of losses from wheat stem rust of KIRBY and ARCHER (1927), reproduced on page 323, is based on the assumption that rust intensity increases with time at a regular rate, and, to the extent that this assumption is correct, it permits forecasting both future rust intensity and ultimate loss. Similarly, the linear regression of loss on symptom expression with sugar beet yellows (WATSON, et al., 1946) can be used in forecasting yields and enabling beet factory operators to make appropriate provision for receiving the crop.

FORERUNNERS OF THE UNITED STATES WARNING SERVICE: -- In America current interest in plant disease forecasting centers in the warning service of the U. S. Plant Disease Survey, an outgrowth of the potato and tomato late blight forecasting developed during World War II. It does not appear to be commonly known in America that forecasting or warning services for potato late blight and downy mildew of grape were initiated in Europe a quarter-century ago and became highly developed during the 1930's.

In France and Italy, the vine mildew warning service developed in parallel fashion, with networks of observation stations and wide publicity of warnings of imminent mildew attacks. In Germany spray warnings were based on MÜLLER'S "incubation calendar", while in Russia this calendar was variously modified to adapt it to local conditions. In the discussion that follows, to avoid unnecessarily extensive citation of papers, references are limited to those of abstracts of the papers in the Review of Applied Mycology, by volume and page.

VINE MILDEW FORECASTING IN EUROPE: -- As early as 1922, a vine spray warning service had been organized in Italy (R.A.M. 2:6; 4:526; 8:150; 9:158; 10:21; 11:692; 12:73, 199; 15:735; 16:86, 152, 230, 513). Meteorological conditions likely to influence disease outbreaks were reported from stations in three Provinces and forwarded to Turin where the data were compiled and, as soon as the information indicated favorable conditions for spore germination and infection, spray warnings were widely published. Responsible farmers, as well as trained personnel, served as observers. By 1929 there were 53 observatories in the province of Alessandria alone, and the warnings were saving large sums of money in avoiding needless spraying, yet protecting the vineyards when conditions were favorable for the disease. That year the program was extended to the Province of Treviso on an experimental basis, which later proved entirely practical. A similar warning service was urged for southern Italy, and one was organized in Sicily in 1936.

The observatories were provided with equipment for measuring temperature and moisture, and the data included direct observation of condensed water, which is most important for spread of the disease by zoospores. While there were some discrepancies between weather reports and subsequent disease at different stations, the practical utility of local forecasting was not considered dependent on correlation of data between stations. Growers were advised that spraying begin when the first infections showed as "oil spots".

The French vine spray warning service operated over the same period as that in Italy (*R.A.M.* 3:468; 9:85;430, 761; 10:581; 11:622; 12:72; 13:149; 14:77, 420; 16:513; 19:5; 24:460; 25:382, 434). Reference is made to a forecasting station in Cadillac where the critical times for infection had been studied since 1898, one initiated in Bordeaux in 1922, an important station at Montpellier, and others at Clermond-Ferrand, Avignon, and Antibes. The Montpellier station received data from 59 outposts in the Montpellier region and others from France and abroad by wire, or, in the earlier days, the reports were relayed by visual or sound signals, and daily code telegrams were issued to subscribers of the warning service giving information on the appearance of pests, spray warnings, and weather. These telegrams received a priority at a reduced cost. In 1931 the Bordeaux station had 1, 425 subscribers.

The French vine mildew forecasting and warning service, which proved to be generally accurate and which resulted in important savings of crops and spray expense, was based on extensive studies of the interrelation between weather, fungus, and disease. At Montpellier the method of forecasting was based on growth stage of the crop and developmental stage of the fungus. Primary invasion was determined by oospore germination, with the incubation periods considered to be regularly nine days for the first cycle and seven days for the later cycles. Germination of the overwintered oospores under natural conditions was used as an index of the time of spring renewal of the disease. At Bordeaux it was considered that the earliness and intensity of infection are determined by the November-April rainfall, with secondary cycles dependent on spore prevalence and amount of rain. This permitted forecasting mildew outbreaks long in advance. A combination of the two methods was used at Clermont-Ferrand. The Italian method of waiting until the first infections appear as "oil spots" was considered unreliable in France.

The French workers have made interesting use of phenology in connection with spray warnings. Finding that the first attack of sycamore by the anthracnose fungus, *Gnomonia veneta*, regularly precedes the first attack of the vine mildew by several days, the sycamore disease is used as an index of imminent vine disease.

The French forecasting and spray warning service has given good practical results,. frequently reducing the empirical five to six spray applications to one or two, with important conservation of spray materials during times of shortage.

In Germany (*R.A.M.* 10:432; 13:678; 16:654; 17:292) vine spray warnings have been based on K. MÜLLER'S "incubation calendar", which was developed in 1913 and which is claimed to have averted immense losses and more than doubled grape yields in the Baden area over a 19-year period. The incubation period of mildew was found to vary from 5 to 18 days, depending on the weather, and the "calendar" was a guide to timely spraying based on temperature and moisture and their effects on the future development of the disease. The French workers have considered that use of the "calendar" requires great care on the part of growers who generally cannot make the necessary observations, and that the method must be supplemented by others. It is also believed to be of limited reliability in Switzerland (*R.A.M.* 19:325).

In Russia (*R.A.M.* 11:93; 14:9; 15:279, 702, 773) MÜLLER'S "incubation calendar" has been found useful if adapted to local conditions, and vine mildew forecasting is considered feasible on this basis. The modified formula for the incubation time in Russia is given as $h\ (t-8) = 60$, in which h is the number of days of the incubation period and t is the average mean daily temperature for the period. This is useable between 10° and 24° C., but at the lower range greater precision results from use of the formula $h = \frac{60\ (t-8)}{(t-16)\ 64D}$ where h is as above, t is the mean day temperature on the day on which infection occurred, and D is the increase in mean daily temperature for 30 days; t and D are obtainable from the long-term weather records. A second Russian method determines the average lenth of the incubation period as $61^{\circ} \div$ the average daily "effective" temperature (which is the actual temperature minus the "critical temperature" or minimum point below which the fungus is suppressed).

POTATO LATE BLIGHT FORECASTING IN EUROPE: -- Forecasting and spray warning services for potato late blight evolved independently in Holland, England, France, and the United States. Holland led the way when, in 1926, VAN EVERDINGEN (*R.A.M.* 5:627) proposed his four rules governing the appearance of late blight. Development of the disease, according to the Dutch rules, required (1) a night temperature below the dew point for at least 4 hours, (2) a minimum temperature of 10° C. or above, (3) mean cloudiness the next day of 0.8 or more, and (4) at least 0.1 mm. of rain during the next 24 hours. Provision for control measures was recommended only after days fulfilling all four of these conditions.

Answers to questionnaires sent out by the Dutch Phytopathological Service in 1926 confirmed the reliability of the Dutch rules, and arrangements were made for the Royal Dutch Meteorological Institute at Te Bilt and its observatories in the potato-growing sections to issue blight warnings that were broadcast with the weather reports and issued through the press (R.A.M. 7:664). Later reports from Holland (R.A.M. 9:15; 11:96; 14:11, 715; 18:153) describe in more detail the "cautionary service" and indicate the very satisfactory results from the service.

Between 1929 and 1933 the Dutch rules for late blight forecasting were tested in England and found to be generally satisfactory, though with occasional irregularity (R.A.M. 9:623; 11:123, 558). BEAUMONT and STANILAND then proposed a 5-rule modification in which a day was counted as favorable for blight if: (1) there was dew either the night before or in the morning, (2) the minimum temperature was 50° F. or above, (3) there was less than 5 hours of sunshine, with (4) at least 0.01 inch of rainfall, and (5) a relative humidity at 3:00 P.M. higher than 75% (R.A.M. 13:8, 561; 14:676; 15:555). These rules worked well in Devon and Cornwall but were later simplified (R.A.M. 16:514; 17:583) to two rules: (1) minimum temperature lower than 50° F. and (2) relative humidity greater than 75% for two or more days. These two rules provided the best of the several forecasting methods tried and were used thereafter in the British warning program.

The French system of observatories and spray warning service has been described in connection with vine mildew. The same system was used for other diseases including potato late blight. At first the simple method was followed of issuing warnings on the appearance of the disease. (R.A.M. 12:75; 13:149). There was difference of opinion as to whether either the Dutch rules (R.A.M. 13:76; 14:189) or the British ones (R.A.M. 18:814; 25:469) applied to French conditions. No new system was proposed, though it was urged by DARPOUX (R.A.M. 24:459) that thorough study be made of the ecology of disease organisms to permit more rational forecasting and spray warning. The French appear to be the first to have used the method, later developed by MELHUS in the United States, of planting late-blight-infected tubers in disease observatories so that absence of disease development could not be ascribed to lack of inoculum (R.A.M. 25:328).

In Germany, during this period, the principal contribution to late blight forecasting was the basic study of the environmental relations of the blight fungus by MÜLLER (R.A.M. 10:545) and ORTH (R.A.M. 17:57). In Russia the Dutch rules proved valid in the Leningrad region though subject to correction in other areas, and a nomogram was prepared to aid determination of the length of the incubation period of late blight, knowing the maximum, minimum, and mean temperatures (R.A.M. 15:522).

POTATO AND TOMATO LATE BLIGHT FORECASTING IN THE UNITED STATES: -- Potato late blight forecasting in the United States has had its foundation in the basic studies on the epiphytology of the disease and the environmental relations of the causal organism, of MELHUS (1915), NAPPER (R.A.M. 13:260), and CROZIER and REDDICK (R.A.M. 13:724; 14:391; 15:45). The critical temperature above which late blight does not develop was determined as 73.7° F. by MARTIN in 1923 (R.A.M. 3:173) and for practical purposes was later regarded as 75° F. by collaborators of the Plant Disease Survey. THOMAS (R.A.M. 25:470) emphasized the importance of microclimate in the "foliarsphere" about the potato plant, in contrast to conditions at the ordinary level of weather instruments, in determining disease development. TEHON (R.A.M. 8:327) devised graphic methods for defining the meteorological conditions permitting disease outbreaks, applying them in particular to potato late blight.

The first regular potato spray warning service in the United States was inaugurated in Maine in 1931. Eighty-one growers cooperated and this number increased to 2,410 in 1933 and 3,000 in 1934. In 1937, W. D. MOORE (R.A.M. 16:831) in South Carolina analyzed the weather record of the past 20 years in relation to late blight and concluded that it should be possible to predict outbreaks, which would be expected when March, April, or May had at least 3.5 inches of rain distributed over 9 days or more, with 5 or more days having 0.2 inch or more of rain. Plans were laid for late blight prediction on this basis.

One of the forerunners of the nationwide disease forecasting service in the United States was initiated by I. E. MELHUS, chairman of a wartime committee on potato late blight. In 1942 he proposed a plan for forecasting the disease, based on a 27-year analysis of Iowa weather and late blight outbreaks. The plan involved planting infected tubers at many points, with subsequent observation of blight development and weather, assembly of data at a central point, and dissemination of forecasts and spray warnings by all effective means of publicity.

The plan was put into operation throughout the upper Mississippi Valley in 1943 (MELHUS, 1945) following a 25,000,000 bushel loss from potato late blight the preceding year. The forecasts were based mainly on the assumption that late blight will be severe, in that region, if June-July average temperatures are above 70° F. This project, along with some other, informal, reporting services, was merged with the Warning Service of the U. S. Plant Disease Survey in 1947-48.

Meanwhile, HAROLD COOK in Virginia (1947, 1948a, b) had been independently studying the problem of forecasting late blight in potato and tomato, through a 17-year analysis of weather and blight. The critical rainfall line, above which the amount was favorable for blight and below which blight was inhibited, was obtained by plotting a cumulative seasonal rainfall line midway between the lines representing the mean rainfall in blight years and in blight-free years. The critical temperature for blight was similarly taken at 75° F. Blight could be predicted with 88% accuracy when the temperature was below and rainfall above the critical levels. A moving graph of 7-day average rainfall and temperatures proved most accurate for analyzing late blight-weather relationships over an entire season. In 1947 the forecasts in Eastern Virginia made possible a saving of $2,000,000 in potato and tomato spray costs.

UNITED STATES PLANT DISEASE WARNING SERVICE: -- The stage was now set for the initiation of a national plant disease forecasting service. In November, 1946, a year of destructive late blight, the National Canners' Association and the Indiana Canners' Association recommended that a tomato and potato blight warning service be established in 1947. The following month the Plant Science Technical Committee urged the U. S. Department of Agriculture to consider carefully the possibility of organizing a forecasting service. The same month the American Phytopathological Society resolved that "in view of the heavy losses sustained by American agriculture from sweeping outbreaks of plant diseases, the Society considers that one of the most important services needed by American farmers is a more effective reporting and forecasting service and a vigorous program of research basic to such a service", and solicited the aid of agricultural research administrators toward this end.

The need for a forecasting service was clear and the demand for it was evident. Just at this time the United States Congress passed the Research and Marketing Act (Flannagan-Hope Bill) authorizing cooperative agricultural research on a regional basis among States and between States and the Federal Government. This provided an ideal implementation for a national and necessarily cooperative disease forecasting service.

The Forecasting Project, as approved under the Act, was an experimental program designed to investigate the practicability of regional forecasting of plant disease occurrence, with special reference to late blight of potato and tomato, tobacco blue mold (Peronospora tabacina), and cucurbit downy mildew (Pseudoperonospora cubensis), and to conduct research on the factors in disease development that are basic to forecasting. Three plant pathologists were added to the Survey staff, stationed in three regions for the experimental developmental studies in cooperation with the States comprising each region, with the Survey acting as coordinator. The current reporting, or "warning service", after its practicability was demonstrated, became a function of the Survey proper. The Survey serves as clearinghouse for receiving and relaying timely reports on the development of the warning service diseases, with the cooperation of State key pathologists. The key pathologists, in turn, are responsible for furnishing information to the Survey, and for whatever publicity or recommendations may be warranted in their own States. Accounts of this organization have been published by P. R. MILLER (1947a, c), MILLER and PERSON (1947), and MILLER, WOOD et al. (1947). Through cooperation with the Weather Bureau, the semi-monthly weather outlook is sent to cooperators, who have found it invaluable in extending the time range of their forecasts.

Thus the work of the Forecasting project, as originally established, has become divided into the "Warning Service" proper, and the research project on the epiphytology of the diseases concerned. Cooperators report to the warning service on an entirely voluntary basis. Disease spread plus weather constitutes the guide to forecasting, but meteorological rules for the variable, wide-range conditions of the United States and Canada remain to be worked out and tested. Extensive and successful use of the more exact method abroad indicates eventual development of similar procedure here. The long-established potato late blight forecasting services of Holland, England, and France furnish invaluable foundation material, but their experience is not wholly applicable under our conditions. Except for its proven usefulness the warning service, therefore, is still largely experimental, as far as its basic criteria for prediction are concerned.

FORECASTING CORN WILT: -- The prediction of disease outbreaks has proven reliable and useful with a number of other types of disease. Pioneering in this work was NEIL STEVENS, who established a correlation between winter survival of adult flea beetles in the bodies of which the corn wilt (Bacterium stewartii) bacteria hibernate, winter temperatures, and outbreaks of wilt the following spring. For several years STEVENS accurately forecast severity of the disease, basing his predictions on December-February temperatures, in time for growers to avoid losses during wilt years (STEVENS and HAENSELER, 1941).

FORECASTING CRANBERRY KEEPING QUALITY: -- STEVENS (1943) also forecast the keeping quality of cranberries in Massachusetts from 1923 to 1928, with accurate results in all but one case; in this case decay was due to abnormal harvesting practices. The predictions were based on the observation that most serious fruit decay occurs in years in which May and June are warm and July and August are wet, with less loss when only one of these conditions prevails and least loss when May and June are cool and July and August are dry.

FORECASTING APPLE SCAB: -- Forecasting the time of primary infections of apple trees by the scab fungus has now become a standard practice underlying spray warning services in leading apple production areas. During late winter and early spring, the sexual fruiting bodies of the scab fungus in overwintered dead leaves gradually mature. Periodic examination of these leaves reveals the time at which the first spores of the fungus are about to be shot out of their containers, in condition to initiate infection, and this information is put to good use in determining the best time to begin spraying.

FORECASTING WHEAT LEAF RUST: -- During the past decade the writer and his associates in Oklahoma have developed a basis for forecasting the severity of wheat leaf rust and have used it successfully in rust forecasting nine years (Plant Disease Reporter 26: 213-217, 1942: Supp. 143, 1943; 28:280-287, 1944; Supp. 156, 1945; 30:162-165, 1946; 31:201-202, 1947; 32:176-181, 1948; 33:223-226, 1949). Two of the forecasts were of serious epiphytotics (1938, 1945), two were of abnormally light rust development (1944, 1948), and the others (1939, 1941, 1946, 1947, 1949) were of no more than normal rust injury. In all cases the outcome in Oklahoma was as anticipated, and usually the condition of rust which was forecast for Oklahoma had its counterpart throughout much or all of the wheat areas to the north. Issued usually on April 1 of each year, the forecasts have aided farmers and grain elevator operators in planning for harvest and disposal of the crop, and in some cases they have been decisive in determining whether to allow crops of borderline condition to go to maturity or, alternatively, to abandon the wheat in favor of spring-planted summer crops.

Since 1942 the forecasts have been based on an intensive analysis of the overwintering and early spring renewal of rust, correlated with late winter and early spring weather conditions, and an extensive survey the last week of March to determine whether the findings of the intensive study have statewide application. The basis of forecasting lies in the facts: (1) that in Oklahoma the weather from April 1 onward rarely if ever is a factor limiting rust development, (2) that the principal source of rust in this area is inoculum from overwintered local infections, (3) that the weather of December, January, February, and especially March is critical in determining spring renewal of the rust, and (4) that the level of rust intensity on April 1 is the principal factor determining its destructiveness from April till harvest in June, since the number of possible generations of rust increase is limited by time, even though the environment is constantly favorable, and the initial intensity of the rust April 1, the other factors being constantly favorable, will determine the final outcome of the disease.

FORECASTING SUGAR BEET DISEASES: -- The exceedingly destructive curly top disease of sugar beets is transmitted to beets by the beet leafhopper, which overwinters and breeds on certain weeds that are also sources of the curly top virus. The degree of damage from the disease in beets depends on the size of the overwintered leafhopper population and the earliness with which this population moves into the beet fields. The size of the leafhopper population, in turn, depends on the prevalence and abundance of weed hosts, and the rate of insect multiplication, while the spring weather conditions influence both the leafhopper multiplication rate and the time of their migration from weed hosts to crop fields.

Knowing these facts it becomes possible, by studying the weather and the behavior of the leafhoppers in their weed hosts, to forecast the time and intensity of infestation of the sugar beet crop, and this can be effectually done before beet-planting time. Warned by a forecast of a season of severe curly top, growers can avoid losses by planting only curly-top-resistant beet varieties or even planting substitute crops.

With another sugar beet disease, black root rot caused by Aphanomyces cochlioides, occurrence of the disease may be forecast before planting time by use of a greenhouse soil infection test (FINK, 1948). Previous to planting, soil samples from prospective beet fields are planted, in the greenhouse, with disinfected seed. After 30 days the percent of infected seedlings, which may range from 0-100%, is recorded, and FINK has shown that these records are very highly correlated ($\underline{r}$ = +0.925) with crop loss in the field ranging from 0-95%. Other instances of measuring the pathogen content of soil, water, air, or wild host plants, and using this information in forecasting disease occurrence are discussed on pages 252-253.

OTHER CASES OF DISEASE FORECASTING: -- It has been pointed out that a knowledge of the tempo of disease development has a practical application in permitting the forecasting of disease destructiveness. In the case of alfalfa wilt the forecast may be projected into future years by using data such as those shown in Figure 7 (page 236), while in dealing with the sugar beet yellows disease (M. A. WATSON, D. J. WATSON, and HULL, 1946) a study of disease tempo makes it possible to forecast yields, which aids in planning beet sugar factory operations.

In Texas, EZEKIEL (1938) found a good correlation between May-July rainfall and the amount of Texas root rot subsequently developing in cotton. Over the extent of the area where it holds, this correlation gives the opportunity for forecasting cotton losses several months before harvest.

No account of plant disease forecasting would be complete without reference to the forecasting of timber decay, the most important hazard in forest yields, which stands out as an exemplary case of putting theory to work with results that are highly reliable and useful. This subject has been discussed on pages 250 and 251.

It should be clear from these examples that the prediction of plant disease outbreaks and losses is not guesswork. It is a useful application of the study of plant disease appraisal and epiphytology, with a record of reliability that compares very favorably with the admittedly justifiable forecasting of weather, crop yields, and other natural occurrences. It is equally clear that plant scientists have made only a bare beginning in developing this phase of their research, and that a great field of service to agriculture lies before us, awaiting cultivation.

Chapter XII

ECONOMIC ASPECTS OF PLANT DISEASE LOSSES

TYPES OF LOSS CAUSED BY PLANT DISEASE: -- KLEMM (1940) has suggested the useful distinctions between direct and indirect, actual and potential, and avoidable and unavoidable losses.

Direct losses result from a reduction in volume of production (quantitative) or in intrinsic value or acceptability of the harvest (qualitative). To the farmer, direct loss usually means a decrease in monetary return for his labor and investment, although, as will be seen later, he may be partially or fully compensated for direct loss by a higher price received per unit of produce or by a lowering in quality requirements such as often occurs when produce is scarce. In any event, the full effects of direct loss are felt by the consuming public, which bears the entire cost of the loss through increased prices or taxes used to compensate the farmer, yet receives less produce for the money spent and frequently must accept produce of inferior quality.

Indirect losses include the decreased purchasing power of the agricultural population and those dependent on it, together with the decreased activity, economical operation, and profits of those industries that are dependent on agriculture, such as grain elevators, mills, processing plants, railroads, banks, farm implement and agricultural chemical manufacturers, and others. Also to be included in indirect losses are the expense of replacing lacking produce by importation from regions outside those affected by crop disease, sometimes including the necessity of accepting less desirable substitute products.

Actual losses include the unredeemed value of decimated crops and all of the direct and indirect effects mentioned above. Even when disease has been partially or entirely averted by intervention of preventive measures, the cost of these measures, -- spraying, soil disinfestation, replanting, and others -- together with the cost of the research that devleops them and the educational programs that diffuse knowledge about them, must be added to the sum of actual losses.

Potential losses are those which would occur in the absence of preventive measures. Where economical disease control practices are possible, agriculture must choose the lesser of two evils, the actual loss due to the cost of control if less than the potential loss in the absence of control. With diseases that are restricted by regulation, the actual loss, the cost of quarantines and other regulatory measures, is usually less than the potential loss were the disease permitted to spread freely, but there have been cases in which a disease has been less costly than its regulatory restriction, i. e., in which actual loss exceeded potential loss.

The terms avoidable loss and unavoidable loss are self-explanatory. Many farmers, through ignorance or inertia, regard avoidable losses as unavoidable, and one of the leading problems in agricultural education is teaching farmers that most plant disease losses are partially if not entirely avoidable.

To KLEMM'S classification may be added the distinction between recognized and hidden losses. The extent to which a "normal" crop falls short of its potential yield is hidden loss and this may be very great, as will be seen later. Market requirements for agricultural produce give little attention to nutritional quality, provided the produce has purchaser-appeal. We are beginning to realize that many of our foodstuffs, regardless of their attractiveness, are deficient in needed minerals, vitamins, proteins, and other nutrients. To the extent that these nutritional deficiencies are expressions of disease, whether contagious or physiogenic, they must be regarded as hidden losses caused by disease.

Recognition and distinction of the several types of loss is useful in analyzing the economics of plant disease. In pointing out the agricultural significance of plant pests, we deal with the total actual losses, direct and indirect, avoidable and unavoidable, recognized and hidden. In describing the agricultural significance of plant protection, attention is focused on the potential losses, those that would occur in the absence of pest control. In calculating the cost of disease control in labor and money, we are concerned with the actual, avoidable, direct forms of loss. In agricultural research and propaganda for the support of research, the currently unavoidable losses are of greatest interest, in contrast to educational programs where the avoidable forms of loss are chiefly involved.

In reports on loss from plant diseases it is frequently impossible to tell what forms of loss are included, and discrepancies in the reports are partly due to differences in the forms of loss considered. Statistics on plant disease losses usually are limited to actual, direct, recognized, avoidable and unavoidable losses. In most cases they are further limited to quantitative losses, but not invariably so, particularly if sale value of the crop, which to some extent includes quality, is the basis of the report.

THE ECONOMIC CLASSIFICATION OF PLANT DISEASES: -- The German Plant Protection Service has classified diseases and insect pests into five groups according to the magnitude of their destructiveness (KLEMM, 1940). These are: (a) those which practically eliminate the culture of a given crop unless rigidly controlled, with average losses exceeding 20% of the crop, illustrated by the phloem necrosis of elm and potato wart; (b) those which are sporadic but wipe out crops during occasional years, as potato late blight and the cereal rusts, with average losses of 5 to 10%; (c) those which are only occasionally and locally important, such as potato scab, or white rust and downy mildew diseases of spinach, with average losses less than 5%; (d) those which are widespread but without an important yield-depressing effect, as the cereal smuts and many of the leaf spot diseases of trees and herbaceous plants, causing about 1% loss on the average; and (e) those diseases which, on the average, have little or no agricultural significance, as ergot of grains and several of the needle rust diseases of conifers. Through ignorance of losses, diseases of considerable importance are sometimes placed in the last of these classes, as KLEMM did with wheat foot and root rots, which are now known to be major diseases. The indicated amounts of average loss are only approximate, with higher losses occurring in individual cases.

Alternatively, diseases may be classified in a qualitative fashion, as YACHEVSKI (1929) has done. Modifying his scheme, we may recognize nine classes: (a) diseases seriously affecting the normal life of plants, frequently killing them, as in the wilt diseases and damping-off; (b) diseases that destroy the commercial parts of the plant, as the smuts of small grains and cotton boll rots; (c) diseases that destroy the reproductive organs, which may or may not coincide with cases under "(b)"; (d) diseases that stunt or retard the growth or weaken the plant without killing it, as is true of many virus diseases; (e) diseases that indirectly injure the commercial product by attacking other plant organs, as the foliage diseases of root, fruit, nut, and seed crops: (f) diseases that confer poisonous or other undesired properties on the product, as ergot of grains or scab of barley; (g) diseases that attack harvested products in storage, commerce, or home; (h) diseases that injure the attractiveness or aesthetic qualities of the product, as peach freckle, apple fly speck, and blemishes of ornamental plants; and (i) mixed and intermediate types, with combined features of two or more of the foregoing classes.

In evaluating the actual or potential destructiveness of a disease, it is necessary to characterize it both quantitatively and qualitatively and to seek to avoid the pitfalls that lie in its incorrect classification.

CONCEPT OF A "NORMAL CROP": -- Theoretically, the severity of disease is the extent to which the diseased plant falls short of its ideal development. Such an ideal plant probably never exists. An instructive exercise is to attempt to find a single "perfect" mature leaf in nature.

While we may never be able to know the absolute maximum yields that might be obtained under ideal conditions, with total freedom from disease, we approach to a knowledge of this with every improvement in the appraisal of losses. Actual yield, $\underline{y}$ = theoretical yield, $\underline{Y}$, minus loss, $\underline{l}$. Knowing $\underline{y}$ and $\underline{l}$, $\underline{Y}$ can be calculated, and the accuracy of determination of theoretical yield depends only on the accuracy with which we determine $\underline{l}$, which is the task of loss appraisal.

Present knowledge, imperfect though it is, gives us reason to believe that under most agricultural conditions theoretical yields are far beyond actual yields of what are considered "normal" crops, and that economically attainable yields are much greater than is commonly believed. NEIL STEVENS (1935) has stated that there is always a 25% loss from fruit rots alone in "normal" cranberry crops. What had been considered good "normal" crops of alfalfa have been increased by 50% by a single application of an insecticide (PEPPER, 1947) and it is probable that control of leaf diseases would step up alfalfa yields another 50%.

WHEELER M^{c}MILLEN, editor of "Farm Journal", has been conducting a most interesting contest aimed at production of 300 bushels of corn on a single corn-belt acre by providing the crop with as nearly ideal conditions as possible. Although the average corn yields in the United States (1935-1944) ranged from 10 bushels per acre in Florida to a maximum of 47 bushels in Iowa, M^{c}MILLEN'S cooperators have succeeded in harvesting as much as 200 bushels per acre even in a season of unfavorable weather. While it can be justly argued that the point of diminishing returns and of uneconomic expense may be reached long before maximum yields are secured, especially with heavy applications of fertilizer and water, there still remains a wide margin between actual, so-called "normal" yields and economically attainable yields from pest-free crops.

Usually this margin of potential profit and the defects of the "normal" crop are wholly unrecognized by farmers and not infrequently even by agricultural scientists. It would be difficult for an Aroostook County potato grower, surveying a better-than-average crop, to recognize that even if the crop were perfect in every other respect it still would be only 87% of a truly healthy crop, since the X-virus, invariably present in all his plants, exacts a regular toll of 13% of potential yield. M^{c}MILLEN'S contest has shown that not all farmers are impervious to the challenge to strive forward toward maximum yields, yet to the majority of farmers a crop yielding 10% more than average for the neighborhood is entirely satisfactory, and a suggestion that it falls seriously short of feasible yields would be met with disbelief if not ridicule.

The term "normal yield" is used with different meanings from one reporter or country to another. In the U. S. Department of Agriculture (VALGREN, 1922) the "normal yield" is that which occurs in good years over extended areas, and a crop exceeding this by 10% is regarded as a perfect undamaged crop for the area. In Germany (KLEMM, 1940), the "normal yield" is the theoretical yield for an entirely normal year, assuming average injury from pests, and in practice it corresponds to a 6- to 8-year average yield. This, which would better be termed "average yield", is somewhat more realistic than the American standard, and avoids the absurdity of reports indicating that particularly well-favored crops have produced somewhat more than 100% of production of the "perfect crop", as well as the false implication that the utmost that can be achieved by a farmer is the increase in yield by a paltry 10% more than the local average in good years.

It seems most logical to avoid the deceptive and nonuniform use of the term "normal yield", restricting usage to the measurable "average yield", and limiting use of the concept of theoretical or perfect yield to experiments aimed at revealing it and to education of growers toward an application of feasible achievements in increasing yields well beyond those commonly called "good" or "normal".

EFFECTS OF PLANT DISEASE ON THE INDIVIDUAL GROWER: -- Plant disease presents a triple threat to the farmer. It may injure him as an individual producer in competition with other farmers, as a member of the national farming profession, and as a consumer of those agricultural commodities that he must purchase.

Were the losses from plant diseases equally prorated among all farmers, we could disregard individual differences, but they are not. Great variations in yields and losses may occur on adjacent farms in the same season. For those who are not close to the land there is comfort in the statistic that the average wheat acre in the United States produced 18 bushels of $2.00 wheat in 1948. How little this means in human values to the farmer who harvested 30 bushels per acre or his neighbor who harvested 5! Some diseases, such as root rot, are like that. Average national losses from disease, serious though they are, have but a small fraction of the social significance of the multitudes of individual catastrophes that are lost sight of in the national or state averages.

From the national standpoint, decreased yield is usually associated with increased prices, as discussed below, but this has no significance to the individual farmer whose decimated crops are too small a fraction of national production to have any effect on the price received. Conversely, the farmer who avoids disease losses by adequate attention to preventive measures, profits out of all proportion to variations in national production.

The same principle extends to groups of farmers whose combined production has little effect on national price, and who suffer losses from regional disease outbreaks. NEIL STEVENS (1935) illustrates this in an outbreak of cranberry false blossom (virus) that caused a local loss of $2,000,000 in New Jersey, without greatly affecting the national price of the crop. There was some price benefit to the national cranberry industry from the reduced supply, but far too little to compensate for the tragic loss to the New Jersey growers.

National losses expressed in dollars may entirely obscure the socio-economic effects of those losses on the farmers concerned. A loss of 0.5% of the national wheat crop would equal, in dollar value, a total loss to the cranberry industry; yet the former would be undetectable to the wheat farmers while the latter would be ruinous to a small but sociologically significant population whose livelihood depends on the cranberry crop.

EFFECTS OF FLUCTUATIONS IN ANNUAL YIELDS: -- It is an elementary principle in economics that fluctuation in income from month to month or year to year works hardships even though the total amount received over a long period is adequate. This principle is well recognized in agriculture. Many farmers can survive one year of crop failure, some can survive too, but very few could remain on the land after three years of failure, which fact would not be altered by the knowledge that total income in ten years, if divided into equal annual increments, would be adequate. In Argentina there is a wheat variety which has a high long-time record for production but with great extremes of high and low yields from year to year. It is called a "wheat for capitalists" and is not recommended to farmers, who are urged to grow other varieties that do not produce as much grain over a long period, but do produce fairly consistently, year in and year out.

Regularity in yield is as important to agricultural welfare as volume of yield and "fluctuations in yield can cause as much embarrassment as unbalanced acreages" (WALLACE). Since plant disease can markedly affect yields, it is instructive to see how this relates to yield fluctuations. Diseases differ in their effects on dependability of yields and, as NEIL STEVENS (1939) points out, "other things being equal, including average loss, that disease is most important which fluctuates most." Regularity in production has a beneficial stabilizing effect on farm prices.

There are some diseases, that, like poverty and taxes, are always with us, always injuring the crop to about the same extent. Among these is wood decay. Others are relatively constant but occasionally they become exceptionally severe or mild, as wilts and other soil-borne diseases. Still others attack with devasting force one year and are practically absent another, as potato late blight and cereal stem rust. Other factors being equal, the latter would be regarded as most destructive.

M^C^CALLAN (1946) has tabulated the ranges in loss percent for 36 major crop diseases during a ten-year period. Some of these show great variation between maximum and minimum, as the losses from corn root, stalk, and ear rots (3.8-16.1%), cotton seedling blight and boll rots (0.2-11.6%), apple scab (2.8-14.1%), wheat stem rust (trace-23.0%), pear blight (1.6-13.6%), potato late blight (0.8-12.8%), and sweet corn wilt (trace-13.1%), while with other diseases the losses vary little between their extremes, as is true of cotton wilt (2.2-4.8%), cotton root rot (2.3-5.0%), corn smut (2.0-4.6%), oat smut (2.5-4.7%), and potato rhizoctonia (1.5-3.5%), scab (1.5-2.6%), leafroll (1.2-3.5%), and mosaic (1.4-2.6%). Other diseases that are responsible for great annual variations in yield are sweet potato surface rot (HARTER and WEIMER, 1919), tomato anthracnose (M^C^NEW, 1943j), and storage and market disease of perishable produce generally (LINK and GARDNER, 1919).

HARTLEY and RATHBUN-GRAVATT (1937) have contributed a valuable discussion of disease damage in relation to host vigor. They have emphasized a point that is not often recognized by agriculturists, namely that all plant diseases may be divided into three classes: (a) those which mainly attack devitalized, weak plants; (b) those found principally on the most vigorous plants; and (c) those that are relatively indiscriminate, attacking vigorous and weak plants alike. In general, the diseases caused by rust fungi and other obligate parasites, as well as those caused by downy mildew fungi and bacteria, belong to the second class, while wilts, roots rots, cankers, and wood decays are usually of the first type.

These two classes of disease are quite contrary in relation to effect on yield fluctuations. A disease that is found principally on weakened plants accentuates that weakness, exaggerating yield depression, deepening the valley in the yield curve between yield peaks from more vigorous and disease-free crops. A disease that attacks only the more vigorous plants lowers the peaks without deepening the valleys, thus reducing yield fluctuations. From this standpoint alone cereal rusts and potato late blight might be regarded as beneficial. These relationships may be expressed as a coefficient of correlation, r, between disease loss and potential yield in the absence of disease, over a period of years. If r is negative, the disease increases the annual yield variation, and if r is positive the disease is associated with reduced yield fluctuation. Thus for cotton wilt, r = -.36, increasing variability, while with potato late blight r = +.82. In the latter case complete control of the disease would increase the yield variability, and late blight may be regarded as a stabilizing factor in potato production under the conditions of the observations.

This apparently beneficial effect of diseases with positive r values does not apply when the diseases attack with epiphytotic force, causing heavy losses over extensive areas, i. e., when the disease is more important than weather fluctuations or other factors contributing to crop vigor.

When two diseases attack a crop simultaneously, the second disease may add to the effect of the first in increasing or decreasing yield variability, or the effect of one disease may neutralize the effect of the other, with decreased net effect in fluctuations of yield. HARTLEY and RATHBUN-GRAVATT mention the antagonistic effect of potato tipburn and late blight in reducing the effects of one another as regards yield variability.

CUMULATIVE EFFECT OF SOIL-, SEED-, AND TUBER-BORNE DISEASES: -- When a potato plant becomes infected by a virus disease, the loss includes not only the reduced yield during the season of infection, but also the series of losses that occur in succeeding years as the virus is perpetuated in the tuber progenies and spread from these, each year, to neighboring healthy plants. SCOTT (1941) has shown that severe potato mosaic increases in seedstocks two- to three-fold and leafroll four-fold from one year to the next. Mild mosaic, according to K. M. SMITH (1933) reduces yields of potatoes 10- to 30 % the first year, with no further loss increase the second and third years, but rugose mosaic, causing 30 to 65% loss the first year, makes potato strains unproductive in two to three years. When potato seedstocks are not selected for freedom from disease, but are replanted year after year, the cumulative increase in disease and decrease in yield are illustrated in the data of GRAM (1923). In one of his tests with the leafroll disease, where tubers were replanted each year for five years, the disease incidence rose from 18 to 96%, accompanied by a decrease in yield, in centners/hectare, from 18.2 the first year to 2.2 the fifth.

Analogous cumulative losses are seen in other virus diseases that are transmitted by vegetative propagation, such as sugar cane mosaic, and in diseases that are carried by the true seed, as with the cereal smuts. With soil-borne diseases, such as root rot, a comparable cumulative loss effect is observed.

SOME ASPECTS OF LOSS IN PERENNIAL CROPS: -- Each season a perennial plant must accumulate reserves for next year's production, as well as produce a crop during the current year. Disease in any given year may not only reduce the production of that year, but may also have carryover effects, reducing the crops of succeeding years. Several injurious effects are involved, -- prevention of food storage, killing of branches and formation of cankers or lesions that cripple the plant for years to come, and the building up of a reservoir of disease inoculum which increases the hazard of exposure with each succeeding year. Defoliation of fruit trees by insects or diseases commonly has an injurious effect on the crop of the following year, though its effect on the present year's crop may hardly be detected. This is well illustrated by the cherry leaf spot disease. If defoliation is repeated for several years, trees commonly cannot survive.

A related effect that disturbs production by contributing to variability in annual yields of perennials, especially fruit and nut trees, is seen in cases in which a bumper crop one year is followed by a very poor crop the following year. This may not be associated with contagious disease; in fact, a disease that results in some fruit thinning during the bumper crop year may be beneficial in contributing to more constant yields.

RELATION OF LOWERED QUALITY TO MARKET QUALITY REQUIREMENTS: -- All plant diseases may be divided into those which reduce yields without affecting the quality of the harvested crop, such as loose smut of wheat except in growing the crop for seed production; those affecting both yields and quality, including the majority of diseases; and those that impair quality of the harvest without affecting yield, as in the case of diseases that only blemish fruits. In the first case, loss is measured purely in terms of volume of production, but in the latter two cases the amount of loss is related to market acceptability of the crop. Although losses due to lowered quality of produce are not often included in loss estimates, nevertheless they frequently represent a large or major share of all loss due to a disease.

Market quality requirements may be difficult to understand. Often they relate to psychological peculiarities or the sales-conditioning of the purchaser, as seen in such nutritionally unsound preferences as those for white bread and blanched vegetables. Moreover, market requirements vary from one location, season, or part of a season to another, and with the intended use of the product.

There is no consistent relation, that might benefit the grower of a disease-injured crop, between supply and quality requirements. If the supply is short there may be some relaxation in quality requirements, and every housewife is familiar with occasions when, for example, apples are scarce in the market, and despite the high price most of the fruit offered for sale is scabbed or blotchy. If this were invariably the case the grower would be somewhat compensated by a normally good price for his inferior produce, but there are many cases in which market practice works in the opposite fashion. For cranberries, NEIL STEVENS (1935) has pointed out that low quality in the first berries marketed may set a low price that affects all berries sold during the season, and the same thing has been observed by P. A. MILLER and BARRETT (1931) for cantaloupes. A striking case of this kind was reported for celery by NELSON (1939), who found that in the worst disease year in two decades, "prices paid to growers reached the lowest level in many years, and a more stagnant condition of the markets had probably not occurred previously ....Large quantities of celery were dumped on the market at prices which lowered the levels established for celery of good quality."

Low quality of produce may divert the buyer to other products, making the poor produce a drug on the market, and, in contrast, abundance with high quality may elevate the price by inducing speculators to buy the superior crop for storage and later sale.

Quality requirements depend on the purpose for which a product is to be used. A product that is inferior for one use may be satisfactory for another, though usually the value received drops as the product is rejected from its first intended use. The quality requirements for potatoes sold as seed tubers are higher than those for table stock, and potatoes rejected for seed might still be accepted, although at a somewhat lower price, for table use. Governmental interference with prices throws another uncertainty into this picture of market requirements, and there have been cases in which culinary potatoes of poorer quality have actually sold in the same market at a higher price, inflated by price support, than that charged for the better quality seed potatoes, which have then been bought by housewives for table use.

The effect of the downy mildew disease on onions varies with the use intended for the crop, being greatest if the crop is grown for greens, less if it is grown for bulbs, and least if it is grown for seed (YARWOOD, 1943). Wood decay exemplifies the same point (HEPTING and HEDGCOCK, 1937; MEINECKE, 1929). As the cull percent in a given stand increases, the volume of marketed timber decreases but its quality is higher. The market has very high quality requirements for timber to be used for railroad ties and much lower requirements for pulpwood. In the first case the effect of decay is chiefly in reducing quantity of the crop, and in the second, it is expressed as lower price.

The reduction of loss in marketing practice depends on selecting a compromise that may involve some loss in volume and some loss in price, but yet brings in the greatest possible return. This has practical application in the case of wood decay, mentioned above, and in the moderate artificial thinning of fruit, where increase in quality and price more than offsets decrease in volume of production.

Customarily the price for an agricultural commodity is highest when the crop first comes onto the market and steadily decreases as the season progresses and the volume of produce offered for sale increases. A disease which reduces the late-season harvest causes a financial loss that is much less than a disease causing an equal volume of loss early in the season. It may be profitable to spray such a crop as tomatoes to save the early fruits, yet not profitable to spray later to protect an equal volume of fruits that, if harvested, would reach the market at a time when the seasonal price has dropped to a low level. This point is commonly overlooked or lost sight of in statistics that report losses in bushels without indicating whether those bushels were of high-priced early season produce, or of late-season, low-value yields.

ABANDONMENT OF CROPS; FARM FAILURES: -- The most unfortunate victims of plant disease are two classes remotely removed from one another socially, the farmer to whom loss means ruin, and the lower fringes of the nonagricultural population to whom high prices and food shortages mean malnutrition if not starvation. Between is the great bulk of population to whom shortages in agricultural production mean only a little privation, a change in habits, or a tightening of the belt. We can say nothing here of those millions to whom a shortage in supply means suffering, -- their plight is a problem involving all agriculture, political economy, and the social structure of our civilization. Here we must limit ourselves to the men, women, and children at the other pole, -- those to whom a disastrous outbreak of plant disease means the end of their livelihood.

The economic history of plant pathology, though never yet assembled and existing only in scattered items, is a tragic chronology of disaster after disaster which have scourged the land, wiping out the livelihood of countless families, communities, and whole agricultural sections, destroying enterprises on which hopeful farmers had staked their lives and all their resources.

NEIL STEVENS (1934b, 1938) has presented a formidable list of agricultural projects known to have failed as a result of plant diseases. Some of these have resulted in virtual elimination of industries on which more or less extensive areas have depended, as the virtual collapse of the Louisiana sugarcane industry when it was successively crippled by red rot, root rot, and mosaic (RANDS and DOPP, 1938), the fate of the sugar beet industry in the intermountain region, throttled by the curly top disease (CARSNER, 1944) and the elimination, by rust, of the coffee growing in Ceylon in the 1880's, and the culture of Coffea arabica in Java (MORSTATT, 1937). Calamities such as these eliminated the livelihood of large populations, closed mills and factories, transformed prosperous communities into ghost towns.

Less spectacular, though no less ruinous to many individual farmers and those dependent on farming, have been the many other instances in which disease has struck locally or on scattered farms, eliminating the culture of once profitable crops, forcing countless individual farm families off the land or into other, less attractive agricultural pursuits. The many plant diseases that have acted in this fashion, mentioned by STEVENS and others, include banana wilt, flax wilt and rust, sweet potato surface rot, wheat stem and leaf rusts, potato and tomato late blight, alfalfa bacterial wilt, rusts of asparagus and snapdragon, fusarium wilts of watermelon, cotton, and other crops, Granville wilt of tobacco, diseases of celery, gooseberry-powdery mildew in Europe.

In these cases the destruction of crop culture has not always been permanent; sooner or later plant scientists have found means of controlling many of these diseases or have developed profitable substitute crops. Yet, during the period of reorganization of farming, untold suffering has been undergone by the stricken farm populations.

We have no yardstick for measuring this kind of loss. Disastrous total loss for a minority of farmers is completely overlooked in national statistics. The introduction of substitute crops to some extent compensates for the damage, but still leaves serious injury involved in adjustment to new ways of agriculture, replacement of equipment suitable only for the old crop, and inexperience in culture of the new one. As the cost of war or famine in human values can never be calculated, neither can the cost of the countless cases of individual total loss, the agricultural failures that lead to abandonment of crops and of farms. However closely we may attempt to arrive at estimates of the cost of plant disease, our figures will always fall short of the true cost by a broad margin of intangible suffering that cannot be measured in dollars.

EFFECT OF PLANT DISEASES ON THE USE AND VALUE OF LAND: -- Cropping practices have evolved through a process of trial and error by farmers. Each area grows the crops that practical experience has shown thrive best in the area, and farmers have gradually come to realize that certain crops will not succeed in given areas. It is often understood that the restriction of crops is due to soil, water, or temperature characteristics of an area, but growers and even agricultural specialists frequently overlook, or do not know that the absence of culture of given crops in some areas is due to the high disease hazard, which led to discouraging results in early, exploratory trials to determine what crops might be profitably grown in those localities. A climate very favorable for powdery mildew and leaf rust, rather than any unfavorable direct environmental influence, is undoubtedly the chief reason limiting the culture of wheat and barley in the cotton belt of the United States, just as Texas root rot, whether recognized or not, is the principal factor that has led to culture of cereals, rather than to more profitable cotton, alfalfa, or horticultural crops, in many infested areas of the Southwest.

Insofar as disease hazards dictate that certain crops may not be grown on land otherwise adapted to their culture, disease is causing a loss which may be very great if the land is not well suited to substitute crops. Uneven sandy lands are suitable for watermelon culture but for little else, and, in the past, when the land became infested with the deadly wilt fungus it had to be abandoned for melon culture and reverted to scrub oak of little value. Crucifers, particularly cabbage, have special soil requirements unlike those of most other crops, and if the land becomes contaminated with the club root organism, no equally valuable crop may be found to replace the crucifers. The same can be said for alfalfa and its wilt disease; sugar beets and the beet nematode, and numerous other cases, of which NEIL STEVENS (1934b) gives a long list.

Where the best adapted crops cannot be grown because of the disease hazard, the land declines in capital value, as was the case of North Carolina tobacco land until scientists found a means of controlling the Granville wilt disease. Acting in the opposite fashion, the development of means for controlling a disease may make it possible to grow a sufficient quantity of the crop to meet market demands on a smaller acreage. This releases land for other purposes and may or may not reduce the capital value of the surplus land.

Whatever the effect of disease, or its control, on land values, it is clear that in many cases the disease hazard is as important a characteristic of land as its fertility, water supply, and topography. Many Texas farmers in root rot areas have learned this fact the hard way, and much hardship and error could be avoided if land appraisal would regularly take into consideration the disease potential. From our point of view we must regard this effect of disease on land usage and values as an indirect, but nevertheless significant, aspect of disease loss.

EFFECT OF PLANT DISEASES FROM THE NATIONAL VIEWPOINT: -- When we consider the effect of plant diseases purely from the point of view of total national production and national prices, at first sight it appears that diseases are beneficial to the farmer, since reduced production is usually more than offset by increased prices, a large crop actually being worth fewer dollars than a smaller one. This is brought out by statistical demand curves that relate production to price.

In a comprehensive study of demand made by H. S. SCHULTZ (1938), it was found that for 10 major crops all but one had inelastic demand curves, i.e., as supply increased the price decreased in greater proportion. The exception was rye, the price of which was very artificial during the period of study (1915-1929) owing, perhaps, to the national prohibition law and other regulations of the distilling industry. In an earlier study period, (1875-1914) rye also had an inelastic demand curve.

With corn, a 0.5% decrease in production was associated with a 1% increase in price. With cotton, a 1% increase in supply depressed the price 1.4%. A 1% increase in supply of wheat reduced the price 2%. Similar trends were observed for sugar, hay, potatoes, oats, and barley, in which 1% increase in production resulted in price decreases of 2.5-3.3%, 2.3%, 3.3%, 1.67%, and 2.56%, respectively, a bigger crop of any of these bringing the farmer a smaller return. It follows that any agricultural practice that contributes to increased production may reduce the cash value of the crop. As HENRY WALLACE put it: "Science has made two blades of grass grow where there was only one before, only to find the second blade depressing the price of both."

Are we to conclude that agricultural science is harmful insofar as it increases production, thereby reducing farm income? If we do, we must sanction WALLACE'S policy of destroying crops and little pigs, we must close our eyes to the millions of nonagricultural consumers to whom decreased production means higher prices that buy poorer quality, and we must close our hearts to the many more millions of people throughout the world to whom anything short of maximum production means malnutrition or death by slow starvation.

Agropolitical assertions to the contrary, there never has and probably never can be overproduction from the sociological and humanitarian point of view. So-called overproduction is simply economic and social indigestion, brought about by artificial restrictions of trade, price manipulation that prevents the needy from purchasing, and economic isolationism. There can never be overproduction so long as there remain, anywhere in the world, multitudes who never know what it is to be properly fed and who die in middle life from the weaknesses of malnutrition. If the humanitarian viewpoint is incompatible with the economic one, in the interests of Christianity and world peace it is the latter, not the former, that must yield.

We have momentarily assumed, as a general principle, that, because of the inelasticity of statistical demand curves of a few leading farm crops, the farmer gains when production is curtailed. Is this assumption valid? There are so many important exceptions to the operation of the demand law and its effects that we may very well be justified in concluding that today the exceptions are the rule. The general applicability of the demand law, if it is to benefit farmers, includes the requirements that decreased production most frequently is more than offset by increased prices, that these benefit the majority of farmers, that the minority of farmers who lose rather than gain by decreased production can be disregarded in the national picture, that the law derived from statistics of 1915-1929 applies today, and that the law applies to crops generally. None of these assumptions is entirely valid.

The practice of farm price supports, which seems to be here to stay, is a repeal of the demand law; it fixes prices regardless of production, and under it the farmers' income increases directly as their production increases.

With decreasing production there is a point beyond which further decrease, even under ideal operation of the demand law, reduces rather than increases income. Simple calculation shows that this is the point of 50% yield reduction. Obviously, if production is reduced to 10% of normal, the price will not increase more than 1000% to guarantee an equal money return. As production approaches zero the price would need to approach infinity in order to sustain farm income, and long before this point is reached the market, at such prices, would vanish. It is only in the minor fluctuations around average yields that the demand law could be expected to operate.

Crop production is so beset by hazards that on the individual farms, which, combined, produce the nation's crops, the fluctuations from normal are great, with losses and gains greater than 50% not uncommon. There is little comfort for a farmer to know that decreased national production has raised the price of a crop a few pennies when his own farm was one of those on which serious loss depressed national production and increased prices at his expense and to the main advantage of other farmers. The suffering minority cannot be disregarded. Most of history has been written by dissatisfied minorities, not by contented majorities. The richest fruits of agricultural science are its benefits to the least productive farms, where hazards are greatest and improvements are most telling, and, even if it could be conclusively shown that science has resulted in nominal price decreases through increased production, this would be a minor loss to farmers themselves, considered as a multitude of individuals and as an impersonal class, compared to the major socioeconomic gain. All insurance exists on the same basis: from the total viewpoint insurance is a loss, since part of its cost is never returned to the policy holders, yet who can deny that the net results of insurance, in its protection of the unfortunate minority, far outweighs the cost of supporting the insurance industry?

Discussions of production-price relationships are based on demand law studies involving use of data of past decades. During these earlier periods, prices were fairly free to respond to production levels, as must be the case if the demand law is to function. Today this is no longer true. Price supports and manipulation by governmental decree, independent of production, with dumping of "excess" produce, huge government purchases for donation to foreign peoples, the increasing importance of the world market, inflation of production costs, long term crop storage activities, a ponderous and inequitable tax structure, and revaluation of money at home and abroad, -- these are among the many factors that interfere with the automatic balancing of production and price, and they lead to the frequent instances in which domestic production appears to bear no consistent relation to price. The demand law cannot explain the rise in wheat prices from 56 cents per bushel in 1938 to more than $2.00 in 1948, while production was also rising, nor can this be explained by inflation alone. Between 1931 and 1932 United States wheat production fell by nearly 200,000,000 bushels, yet the price, instead of rising, actually dropped.

Finally, the demand law is based on ten leading crops that must be purchased with little regard to quality. Plant diseases that reduce production commonly reduce quality at the same time, and with the perishable crops, consumption of which may be replaced by others, the lowered quality often reduces the demand and price far beyond any gain due to the reduced volume. If beans are scarce and rusty, the housewife will buy peas or corn; if citrus fruits are low in quality, she knows that the plentiful tomato juice has comparable food value; and in cases like these the scarce and less desirable produce, instead of commanding a compensating higher price, may have no price at all.

The moral of this discussion is clear and simple: the agriculturist who takes comfort in the thought that reduced production will bring its reward in higher prices is living in a world of unreality. Even from shortsighted and selfish restriction of interest to the farming class, there is little to gain and much to lose from hazards that reduce production. Crop losses do not create value; frequently they depress it. The prosperity of the farmer, as an individual and as a class, can only increase with more efficient methods of production and with increasing control over the hazards of production.

SECULAR PRICE EFFECTS OF NEW DISEASES: -- Now and then, in the history of agriculture, a new disease of devastating potency assails a crop, drastically curtailing its production. The effect of this on prices follows a standard pattern.

When the disease first appears, its inroads on production lead to scarcities that, to greater or less extent, may elevate the price of the crop attacked. As the price rises beyond that of competitive products, more and more consumers introduce themselves to substitute products and more and more growers turn to the production of these substitutes. Gradually the market value of the disease-stricken crop declines, as demand for it falls. This results in a situation in which the demand law has completely ceased to function and the loss in volume is multiplied by the loss in market value. This course of events may be considered as the secular effect of disease on price.

The fate of the American chestnut illustrates the secular effect. When the blight disease (Endothia parasitica) began its deadly course, wiping out the chestnut, there was a mad scramble for the highly prized timber, and the prices of tannin and nuts reflected the growing scarcity of supply. But as the years passed, other woods gained the former popularity of chestnut, other sources of tannin were found, and the taste for chestnuts waned with growing acceptance of other nuts, until the combined effects of lowered volume and reduced demand and price relegated the chestnut to a position of minor importance. Outside the field of agriculture, the decline in the whale fisheries, together with a decline in the demand for its products, illustrates the general application of the secular law.

LOSS ESTIMATES IN DOLLARS VERSUS THOSE IN PRODUCTION UNITS: -- For many years there has been disagreement whether crop losses should be expressed only in terms of lost bushels, bales, barrels, and tons, or whether it is permissible to translate these into dollars or other types of currency.

The antagonists of dollar estimates, a minority who include the succession of editors of the Plant Disease Reporter (Anon., 1918-1936), HAENSELER (1944), H. S. SMITH et al. (1933), and WEISS (1940), raise as their principal objection the opinion that it is unwise to multiply the number of lost production units by the prevailing price for those units that are harvested, since, if the lost units had been offered on the market the volume of production would have been increased, which, according to the demand law, would have reduced the price per unit. Loss estimates in dollars are described as "unsound", "too complex", "too theoretical", "not needed to justify support", "leading to exaggeration", "meaningless", and even "fantastic".

These objections, whatever the adjectives employed, are valid if, and to the extent that, the demand law is the principal factor that would have altered the price had the production units not been lost. We have seen that the demand law, which once applied imperfectly to a few staple crops, now appears to be the exception rather than the rule. Since most crop loss statistics are used in relation to agriculture, the basing of an argument on the demand law implies acceptance of that law with all its implications, one of which is that, so far as the farmer is concerned, there is no such thing as loss from non-catastrophic production hazards, -- every crop loss is that much gain financially.

Another argument frequently heard is that a damaged, smaller crop costs less to harvest than a larger, healthy one, which decreases the dollar loss. The cost of harvesting is only one of many costs in producing a crop. Frequently, as in combining small grains, it costs just as much to cut and thresh the smaller crop as the larger one. Finally there is an error of logic in deducting non-incurred harvesting costs from estimates of lost profits. In the case of a 10% crop reduction, it must be assumed that all costs of production are reduced by 10% if the amount of profit is to bear a constant relation to the amount of crop grown and sold. Savings in harvesting cost are not offsets of the 10% loss; on the contrary, all costs of production, including harvesting, must be decreased by 10% if the loss is not to be greater than 10%. Inevitably some of these production costs cannot be saved, and as a result a 10% field loss regularly results in more, sometimes much more, than 10% loss in profit.

For a number of reasons the translation of loss statistics into dollars is not only justified, but actually gives a more accurate conception of loss than number or percent of production units.

Chief among these reasons is the fact that the loss from disease is often expressed as reduced quality, commanding lower prices, which may represent as much as or more loss than reduction in the number of production units. The only tangible way that the quality loss can be included in the over-all loss estimate is to list the loss in terms of market value, in dollars. As one of many examples that might be cited, McMURTREY (1928) showed that tobacco, infected with mosaic one month after transplanting, suffered a reduction of 24% in acre yield, but the quality was so reduced that the tobacco sold at a loss of 40% per 100 pounds, which combined gave a total dollar loss per acre of 54.5%. In this case less than half of the true loss was reflected in the expression of loss in production units.

In CRAIGIE'S (1944) excellent analysis of losses of wheat from stem rust in Canada, he expresses the loss in dollars with the explanation: "It is realized that.....an increased production would have probably lowered the price of wheat, but any fall in the price of wheat as a result of higher production would have been largely offset by a fall in price due to the loss of grade resulting from damage by rust".

Loss expressed in production units usually includes only those forms of loss that occur up to harvest time. Yet many plant diseases continue to exact their toll through storage, transport, and marketing. It would be possible to extend loss estimates in production units to include the post-harvest shrinkage of the crop, but in actual practice, all of the loss, including such items as extra refrigeration costs, culling expense, and insurance indemnities for spoiled produce, could most feasibly and accurately be summarized in dollars.

Because of these considerations it seems equitable and more correct to express national losses in terms of dollars, but this is even more true when dealing with losses on a local scale, where the amount of loss is not sufficient to alter the market price. In many disease control tests, where the cost of control measures is an important production item, it is essential to determine whether the economics of disease control are in favor of the grower. Control is measured in dollars, and, to obtain realistic and useful results, the production gain, which is the converse of disease loss, must be measured in the same terms, giving a net value in dollars for or against the economics of disease control.

The besetting evil of most plant disease loss estimates has been that they have seriously understated the damage. In an effort to be conservative, plant pathologists have been led to as great errors in understatement as they have feared in overstatement, forgetting that a body can lose equilibrium and fall over as easily from leaning backward as from leaning forward. The imagined error in the assumption that loss is compensated by increased unit value has far less significance than the real losses that can best be measured in dollars. There is certainly as much guesswork in scaling down losses because of assumed price increases as there is in translating percent loss into market price, and it is encouraging to find such leaders of plant disease science as HORSFALL, McNEW, VALLEAU, MORSTATT, and KLEMM reporting losses realistically in dollars and marks.

Finally, the writer cannot agree with HAENSELER (1944) that loss estimates in money are not needed to justify support for plant disease control activities. Millions of bushels of wheat or corn, more or less, mean little to the layman who controls the purse strings, but he is impressed with millions of dollars. Proposed agricultural activities are measured in dollars and their justification must be in the same terms if their real significance is to be grasped.

EFFECT OF PLANT DISEASE LOSSES ON THE CONSUMER AND SOCIETY: -- The consumer has a greater stake in crop loss prevention than does the farmer. Whatever the losses in agriculture, it is the consumer who must absorb them in higher prices, lower quality, and taxes to permit the farmer to operate despite agricultural hazards.

The consumer's stake is all the greater because the unit value of produce, when it reaches the consumer, is much higher than at the farm. "The consumer's apple is the producer's apple plus the cost of picking, packing, shipping, storage, and handling, as well as sales costs and profits" (NEIL STEVENS). A farm loss, measured in pennies per bushel, becomes a consumer's loss measured in pennies per pound or dollars per bushel.

The farmer's loss, which may be offset to some extent by higher prices or subsidies, involves only the hazards that exist up to harvest time. The consumer's loss includes these plus all the forms of loss that occur between harvest and the dinner table, and these post-harvest losses may be relatively much greater than losses on the farm. SHEAR (1918) has emphasized that "few people, even pathologists, realize what enormous quantities of fruits and vegetables are lost through disease, decay, and other preventable causes between the producer and the consumer". He, as well as LINK and GARDNER (1919), cite many cases of the enormous amounts of produce that are lost from disease during the marketing process. These included condemnation of 19,000,000 pounds of fruits and vegetables in New York during one year, and railroad indemnities exceeding 2.6 million dollars for spoilage of perishables during a year.

It is not uncommon for 25 to 50% of perishable produce to be lost between farm and home. The most shocking part of this is the fact that these huge losses are regarded by the marketer as "normal shrinkage". Culling, resorting, and repacking occur again and again as the produce moves forward to the home, each step being marked by additional loss, and this is considered "part of the game", not as preventable waste. The consumer has been conditioned to pay the bill.

To the direct losses that are reflected in the cull piles behind warehouse and market and in the family garbage container, must be added the many indirect forms of loss that also are chargeable to the customer, as hidden taxes. These include the added costs imposed by spoilage on the food packing industry, the transportation agencies, and the marketer, transit insurance costs, and taxation at many points, which increases as the loss-inflated value of the produce increases.

Accompanying volume loss at all stages in production and marketing are the quality losses in the produce that finally reaches the ultimate consumer, seen, for example, in scabby potatoes from which a thick, wasteful paring must be removed, blemished fruit that is unappetizing and subject to rapid decay in the home, lettuce and cabbage from which a wastefully large number of leaves must be removed before reaching the uninjured centers, and construction timber with incipient stages of decay that inevitably mean costly, early replacement. Frequently, it is more economical for the consumer to pay a higher price for the best quality available, but either way, it is his bill to pay.

"The consumer always benefits from an abundance of production and should be more interested in maintaining loss-preventive measures that insure such abundance than growers as a group" (H. S. SMITH, et al., 1933). If production is curtailed and this is followed by high prices for the reduced crop, whatever the producer gains the consumers lose in money, and there is net social loss. The word "surplus" has been abused. Any quantity of produce that reduces the returns to producers is called a surplus, but rarely, if ever, is there a surplus in the social sense.

Today the world is our market, the world's vast population is the consumer. There can be no surplus so long as any part of that population is unfed or unclothed. Our economics and social understanding can no longer be limited to domestic supply and demand; so to limit them is to court world disaster. The principles of farm economy that once applied to an isolated America must be modified to conform to our new responsibility.

Any hazard that decreases production works hardship to some segment of society, creating damage that outweighs any limited profit to a favored few. It is the responsibility of agricultural science to reduce such hazards whenever and wherever they occur, let the economic chips fall where they may.

The science of plant pathology has the obligation and opportunity to relieve production of a major category of hazards, those due to plant disease. To accomplish this we must know the measure of the losses, so that our efforts at preventing them will be exerted at the most vital points. It has been the purpose of this book to attempt to blaze a trail into the relatively unexplored science of crop loss appraisal in the hope and belief that along this trail lie new and important opportunities for the science of plant disease prevention to make a more effective contribution, not to the farmer alone, but to human welfare.

POSTSCRIPT: LOOKING FORWARD

The need for accurate information on plant disease losses and their economic effects is very great. This need has not been met, yet the means for so doing are readily available. How may the resources of plant pathology be mobilized and activated toward this end?

A start would be formal recognition of this need by authoritative institution of a national committee charged with the responsibility of developing the understanding of plant disease losses and their effects. There are numerous public and private organizations that have a stake in such an undertaking and that may be expected to support it. Nomination to the committee should not be honorary but on the basis of interest, ability, and capacity for hard work, for the task is great. This committee might consider the following as worthwhile undertakings in the fulfillment of its mission:

First, the assembly and analysis of existing data on plant disease losses. Though fragmentary and often in error, the technical literature does contain much information on the destructiveness of plant diseases, and, with judgment, due allowance for over- or under-statement, and consideration of limits of applicability, this source of information can yield much of value.

At the same time there can be assembled existing data on methods of disease appraisal with respect to given crops and diseases, and constants for converting disease intensity into loss percent. The best of such methods and constants can be recommended for use in the future, to be supplemented in those cases in which existing information is inadequate.

Having assembled, selected, digested, and organized in useful form existing knowledge on losses and loss-appraisal methods, and made provision for supplementing and revising this knowledge on the basis of new publications as they appear, the committee will be conscious of many imperfections and lacunae in that knowledge, and will be concerned with means for amending them.

One of these means is to encourage those plant pathologists who are engaged in comprehensive studies of certain plant diseases to include, as a routine part of any thorough disease study, the measurement of loss and analysis of factors contributing to loss. The time has passed when any study of a plant disease that lays claim to being fairly thorough can dismiss the subject of economic importance with such a phrase as "very destructive". It is as though a plant pathologist passed over etiology by saying only "this disease is caused by a fungus".

A second means for adding to our knowledge of loss is to stimulate agricultural workers who are performing disease control tests or demonstrations to record their data in sufficient completeness that they bring out the amounts of loss associated with given intensities of disease. All that is needed is to indicate, in an understandable fashion, the amount of disease present and the difference in yields between treated, disease-free crops and untreated, diseased ones, yet it is dismaying to find how often experiments that have been well conducted at considerable expense are quite valueless from the standpoint of assaying loss, because of failure to make simple records of disease intensity and of yields of treated and control plants.

As a third method of supplementing our information on losses, a few young plant pathologists who are just entering their scientific careers might well be encouraged to specialize on loss appraisal. Here is a field of investigation worthy of the best in intellect and energy, with its far-reaching significance to human welfare. Such young men should be well trained in economics, as well as plant pathology and crop production, since we have here one of those new and profitable fields of endeavor that bridges two sciences. The same interests that stand to gain by loss appraisal studies may be expected to encourage such specialization by educational assistance.

Having catalyzed and set in motion a program of loss appraisal and interpretation, the national committee might gradually develop an educational program to make use of the findings. This could be done in several ways.

Among these would be a periodic survey training and experimental course for plant disease survey personnel. The meetings could be devoted to pooling information on survey methods and results, testing and standardizing disease measurement and estimation practices, and "calibrating the observer". Among the objectives of such groups would be the development of methods for making disease hazard appraisals of individual farms or localities, designed to aid in working out economic disease control programs and to provide a basis for pathological evaluation of farm land and for instituting crop disease insurance practices.

Meanwhile there is a large body of personnel engaged in agricultural survey work who have little or no training in plant pathoolgy or understanding of plant disease hazards. These men, economists, agronomists, crop scouts, crop insurance adjustors, railroad agricultural representatives, and others, could profit by attendance at short courses designed to offer them simple yet reliable guidance in assessing plant disease problems for what they actually are, economically. The organization and conducting of such short courses might be one of the most valuable contributions of the national committee.

The educational work, for plant pathologists and other agriculturists alike, would be notably aided by preparation of a manual or handbook giving in simple fashion the methods of reliable crop disease appraisal, facilitated by disease intensity charts, score cards, intensity-loss curves, tables, or ratios, and containing, for each major crop, explicit instruction on appraising loss from principal diseases. The preparation of this manual would be a major accomplishment of the committee.

Finally, having in hand reliable and defensible statistics on the losses from plant diseases, the committee could reap the full benefits of its endeavors by making available these statistics to the many individuals needing them, to agricultural administrators who need to know the most strategic points toward which research and educational resources should be directed and who must substantiate their claims for support with reliable loss estimates, to industries that need to know the markets for their disease-preventive products, to the planners of new agricultural enterprises who must be advised of potential hazards, to the legislator, and to the man of the street, the consumer, who, most of all, stands to profit by the reduction of crop losses, and on whose goodwill and understanding the future of agricultural science depends.

BIBLIOGRAPHY

Anonymous. 1899. Committee on Plant Diseases, Eastern New York Horticultural Society. The survey: Methods and general results. New York Agr. Exp. Sta. Bull. 167: 277-282.

__________. 1918-1936. U. S. Dept. Agr., Plant Disease Survey, 1918, 1920, 1932, 1936. Method of obtaining estimates. Methods of calculating losses. Plant Disease Reptr. Suppl. 6: 188-189; 12: 307-308; 83: 1-3; 94: 44-45.

__________. 1926. Percentage reduction from full yield per acre of 11 crops from stated causes, 1909-1925; percentage reduction from full yield per acre of corn in 4 states from stated causes, 1916-1925, as reported by crop correspondents. U. S. Dept. Agr. Crops and Markets 3, Suppl. 10: 320-323.

__________. 1933. Cereal leaf rust investigations. Indiana Agr. Exp. Sta. Rept. 1933: 48-49.

__________. 1934. Plant disease studies in Indiana. Indiana Agr. Exp. Sta. Rept. 1934: 26-27, 64.

__________. 1936. Wheat disease investigations. Indiana Agr. Exp. Sta. Rept. 1936: 65-66.

__________. 1938. Bacterial wilt of alfalfa. Utah Agr. Exp. Sta. Bienn. Rept. 1936/1938 (Bull. 282).

__________. 1942. Mosaic disease of cowpea reduces yield. North Carolina Agr. Exp. Sta. Rept. 1942.

__________. 1943. Measurement of plant diseases in the field. Trans. Brit. Mycol. Soc. 26: 172-173.

__________. 1946. An editorial view of sampling at Iowa State. Reprinted from Des Moines Register, Nov. 4, 7, 11, 1946.

__________. 1947. Weather effects on corn yields studied. Statlab. Rev. (Iowa State Coll., Statistics Lab.) 2 (4): 3-4, 6. Sept. 1, 1947.

__________. 1948. Livestock - loss survey completed. Statlab. Rev. (Iowa State Coll., Statistics Lab.) 3 (1): 1-2.

AFANASIEV, M. M. 1945. Correspondence, Aug. 10, 1945.

__________, and H. E. MORRIS. 1942. Control of seedling diseases of sugar beets in Montana. Phytopath. 32: 477-486.

__________, and __________. 1943. Diseases of sugar beets in crop rotations at the Huntley Branch Station, Huntley, Montana, from 1936-1941. Montana Agr. Exp. Sta. Bull. 419.

ANDERSEN, E. M. 1946. Tipburn of lettuce. Cornell Univ. Agr. Exp. Sta. Bull. 829. 14 pp.

ARMSTRONG, G. M. 1946. Control of the root knot nematode by soil fumigation. South Carolina Agr. Exp. Sta. 58th Ann. Rept. (1945), 1946: 49.

ARMSTRONG, S. F. 1922. The Mendelian inheritance of susceptibility and resistance to yellow rust (Puccinia glumarum Erikss. et Henn.) in wheat. Jour. Agr. Sci. 12: 57-96.

ARRUDA, S. C. 1941. A história das grandes epifitias da cana de açucar. Biológico 7: 313-318.

BAILEY, M. V. 1945. Defoliation of plants for profit. Sci. Month. 61: 234-236.

__________. 1947. Chemical defoliation. Agr. Chem. II(11): 24-27, 70.

BAKER, W. L. 1941. Effect of gipsy moth defoliation on certain forest trees. Jour. For. 39 (12): 1017-1022.

BALD, J. G. 1937. Investigations on "Spotted Wilt" of tomatoes. III. Infection in field plots. Austr. Counc. Sci. Indus. Res. Bull. 106. 32 pp.

__________. 1943a. Estimation of the leaf area of potato plants for pathological studies. Phytopath. 33: 922-932.

__________. 1943b. Potato virus X: Mixtures of strains and the leaf area and yield of infected potatoes. Austr. Counc. Sci. Indus. Res. Bull. 165. 32 pp.

__________. 1944. Development of differences in yield between FX and virus X-infected Up-to-Date potatoes. Jour. Counc. Sci. Indus. Res. 17: 263-273.

BARCLAY, A. 1892. Rust and mildew in India. Jour. Bot. 30: 1-8, 40-49.

BARRATT, R. W. 1945. Intraseasonal advance of disease to evaluate fungicides or genetical differences. (Abst.) Phytopath. 35: 654.

BARRONS, K. C. 1938. A method of determining root-knot resistance in beans and cowpeas in the seedling stage. Jour. Agr. Res. 57: 363-370.

BARSS, H. P. 1944. Some results of value to states from the emergency plant disease prevention program in 1943 and 1944; important plant disease problems needing further research or farmer education in 1944. Unnumbered mimeographed publ., U. S. Dept. Agr., Office of Exp. Sta.

BARSS, H. P., S. A. WINGARD, E. M. BUHRER, G. STEINER, and J. TYLER. 1937. Proceedings of the root-knot nematode conference. Plant Disease Reptr. Suppl. 102: 97-122.

BATEN, W. D. 1942. A nomogram for finding the areas of bean leaves. Jour. Amer. Soc. Agron. 34: 290-292.

__________, and R. E. MARSHALL. 1943. Some methods for approximate prediction of surface area of fruits. Jour. Agr. Res. 66: 357-373.

__________, and J. H. MUNCIE. 1943. A new method for computing sugar beet leaf area. Phytopath. 33: 1071-1075.

BAXTER, D. V. 1943. Loss and appraisal of damage. *In* Pathology in Forest Practice, pp. 57-83. John Wiley & Sons., Inc., New York.

BEAUMONT, A. and E. C. LARGE. 1944. Potato spraying in the South-West, 1942 and 1943. Agriculture: Jour. Min. Agr. (Gt. Brit.) 51: 71-75.

__________, R. W. MARSH, H. B. BESCOBY, and W. B. BRIERLEY. 1933. Symposium and discussion on the measurement of disease intensity. Trans. Brit. Mycol. Soc. 18: 174-186.

__________, and L. N. STANILAND. 1933. Ninth Annual Report of the Seale-Hayne Agricultural College, Newton Abbot, Devon, for the year ending Sept. 30, 1932. 43 pp.

__________, and __________. 1934. Tenth Annual Report of the Seale-Hayne Agricultural College, Newton Abbot, Devon, for the year ending Sept. 30, 1933.

__________, and __________. 1935. Eleventh Annual Report of the Department of Plant Pathology, Seale-Hayne Agricultural College, Newton Abbot, Devon, for the year ending Sept. 30, 1934. 59 pp.

BERGMAN, H. F. 1933. Measurement of leaf areas by means of the photoelectric cell. Report presented at 10th annual meeting Amer. Soc. Plant Phys., Boston, Dec. 30, 1933.

BEVER, W. M. 1937. Influence of stripe rust on growth, water economy, and yield of wheat and barley. Jour. Agr. Res. 54: 375-385.

BLISS, D. E. 1933. The pathogenicity and seasonal development of *Gymnosporangium* in Iowa. Iowa State Coll. Agr. Res. Bull. 166: 340-392.

BLODGETT, F. M. 1941. A method for the determination of losses due to diseased or missing plants. Am. Pot. Jour. 18: 132-135.

__________, P. DECKER, and C. S. TUTHILL. 1941. A method of determining loss in yield caused by diseased or missing plants and trials with leaf roll of potato. (Abst.) Phytopath. 31: 3.

BOLAS, B. D. and R. MELVILLE. 1933. The influence of environment on the growth and metabolism of the tomato plant. I. Methods, technique and preliminary results. Ann. Bot. 47: 673-688.

BONDE, R. and E. S. SCHULTZ. 1940 Effect on potato yield of different percentages of virus diseases. Maine Agr. Exp. Sta. Bull. 400: 262-263.

__________, and __________, and W. P. RALEIGH. 1943. Rate of spread and effect on yield of potato virus diseases. Maine Agr. Exp. Sta. Bull. 421. 27 pp.

__________, and E. G. SNYDER. 1946. Comparison of different organic and copper fungicides and some combinations of fungicides with DDT for the control of potato diseases and insects. Am. Pot. Jour. 23: 415-425.

BÖNING, K. 1936. Der pflanzenschutzliche Beobachtungs und Meldedienst und seine Aufgaben in der Erzeugungschlacht. Prakt. Bl. Pflanzenb. 13(12): 330-338.

BRANDES, E. W. 1919. The mosaic disease of sugar cane and other grasses. U. S. Dept. Agr. Bull. 829. 26 pp.

BREWBAKER, H. E., and F. R. IMMER. 1931. Variations in stand as sources of experimental error in yield tests with corn. Jour. Amer. Soc. Agron. 23: 469-480.

BRIZGALOVA, V. A. 1935. [Brown rust of wheat under conditions of the Irkutsk-Nizhniyeudinsk zone of the East Siberian district] Trudy po Zashch. Rast. V. Sib. No. 2(4): 99-173.

BROADFOOT, W. C. 1931. Preliminary experiments on the control of cereal rusts by Kolodust. Phytopath. 21: 347-372.

__________. 1934. Studies on foot and root rot of wheat. III. Can. Jour. Res. 10: 95-114.

BROWN, E. B., and H. S. GARRISON. 1923. Influence of spacing on productivity in single-ear and prolific types of corn. U. S. Dept. Agr. Bull. 1157. 10 pp.

BROWN, H. D. 1929. Loss caused by *Septoria* leaf spot in the tomato canning crop of Indiana - 1928. Plant Dis. Reptr. 13: 164-165.

BROWN, H. M. 1944. Reduction in yield of winter wheat due to removal of heads at heading time. Jour. Am. Soc. Agron. 36: 779-782.

BROWN, R. M. 1934. Statistical analyses for finding a simple method for estimating the percentage heart rot in Minnesota aspen. Jour. Agr. Res. 49: 929-942.

BUTLER, K. D. 1940. The protection of cereal crops with sulphur dusts. Abst. Theses Cornell Univ. 1940: 317-318.

CALDWELL, R. M., and L. E. COMPTON. 1939. Effects of leaf rust and artificial defoliation on yield, composition and quality of winter wheats. Indiana Agr. Exp. Sta. Rept. 1939.

_______________, H. R. KRAYBILL, J. T. SULLIVAN, and L. E. COMPTON. 1934. Effect of leaf rust (Puccinia triticina) on yield, physical characteristics, and composition of winter wheats. Jour. Agr. Res. 48: 1049-1071.

CARSNER, E. 1944. The sugar beet in Europe and America. Jour. New York Bot. Gard. 45: 25-31.

CARUTHERS, R. S. 1929. A scale for measuring areas of Ribes leaves. Phytopath. 19: 399-405.

CHESTER, K. STARR. 1939. The 1938 wheat leaf rust epiphytotic in Oklahoma. Plant Dis. Reptr. Suppl. 112. 18 pp.

_______________. 1944. Methods of appraising intensity and destructiveness of cereal rusts with particular reference to Russian work on wheat leaf rust. Plant Dis. Reptr. Suppl. 146: 99-121.

_______________. 1945a. Defoliation and crop loss. Plant Dis. Reptr. 29: 162-168.

_______________. 1945b. How accurately are we estimating plant disease losses? Plant Dis. Reptr. 29: 503-504, 539, 716-718.

_______________. 1946a. The loss from cotton wilt and the tempo of wilt development: A study of new uses for old data. Plant Dis. Reptr. 30: 253-260.

_______________. 1946b. The Nature and Prevention of the Cereal Rusts as Exemplified in the Leaf Rust of Wheat. Chronica Botanica Co., Waltham, Mass. 269 pp.

_______________. 1947. The Nature and Prevention of Plant Diseases. Ed. 2. The Blakiston Co., Philadelphia.

_______________, and D. A. PRESTON. 1948. Experimental forecast of wheat leaf rust in Oklahoma for 1948. Plant Dis. Reptr. 32: 176-181.

CHRISTENSEN, J. J. 1942. Long distance dissemination of plant pathogens. In Aerobiology. Publ. Amer. Assoc. Adv. Science 17: 78-87.

CHU, V. M. 1945. The prevalence of the wheat nematode in Chica and its control. Phytopath. 35: 289-295.

CHUPP, C. 1945. Ways in which the Emergency Plant Disease Prevention Program aids extension. Plant Dis. Reptr. Suppl. 152: 3-5.

CLINCH, P. E. M., and R. McKAY. 1947. Effect of mild strains of virus X on the yield of Up-to-Date potato. Proc. Roy. Dublin Soc. Sci. (N.S.) 24: 189-198.

COBB, N. A. 1890-94. Contribution to an economic knowledge of Australian rusts (Uredineae). Agr. Gaz. N. S. Wales 1: 185-214, 3: 44-68; 181-212; 5: 239-252.

COCHRAN, W. G., P. G. HOMEYER, and C. A. BLACK. 1945. Sampling methods for yield determination in experimental plots. Iowa Agr. Exp. Sta. Rept. for 1945, I: 308-309.

COMPTON, L. E., and R. M. CALDWELL. 1946. Yield reduction by loose smut of wheat. Phytopath. 36: 1040-1042.

CONNERS, I. L. 1936. Can. Pl. Dis. Surv., 16th Ann. Rept. 3.

COOK, H. T. 1947. Our method for forecasting tomato late blight. Plant Dis. Reptr. 31: 245-249.

__________. 1948a. 1947 results of late blight forecasting in Eastern Virginia. Plant Dis. Reptr. 32: 54-57.

__________. 1948b. Forecasting late blight in Eastern Virginia in 1947. (Abst.) Phytopath. 38: 6.

COOK, M. T. 1947. Viruses and Virus Disease of Plants. Economic importance of virus diseases. Burgess Publ. Co., Minneapolis, Minn. pp. 13-14.

COONS, G. H. 1918. Seed tuber treatments for potatoes. Phytopath. 8: 457-468.

CRAIGIE, J. H. 1944. Increase in production and value of the wheat crop in Manitoba and Eastern Saskatchewan as a result of the introduction of rust resistant wheat varieties. Sci. Agr. 25: 51-64.

CRALLEY, E. M., and E. C. TULLIS. 1937. Effect of seed treatments on seedling emergence, severity of seedling blight, and yield of rice. Ark. Agr. Exp. Sta. Bull. 345: 2-24.

CROWTHER, F. 1941. Studies in growth analysis of the cotton plant under irrigation in the Sudan. Sudan. II. Seasonal variation in development and yield. Ann. Bot., N. S. 5: 509-533.

DARROW, G. M. 1930. Experimental studies on the growth and development of strawberry plants. Jour. Agr. Res. 41: 307-325.

DAVIS, J. F. 1940. The relationship between leaf area and yield of the field bean with a statistical study of methods for determining leaf area. Jour. Am. Soc. Agron. 32: 323-329.

DEMIDOVA, Z. A. 1928. [Instructions on conducting observations on diseases of the principal field crops.] Publ. of the Ural Oblast. Zemel. Uprazl. *In* Yachevski, 1929.

DOUGHTY, L. R., F. L. ENGLEDOW, and T. K. SANSON. 1929. Investigations on yield in cereals. VI. A. A developmental study of the influence of nitrogenous top-dressing on wheat. B. A measurement of the influence of disease ("take-all") upon the yield of wheat. Jour. Agr. Sci. 19: 472-490.

DUCOMET, V., and E. FOËX. 1925. Introduction à une étude agronomique des rouilles des céréales. Ann. Epiphyties 11: 311-411.

______________, and __________. 1928. De l'appréciation de l'intensité des rouilles du blé. Bull. Assoc. Intern. Sélectionneurs de Plantes de Grande Cult., Gembloux. 1. 22 pp.

DUNEGAN, J. C. 1945. Correspondence, July 23, 1945.

DUNGAN, G. H. 1928. Effect of hail injury on the development of the corn plant. Jour. Am. Soc. Agron. 20: 51-54.

______________. 1929. Artificial hailing shows damage to corn by storms. Illinois Agr. Exp. Sta. Ann. Rept. 42: 49-50.

______________. 1930. Relation of blade injury to the yielding ability of corn plants. Jour. Am. Soc. Agron. 22: 164-170.

______________. 1931. Hail damages corn worst when plants are tasseling. Illinois Agr. Exp. Sta. Ann. Rept. 44: 57-59.

______________. 1932. Corn grows even after hail destroys all blades. Illinois Agr. Exp. Sta. Ann. Rept. 45: 55-56.

DUNLAP, A. A., W. N. EZEKIEL, H. E. REA, C. H. ROGERS, and P. A. YOUNG. 1940. Economic significance of cotton disease control. Paper given at Cotton Res. Congr., Waco, Texas, June 28, 1940.

EDGERTON, C. W., I. L. FORBES, and P. J. MILLS. 1937. Losses caused by the mosaic and red rot diseases of sugar cane. Louisiana Agr. Exp. Sta. Bull. 288: 3-8.

EIDELMAN, Z. M. 1933a. [Principal results of experiments on artificial reduction of leaf surface at different geographical points.] Trudy po Zashch. Rast. Ser. 3, 3: 65-72.

________________. 1933b. [Influence of mechanical reduction of leaf surface on the growth and development of cultivated plants in connection with methods for estimating disease infection.] Trudy po Zashch. Rast. Ser. 3, 3: 15-42.

________________, and E. A. BANKUL. 1933. [Influence of mechanical reduction of leaf area and different nutritional regimes on the accumulation of dry matter in cereals.] Trudy po Zashch. Rast. 3, 3: 113-130.

ELDREDGE, J. C. 1935. The effect of injury in imitation of hail damage on the development of the corn plant. Iowa Agr. Exp. Sta. Res. Bull. 185: 1-61.

________________. 1937. The effect of injury in imitation of hail damage on the development of small grain. Iowa Agr. Exp. Sta. Res. Bull. 219: 284-302.

________________, and R. R. KALTON. 1945. The effect of injury simulating hail damage to soybeans. Iowa Agr. Exp. Sta. Ann. Rept. for 1945, 1: 125-126.

ERIKSSON, J. and E. HENNING. 1896. Die Getreideroste. Ihre Geschichte und Natur sowie Massregeln gegen dieselben. Stockholm. 463 pp.

EZEKIEL, W. N. 1938. Cotton root rot in Texas in 1937, and conditions affecting its local prevalence. Plant Disease Reptr. 22: 315-324.

________________, and A. A. DUNLAP. 1940. Cotton diseases in Texas in 1939. Plant Disease Reptr. 24: 434-439.

________________, and J. J. TAUBENHAUS. 1931. Estimation of losses from cotton root rot. Texas Agr. Exp. Sta. Ann. Rept. 44: 66-67.

________________, and ______________________ 1932. Estimation of cotton-crop losses. *In* Rept. of 5th Ann. Cotton-Root-Rot Conference. Phytopath. 22: 988.

________________, and ______________________. 1934. Cotton crop losses from *Phymatotrichum* root rot. Jour. Agr. Res. 49: 843-858.

FAJARDO, T. G. 1930. Studies on the mosaic disease of the bean (*Phaseolus vulgaris* L.) Phytopath. 20: 469-494.

FERNOW, K. H. 1944. Relation of sample size to accuracy. Am. Potato Jour. 21: 229-234.

FICHT, G. A. 1939. Root-knot nematode of tomatoes in relation to the Indiana canning crop. Indiana Agr. Exp. Sta. Bull. 434. 15 pp.

FINK, H. C. 1948. Correlation between sugar beet crop losses and greenhouse determinations of soil infestations by *Aphanomyces cochlioides*. (Abst.) Phytopath. 38: 9.

FISCHER, G. J. 1929. Observaciones sobre el rendimento, la precocidad y la resistencia à la *Puccinia triticina* del trigo 38 M.A. Nuestra Chacra 4(23): 17-20.

FITCH, C. L., and E. R. BENNETT. 1910. The potato industry in Colorado. Colorado Agr. Exp. Sta. Bull. 175: 3-80.

FLOR, H. H. 1941. Flax rust. North Dakota Agr. Exp. Sta. Bimonth Bull. 3(6): 7-9.

———, E. F. GAINES, and W. K. SMITH. 1932. The effect of bunt on yield of wheat. Jour. Am. Soc. Agron. 24: 778-784.

FOLSOM, D. 1920. Potato mosaic. Maine Agr. Exp. Sta. Bull. 292: 157-184.

———. 1927. Virus diseases of the potato. Quebec Soc. Prot. Plants, 17th Ann. Rept. 1925/26: 14-29.

———. 1942. Sample size and reliability. Am. Potato Jour. 19: 197-199.

———, F. V. OWEN, and H. B. SMITH. 1931. Comparison of apparently healthy strains and tuber lines of potatoes. Maine Agr. Exp. Sta. Bull. 358. 104 pp.

FRACKER, S. B. 1918. Is crown gall injurious to apple nursery stock? Jour. Econ. Ent. 11: 133-135.

FREAR, D. E. H. 1935. Photoelectric apparatus for measuring leaf areas. Plant Phys. 10: 569-574.

FREISE, F. W. 1930. Cane diseases and plagues in Brazil. Facts about Sugar 25: 613-614.

GADDIS, B. M. 1947. Some of the fundamentals underlying plant pest surveys in the quarantine and control field. Mimeogr. Paper given at the Western Plant Board meeting, Bowen Island, B. C., June 10, 1947.

GARBER, R. J., and M. M. HOOVER. 1928. The relation of smut infection to yield in maize. Jour. Am. Soc. Agron. 20: 735-746.

GARDNER, M. W., and J. B. KENDRICK. 1924. Potato leaf roll in Indiana. Purdue Univ. Agr. Exp. Sta. Bull. 284: 1-23.

———, and ———. 1928. Potato mosaic and leaf roll: spread and effect on yield. Trans. Indiana Hort. Sci. 1927: 158-168.

GASKILL, J. O. 1940. Effect of mosaic upon yield of seed by sugar beet roots. Proc. Am. Soc. Sug. Beet Tech. 1940: 199-207.

GASSNER, G. 1915. Die Getreideroste und ihr Auftreten im subtropischen ostlichen Sudamerika. Ctbl. Bakt. II, 44: 305-381.

———, and W. STRAIB. 1936. Untersuchungen zur Bestimmung der Ernteverluste des Weizens durch Gelb- und Schwartzrostbefall. Phytopath. Zeitschr. 9: 479-505.

GERDEL, R. W., and R. M. SALTER. 1928. Measurement of leaf area using the photoelectric cell. Jour. Am. Soc. Agron. 20: 635-642.

GIBSON, R. M., R. L. LOVVORN, and B. W. SMITH. 1943. Response of soybeans to experimental defoliation. Jour. Am. Soc. Agron. 35: 768-778.

GODFREY, G. H. 1934. Indicator plants for measuring soil populations of the root-knot nematode, *Heterodera marioni* (Cornu) Goodey. Soil Sci. 38: 3-27.

GOETZ, O. 1937. Das Reichspflanzenschutzgesetz. Obst- u. Gemüseb. 83: 35.

GOSS, R. W. 1934. A survey of potato scab and Fusarium wilt in Western Nebraska. Phytopath. 24: 517-527.

GOULDEN, C. H., and A. T. ELDERS. 1926. A statistical study of the characters of wheat varieties influencing yield. Sci. Agr. 6: 337-345.

———, and F. J. GREANEY. 1930. The relation between stem rust infection and the yield of wheat. Sci. Agr. 10: 405-410.

GRABER, L. F., and F. R. JONES. 1935. Varietal survival of alfalfa on wilt-infested soil. Jour. Am. Soc. Agron. 27: 364-366.

GRAHAM, S. A. 1931. The effect of defoliation on tamarack. Jour. For. 29: 199-206.

GRAM, E. 1923. Einfluss des Anbauortes auf die Blattrollkrankheit der Kartoffel. Angew. Bot. 5: 1-20.

———. 1938. Statens plantepatologiske Forøg. 1913-1938. Tidsskr. Planteavl. 43: 159-176.

GREANEY, F. J. 1933a. Method of estimating loss in yield from cereal diseases. (Abst.) Phytopath. 23: 12.

———. 1933b. Method of estimating losses from cereal rusts. Proc. World's Grain Exhib. and Conf., Canada, 1933, 2: 224-236.

———. 1934. The prevention of cereal rusts by the use of fungicidal dusts. Can. Dept. Agr. Bull. 171, N.S. 89 pp.

———. 1936. Cereal rust losses in Western Canada. Sci. Agr. 16: 608-614.

GREANEY, F. J., and J. E. MACHACEK. 1934. Studies on the control of root rot diseases of cereals caused by *Fusarium culmorum* (W.G.Sm.) Sacc. and *Helminthosporium sativum* P., K., and B. I. Sci. Agr. 15: 228-240.

______, and ______. 1935. Studies on the control of root rot diseases of cereals caused by *Fusarium culmorum* (W.G.Sm.) Sacc. and *Helminthosporium sativum* P., K., and B. II. Sci. Agr. 15: 377-386.

______, J. C. WOODWARD, and A. G. O. WHITESIDE. 1941. The effect of stem rust on the yield, quality, chemical composition, and milling and baking properties of Marquis wheat. Sci. Agr. 22: 40-60.

GULL, P. W., and J. E. ADAMS. 1945. Mechanical production of cotton. Mississippi Agr. Exp. Sta. Bull. 423. 14 pp.

______, and ______. 1946. Cotton defoliation. Unnumbered mimeogr. Publ., Delta Branch Exp. Sta., Miss. 2 pp.

GUSTAFSON, F. G., and E. STOLDT. 1936. Some relations between leaf area and fruit size in tomatoes. Plant Phys. 11: 445-451.

HAENSELER, C. M. 1944. Standardization of plant disease surveys. Plant Disease Reptr. 28: 38-41.

HALLER, M. H., and J. R. MAGNESS. 1925. The relation of leaf area to the growth and composition of apples. Proc. Am. Soc. Hort. Sci. 22: 189-196.

HARDENBERG, E. V. 1922. A study, by the crop survey methods, of factors influencing the yield of potatoes. Cornell Agr. Exp. Sta. Mem. 57: 1143-1279.

HARRISON, A. L. 1935. Mosaic of the Refugee bean. New York State Agr. Exp. Sta. (Geneva) Bull. 656. 19 pp.

HARTER, L. L., and J. L. WEIMER. 1919. The surface rot of sweet potatoes. Phytopath. 9: 465-469.

HARTLEY, C., and A. RATHBUN-GRAVATT. 1937. Some effects of plant diseases on variability of yields. Phytopath. 27: 159-171.

HASKELL, R. J., and E. G. BOERNER. 1931. Relation of stinking smut of wheat in the field to smuttiness of threshed grain. Plant Disease Reptr. Suppl. 79. 6 pp.

HATFIELD, W. C., J. C. WALKER, and J. H. OWEN. 1948. Antibiotic substances in onion in relation to disease resistance. Jour. Agr. Res. 77: 115-135.

HAWTHORN, L. R. 1943. Simulated hail injury on yellow Bermuda onions. Proc. Am. Soc. Hort. Sci. 43: 265-271.

______. 1946. Defoliation studies as a basis for the estimation of hail losses in onions. Texas Agr. Exp. Sta. Bull. 682. 22 pp.

HAYES, H. K. 1926. Present day problems of corn breeding. Jour. Am. Soc. Agron. 18: 344-363.

HEPTING, G. H. 1941. Prediction of cull following fire in Appalachian oaks. Jour. Agr. Res. 62: 109-120.

______, K. H. GARREN, and PAUL W. WARLICK. 1940. External features correlated with top rot in Appalachian oaks. Jour. For. 38: 873-876.

______, and G. C. HEDGCOCK. 1937. Decay in merchantable oak, yellow poplar, and basswood in the Appalachian region. U. S. Dept. Agr. Tech. Bull. 570: 1-30.

HEUBERGER, J. W., and J. B. S. NORTON. 1933. The mosaic disease of tomatoes. Maryland Agr. Exp. Sta. Bull. 345: 447-486.

HIBBARD, R. P., B. H. GRIGSBY, and W. G. KECK. 1938. A low light intensity photoelectric device for the measurement of leaf areas. Papers Mich. Acad. Sci. 23: 141-147.

HILL, C. C., E. J. UDINE, and J. S. PINCKNEY. 1943. A method of estimating reduction in yield of wheat caused by Hessian fly infestation. U. S. Dept. Agr. Circ. 663. 9 pp.

HITCHCOCK, A. S., and J. B. S. NORTON. 1896. Corn smut. Kansas Agr. Exp. Sta. Bull. 62: 169-212.

HOLBERT, J. R., J. F. TROST, and G. N. HOFFER. 1919. Wheat scab as affected by systems of rotation. Phytopath. 9: 45-47.

HOMEYER, P. G., and C. A. BLACK. 1946. Sampling replicated field experiments on oats for yield determinations. Proc. Soil Sci. Soc. Am. 11: 341-344.

HORSFALL, J. G. 1930. A study of meadow crop diseases in New York. Cornell Univ. Agr. Exp. Sta. Mem. 130. 139 pp.

______. 1945. Fungicides and their action. Assessing field data. Ann. Crypt. et. Phytopath. 2: 38-41. Chronica Botanica Co.

______, and R. W. BARRATT. 1945. An improved grading system for measuring plant diseases. (Abst.) Phytopath. 35: 655.

HORSFALL, J. G., and J. W. HEUBERGER. 1942a. Measuring magnitude of a defoliation disease of tomatoes. Phytopath. 32: 226-232.

__________________, and __________________. 1942b. Causes, effects and control of defoliation on tomatoes. Connecticut Agr. Exp. Sta. Bull. 456: 183-223.

HOUSEMAN, E. E., C. R. WEBER, and W. T. FEDERER. 1946. Preharvest sampling of soybeans for yield and quality. Iowa Agr. Exp. Sta. Res. Bull. 341: 808-826.

HUFFINE, W. 1947. The effect of artificial defoliation on grain yield of Darso grain sorghum. Thesis, Oklahoma Agr. & Mech. Coll.

HUGHES, H. D., and E. R. HENSON. 1930. Crop Production. The Macmillan Co., New York. 816 pp.

HULL, R., and M. WATSON. 1947. Factors affecting the loss of yield of sugar beet caused by beet yellows virus. II. Nutrition and variety. Jour. Agr. Sci. (London) 37: 301-310.

HUME, A. N., and C. FRANZKE. 1929. The effect of certain injuries to leaves of corn plants upon weight of grain produced. Jour. Am. Soc. Agron. 21: 1156-1164.

HYSLOP, J. A. 1927. A monthly survey report form. Jour. Econ. Entom. 20: 717-725.

IMMER, F. R., and J. J. CHRISTENSEN. 1928. Determination of losses due to smut infections in selfed lines of corn. Phytopath. 18: 599-602.

__________________, and __________________. 1931. Further studies on reaction of corn to smut and effect of smut on yield. Phytopath. 21: 661-674.

__________________, and F. J. STEVENSON. 1928. A biometrical study of factors affecting yield in oats. Jour. Am. Soc. Agron. 20: 1108-1119.

JOHNSON, E. M., and W. D. VALLEAU. 1941. Effect of tobacco mosaic on yield and quality of dark fire-cured tobacco. Kentucky Agr. Exp. Sta. Bull. 415: 111-114.

JOHNSON, I. J., and J. J. CHRISTENSEN. 1935. Relation between number, size, and location of smut infections to reduction in yield of corn. Phytopath. 25: 223-233.

JOHNSTON, C. O. 1931. Effect of leaf rust infection on yield of certain varieties of wheat. Jour. Am. Soc. Agron. 23: 1-12.

__________________. 1937. Resistance of winter wheat to leaf rust. Kansas Agr. Exp. Sta. Bienn. Rept. 1934/1936: 93-94.

__________________. 1938. Resistance of winter wheat to leaf rust. Kansas Agr. Exp. Sta. Bienn. Rept. 1936/1938: 103-104.

JONES, F. R., and M. B. LINFORD. 1925. Pea disease survey in Wisconsin. Wisconsin Agr. Exp. Sta. Res. Bull. 64. 31 pp.

JONES, I. D. 1931. Preliminary report on relation of soil moisture and leaf area to fruit development of the Georgia Belle peach. Proc. Am. Soc. Hort. Sci. 28: 6-14.

JONES, L. K. 1944. Leaf roll of potato in Washington. (Abst.) Phytopath. 34: 935.

__________________, and G. BURNETT. 1935. Virous diseases of greenhouse-grown tomatoes. Washington Agr. Exp. Sta. Bull. 308: 5-36.

JORGENSON, L. R. 1929. Effect of smut infection on the yield of lines and F_1 crosses in maize. Jour. Am. Soc. Agron. 21: 1109-1112.

KALTON, R. R., and J. C. ELDREDGE. 1947. Can hail ruin soybeans? Iowa Agr. Exp. Sta. "Iowa Farm Science" 2(1): 5-8.

KATZ, M., and G. A. LEDINGHAM. 1939. Experiments on yield of barley and alfalfa. Chap. 13 of Effect of Sulphur Dioxide on Vegetation. National Res. Counc. of Can., Ottawa.

KENT, G. C., I. E. MELHUS, W. J. HOOKER, and A. T. ERWIN. 1944. The control of potato scab in highly calcareous peat and muck soils in northern Iowa. Iowa Agr. Exp. Sta. Ann. Rept. 1944 (I): 167-169.

KIESSELBACH, T. A. 1918. Studies concerning the elimination of experimental error on comparative crop tests. Nebraska Agr. Exp. Sta. Res. Bull. 13.

__________________. 1922. Corn investigations. Nebraska Agr. Exp. Sta. Res. Bull. 20. 151 pp.

__________________, and W. E. LYNESS. 1939. The effects of stinking smut (bunt) and seed treatment upon the yield of winter wheat. Nebraska Agr. Exp. Sta. Res. Bull. 110. 22 pp.

__________________, and __________________. 1945. Simulated hail injury of corn. Nebraska Agr. Exp. Sta. Bull. 377. 22 pp.

__________________, and R. M. WEIHING. 1933. Effect of stand irregularities upon the acre yield and plant variability of corn. Jour. Agr. Res. 47: 399-416.

KIGHTLINGER, C. V., and H. H. WHETZEL. 1926. Second report on dusting for cereal rusts. (Abst.) Phytopath. 16: 64.

KING, A. J., W. G. COCHRAN, R. J. JESSEN, M. HANSEN, and W. HURWITZ. 1945. Research pertaining to the construction and use of a national sample of farms. Iowa Agr. Exp. Sta. Rept. for 1945, I: 310-311.

__________, and R. J. JESSEN. 1945. The master sample of agriculture. I. Development and use. II. Design. Jour. Am. Statistical Assoc. 40: 38-56.

KIRBY, R. S., and W. A. ARCHER. 1927. Diseases of cereal and forage crops in the United States in 1926. Plant Disease Reptr. Suppl. 53.

KIRKPATRICK, H. C., and F. M. BLODGETT. 1943. Yield losses caused by leaf roll of potatoes. Am. Pot. Jour. 20: 53-56.

KLAGES, K. H. W. 1933. The effects of simulated hail injury on flax. Jour. Am. Soc. Agron. 25: 534-540.

KLEMM, M. 1937. Pflanzenschutzmeldedienst und Erzeugungsschlacht. Nachr. Bl. dtsch. Pflanzenschutzdienst 17: 69-70.

__________. 1940. Ernteverluste, Schadensschätzung und Pflanzenschutzstatistik. Forschungsdienst 10(3/4): 265-275. (R.A.M. 25(1946): 226-227.

__________. 1941. Pflanzenschutz in der UdSSR. Angew. Bot. 23: 41-62.

KNAPP, W. H. C. 1927. [Control of plant diseases. Are annual estimates of the damage desirable?] Tijdschr. over Plantenziek. 33: 283-291.

KOEHLER, B. 1945. Correspondence, Aug. 22, 1945.

KOEPPER, J. M. 1942. Relative resistance of alfalfa species and varieties to rust caused by *Uromyces striatus*. Phytopath. 32: 1048-1056.

KOTILA, J. E. 1923. Mosaic and potato yields in Michigan. Michigan Agr. Exp. Sta. Quart. Bull. 5: 188-189.

KRAMER, P. J. 1937. An improved photoelectric apparatus for measuring leaf areas. Am. Jour. Bot. 24: 375-376.

LANGFORD, M. H. 1945. South American leaf blight of Hevea rubber trees. U. S. Dept. Agr. Tech. Bull. 882. 31 pp.

LEACH, L. D. 1934. Quantitative determinations of *Sclerotium rolfsii* in the soils of sugar beet fields. (Abst.) Phytopath. 24: 1138.

LeCLERG, E. L., P. M. LOMBARD, A. H. EDDINS, H. T. COOK, and J. C. CAMPBELL. 1944. Effect of different amounts of spindle tuber and leaf roll on yields of Irish potatoes. Am. Pot. Jour. 21: 60-71.

__________, __________, __________, __________, and __________. 1946. Relation of spindle tuber and leaf roll to percentage reduction in yield of Irish potatoes as an aid in plant-disease-survey practice. Plant Disease Reptr. 30: 440-445.

LEE, H. A. 1929. Estimating damage from mosaic. Ann. Rept. 7th Conven. Philipp. Sugar Assn.

LEUKEL, R. W. 1937. Studies on bunt, or stinking smut, of wheat and its control. U. S. Dept. Agr. Tech. Bull. 582. 47 pp.

LEWIS, F. H. 1944. Effect of spray injury on pre-harvest drop of McIntosh apples. Phytopath. 34: 1015-1019.

LEXEN, BERT. 1947. The determination of net volume by sample-tree measuring. Jour. For. 45: 21-32.

LI, H. W., and T. N. LIU. 1935. Defoliation experiments with Kaoliang (*Andropogon sorghum*). Jour. Am. Soc. Agron. 27: 486-491.

LINK, G. K. K., and M. W. GARDNER. 1919. Market pathology and market diseases of vegetables. Phytopath. 9: 497-520.

LITTAUER, F., J. PALTI, and S. MOELLER. 1946. Potato blight control in Palestine. Palestine Jour. Bot., Rehovot Ser. 5: 186-201.

LITTLE, W. C. 1883. Report on wheat-mildew. Jour. Roy. Agr. Soc. England 19: 634-693.

LITVINOV, N. I. 1912. [On the differences in resistance of spring wheats in relation to rust infection] Tr. Bur. Prikl. Bot. 5: 347-403.

LIVERMORE, J. R. 1927. A critical study of some of the factors concerned in measuring the effect of selection in the potato. Jour. Am. Soc. Agron. 19: 857-895.

LIVINGSTON, J. E. 1947. Barley fertilizer and seed treatment test. Phytopath. 37: 426-428.

LOTT, R. V., and H. W. LeMERT. 1932. A simple device for use in leaf area studies. Proc. Am. Soc. Hort. Sci. 29: 83-84.

LUBIMENKO, V. N. 1933. [On the coefficients of injury.] Trudy po Zashch. Rast. No. 3, 3: 3-14.

LUBISHCHEV, A. A. 1940. [On the determination of injuriousness by the method of artificial injury.] Jour. Bot. Acad. Sci. Ukr. 1: 159-188.

LUDWIG, C. A. 1927. Some effects of late defoliation on cotton. South Carolina Agr. Exp. Sta. Bull. 238. 23 pp.

LUKYANENKO, P. P. 1934. [On the susceptibility of winter wheat hybrids to *Puccinia triticina* Erikss. during 1932 in connection with the results obtained in breeding for immunity.] [No. Cauc. Sel. Cent., Winter Wheat Seed Lab.] Azovo-Chernomorskoe Kraevoe Knigoizdatelstvo, Roshov-na-Donu, 1934. 46 pp.

LYMAN, G. R. 1918. The relation of phytopathologists to plant disease survey work. Phytopath. 8: 219-228.

MACHACEK, J. E. 1943. An estimate of loss in Manitoba from common root rot in wheat. Sci. Agr. 24: 70-77.

MAGNESS, J. R. 1928. Relation of leaf area to size and quality in apples. Proc. Am. Soc. Hort. Sci. 25: 285-288.

________, and F. L. OVERLEY. 1929. Relation of leaf area to size and quality of apples and pears. Proc. Am. Soc. Hort. Sci. 26: 160-162.

________, and ________, and W. A. LUCE. 1931. Relation of foliage to fruit size and quality in apples and pears. Washington Agr. Exp. Sta. Bull. 249: 5-26.

MAHALANOBIS, P. C. 1946. Use of small-size plots in sample surveys for crop yields. Nature 158: 798-799.

MAINS, E. B. 1923. (Quoted in "Leaf rust caused by *Puccinia triticina* Erikss.") Plant Disease Reptr. Suppl. 27: 192-196.

________. 1927. The effect of leaf rust (*Puccinia triticina*) on the seed production of wheat. (Abst.) Phytopath. 17: 40.

________. 1930. Effect of leaf rust (*Puccinia triticina* Erikss.) on yield of wheat. Jour. Agr. Res. 40: 417-446.

MARSH, R. W., H. MARTIN, and R. G. MUNSON. 1937. Studies upon the copper fungicides. III. The distribution of fungicidal properties among certain copper compounds. Ann. Appl. Biol. 24: 853-866.

MARSHALL, R. E. 1933. An apparatus for the ready determination of areas of compound leaves. Jour. Agr. Res. 47: 437-439.

MARTIN, W. H. 1923. Late blight of potatoes and the weather. New Jersey Agr. Exp. Sta. Bull. 384. 23 pp.

McCALLAN, S. E. A. 1946. Outstanding diseases of agricultural crops and uses of fungicides in the United States. Cont. Boyce Thomps. Inst. 14: 108-116.

McCUBBIN, W. A. 1946. Preventing plant disease introduction. Bot. Rev. 12: 101-139.

McKAY, M. B., and T. P. DYKSTRA. 1932. Potato virus diseases. Oregon Agr. Exp. Sta. Bull. 294. 40 pp.

McKINNEY, H. H. 1923. Influence of soil temperature and moisture on infection of wheat seedlings by *Helminthosporium sativum*. Jour. Agr. Res. 26: 195-218.

McMURTREY, J. E. 1928. Effect of the mosaic disease on yield and quality of tobacco with suggestions for control. Maryland Agr. Exp. Sta. Bull. 302: 147-158.

________. 1929. Effect of mosaic disease on yield and quality of tobacco. Jour. Agr. Res. 38: 257-267.

McNEW, G. L. 1943a. Effect of soil fertility on returns from use of fungicides. The Canner 96(7): 14, 15, 42, 44.

________. 1943b. Value of different seed treatments for lima beans. The Canner 96(8): 14, 15, 16, 17.

________. 1943c. Effect of weather conditions on response of sweet corn to different seed treatments. The Canner 96(9): 12-15, 24.

________. 1943d. Seed treatments for spinach. The Canner 96(11): 18-20, 70, 72.

________. 1943e. Which varieties of peas need treatment? The Canner 96(12): 14-16, 30, 32, 35.

________. 1943f. The prevention of tomato leaf blight. The Canner 96(14): 12-14, 16, 26, 27.

________. 1943g. Effect of different fungicides on leaf blight and yield of tomatoes. The Canner 96(15): 12-14, 24, 26, 28.

________. 1943h. Economical use of copper in tomato spraying. The Canner 96(16): 16, 36-40.

________. 1943i. The control of Phytophthora fruit rot in tomatoes. The Canner 96(17): 12-14, 23-26.

________. 1943j. Control of anthracnose on cannery tomatoes. The Canner 96(18): 16, 17, 26-28.

MEINECKE, E. P. 1928. The evaluation of loss from killing diseases in the young forest. Jour. For. 26: 283-298.

______________. 1929. Quaking aspen. A study in applied forest pathology. U. S. Dept. Agr. Tech. Bull. 155: 1-33.

MELCHERS, L. E. 1917. *Puccinia triticina* Erikss. Leaf rust of wheat causes damage in Kansas. Phytopath. 7: 224.

______________. 1931. A check list of plant diseases and fungi occurring in Egypt. Trans. Kansas Acad. Sci. 34: 41-106.

______________, and C. O. JOHNSTON. 1939. The wheat stem and leaf rust epidemics in 1938 in Kansas. Plant Disease Reptr. Suppl. 166: 54-68.

______________, and J. H. PARKER. 1922. Rust resistance in winter wheat varieties. U. S. Dept. Agr. Bull. 1046. 32 pp.

MELHUS, I. E. 1915. Germination and infection with the fungus of the late blight of potato. Wisconsin Agr. Exp. Sta. Res. Bull. 37. 64 pp.

______________. 1942. The late blight outbreak of 1942 and a proposed forecasting service. Trans. Iowa State Hort. Soc. 77: 287-293.

______________. 1945. Late blight forecasting service. Phytopath. 35: 463-479.

MENZIES, J. D., and C. O. STANBERRY. 1947. The effect of terminal smut galls on yield and seed grade of detasseled hybrid corn. (Abst.) Phytopath. 37: 363.

MILLER, J. H. 1935. Cereal diseases in northern Georgia. Plant Disease Reptr. 19: 221-224.

MILLER, P. A., and J. T. BARRETT. 1931. Cantaloupe powdery mildew in the Imperial Valley. California Agr. Exp. Sta. Bull. 507.

MILLER, P. R. 1934. A method of estimating the percentage of infection of apple leaves by rust with observations on the relative susceptibility of species and varieties of *Malus* and *Juniperus*. Plant Disease Reptr. 18: 159-163.

______________. 1935. Fruit and vegetable losses in market and kitchen caused by plant diseases. Plant Disease Reptr. Suppl. 88: 1-25.

______________. 1946. Some psychological aspects involved in conducting plant disease surveys: Personal bias a factor to be reckoned with in estimating and evaluating plant disease losses. Plant Disease Reptr. 30: 74-77.

______________. 1947*a*. Tomato blight warning service. Agr. Chem. 2(3): 41.

______________. 1947*b*. G-men of plant diseases. U. S. Dept. of Agr., Yearbook of Agriculture 1943-47: 443-450.

______________. 1947*c*. Warning service for late blight with special reference to tomato. Plant Disease Reptr. 31: 140-143.

______________, and L. H. PERSON. 1947. Correspondence, Nov., Dec., 1947.

______________, and J. I. WOOD. 1947. An evaluation of certain phases of the Emergency Plant Disease Prevention Project. Plant Disease Reptr. Suppl. 167. 26 pp.

______________, and ____________, and OTHERS. 1947. Tomato late blight in the warning service area in 1947. Plant Disease Reptr. Suppl. 171: 192-236.

MILTHORPE, F. L. 1942. A simplified photoelectric cell method of measuring leaf areas. Jour. Austral. Inst. Agr. Sci. 8: 27.

MINOTT, C. W., and I. T. Guild. 1925. Some effects of the defoliation of trees. Jour. Econ. Entom. 18: 345-348.

MITCHELL, J. W. 1936. Measurement of the area of attached and detached leaves. Science 83: 334-336.

MOLOTKOVSKY, G. KH. 1945. [On the problem how to avoid potato deterioration in the South.] C. R. (Dokl.) Acad. Sci. U. R. S. S. 46: 379-381.

MOORE, J. D. 1946. Relation of sour cherry yellows to yield. (Abst.) Phytopath. 36: 406.

______________, and KEITT, G. W. 1946. Cherry yellows drastically reduces yields. Wisconsin Agr. Exp. Sta., Bull. 469: 44-45.

MOORE, W. C. 1943. The measurement of plant diseases in the field. Trans. Brit. Mycol. Soc. 26: 28-35.

MOORE, W. D. 1937. The relation of rainfall to the development of late blight of Irish potatoes in the coastal section of South Carolina. South Carolina Agr. Exp. Sta., Cir. 57. 8 pp.

MORRIS, H. E., and M. M. AFAVASIEV. 1945. Sugar beet diseases and their control in Montana. Montana Agr. Exp. Sta. Bull. 427. 22 pp.

MORSTATT, H. 1929. Die jährlichen Ernteverluste durch Pflanzenkrankheiten und Schädlinge und ihre statistische Ermittlung. Ber. über Landw., N. F. 9: 433-477.

MORSTATT, H. 1937. Ermittlung der Schadenswerte. Schadenzahlen. In APPEL, O. et al., Handbuch der Pflanzenkrankheiten, 6: 3-13.

MOURASHKINSKY, K. E. 1932. [On the determination of the degree of infection of wheat with bunt.] Bolezni Zernovii Kultur. Sib. Scient. Res. Inst. Cereal Indus., Omsk: 62-71.

MURAVEV, V. P., and Z. N. SCHEVCHENKO. 1928. [Instructions for phytopathological observations.] Kiev. 1928. In YACHEVSKI, 1929.

MURPHY, H. C. 1935. Effect of crown rust infection on yield and water requirement of oats. Jour. Agr. Res. 50: 387-411.

______________, and L. C. BURNETT. 1943. More oats, fewer acres. Farm Science Reporter (Iowa), Jan. 1943: 6-7.

MURPHY, P. A. 1921. Investigation of potato diseases. Canada Dept. Agr., Dom. Exp. Farms, Bull. 44: 7-86.

______________. 1923. Investigations on the leaf-roll and mosaic diseases of the potato. Jour. Dept. Agr. and Tech. Instruc. (Ireland) 23: 20-34.

______________, and R. M^{c}KAY. 1924. Investigations on the leaf-roll and mosaic diseases of the potato. Jour. Dept. Agr. and Tech. Instruc. (Ireland) 23: 344-364.

NAUMOV, N. A. 1924. [On the question of the possibilities for determining the degree of plant infection by fungous parasites] Trudy IV Entom. - Phytopath. Congr., Moscov, 1922: 217-228.

______________. 1939. [Rusts of cereals in U.S.S.R.] Moscov and Leningrad, Selkhozgiz, State Printing Off. Sect. Colkhos and Sovkhos. 403 pp.

NEAL, D. C. 1928. Cotton wilt: A pathological and physiological investigation. Mississippi Agr. Exp. Sta., Tech. Bull. 16. 51 pp.

NELSON, RAY. 1939. Tests of new dust and liquid fungicides in 1938 for control of celery leaf blights. Michigan Agr. Exp. Sta., Quart. Bull. 21: 295-307.

______________, and L. C. COCHRAN. 1936. Copper dusts control celery early blight. Michigan Agr. Exp. Sta., Quart. Bull. 18: 163-169.

NEVODOVSKII, G. 1925. [Instructions for correspondents on observations of the principal diseases of plants.] Kiev. In YACHEVSKI, 1929.

NEWELL, L. C., and H. M. TYSDAL. 1945. Numbering and note-taking systems for use in the improvement of forage crops. Jour. Am. Soc. Agron. 37: 736-749.

NEWTON, M., B. PETURSON, and W. O. S. MEREDITH. 1945. The effect of leaf rust of barley on the yield and quality of barley varieties. Canada Jour. Res., C. 23: 212-218.

NILSSON-EHLE, H. 1911. Kreuzungsuntersuchungen an Hafer und Weizen. Lund:s Universit. Åarskr., N. F., 6. 84 pp.

NORTON, J. B. S. 1914. Loss from mosaic disease of tomato. (Abst.) Phytopath. 4: 398.

OLSON, P. J. 1928. Relation of stand to yield in corn. Jour. Am. Soc. Agron. 20: 1235-1237.

OSBORN, L. W. 1925. Experiments with varying stands and distribution of corn. I-IV. Arkansas Agr. Exp. Sta., Bull. 200. 36 pp.

PAL, B. P. 1936. Effect of brown rust attack on wheat. Indian Jour. Agr. Sci. 6: 127-128.

PEPPER, B. B. 1947. Early estimates of loss too low. Agr. Insecticide and Fungicide News 6 (2): 3.

PETERSON, R. F., A. B. CAMPBELL, and A. E. HANNAH. 1948. A diagrammatic scale for estimating rust intensity on leaves and stems of cereals. Canada Jour. Res., C. 26: 496-500.

PETURSON, B., and M. NEWTON. 1939. The effect of leaf rust on the yield and quality of Thatcher and Renown wheat in 1938. Canada Jour. Res., C, 17: 380-387.

PHIPPS, I. F. 1938. The effect of leaf-rust on yield and baking quality of wheat. Jour. Aust. Inst. Agr. Sci. 4: 148-151.

PIRONE, P. P., A. G. NEWHALL, W. W. STUART, J. G. HORSFALL, and A. L. HARRISON. 1933. Copper seed treatments for the control of damping-off of spinach. New York (Cornell) Agr. Exp. Sta., Bull. 566. 25 pp.

POPE, O. A. 1947. Effect of skips, or missing row segments, on yield of seed cotton in field experiments. Jour. Agr. Res. 74: 1-13.

POPP, W. 1947. A rapid method of examining wheat heads for bunt infection. Phytopath. 27: 418-420.

PORTER, A. M. 1932. The influence of defoliation and fruit thinning on the growth of tomatoes. Thesis, Michigan State College.

PORTER, R. H. 1926. A preliminary report of surveys for plant diseases in East China. Plant Disease Reptr. Suppl. 46: 153-166.

RAGL, F. X. 1944. History of the fight against Peronospora in Germany. Deutsch. Brauindustr. 52: 161.

RAMSEY, G. B., M. A. SMITH, and B. C. HEIBERG. 1947. Fruit and vegetable losses on the Chicago market as indicated by dumping certificates. Plant Disease Reptr. 31: 387-390.

RANDS, R. D., and E. DOPP. 1938. Pythium root rot of sugar cane. U. S. Dept. Agr. Tech. Bull. 666. 95 pp.

RANKIN, W. H. 1931. New Methods for determining rate of decay behind cavity fillings in trees. (Abst.) Phytopath. 21: 126.

RAY, W. W. 1945. (Unpublished photographs on file at Oklahoma Agr. and Mech. Coll., Botany Dept., Stillwater, Oklahoma)

REICHERT, I., G. MINZ, J. PALTI, and N. HOCHBERG. 1944. Trials for the control of grape vine diseases. Jew. Agency for Palestine, Agr. Res. Sta., Bull. 35. 12 pp.

______, PALTI, J. G. MINZ, and B. KAPULER. 1942a. Field trials for the control of downy and powdery mildew of cucumbers. I. On the efficacy of various copper compounds. Palestine Jour. of Bot., Rehovot Ser. 4(2): 96-116.

______, ______, ______, ______, and S. STOLAR. 1942b. Field trials for the control of tomato leaf diseases. Palestine Jour. Bot., Rehovot. Ser. 4(2): 117-141.

REITZ, L. P. 1947. Unpublished address, Hard Red Winter Wheat Conf., Stillwater, Oklahoma.

RICHARDS, B. L. 1937. Susceptibility of alfalfa varieties to bacterial stem blight. Proc. Utah Acad. Sci., Arts and Lett. 14: 33-38.

RIEHM, E. 1910. Welchen Wert besitzen statistische Erhebungen für die Phytopathologie Mitt. f. d. Landw. 1910, Stück 47: 682-685.

ŘIHA, J. 1928. [Correlation coefficients for estimating the reduction in yield caused by the more important of our potato diseases.] Ochrana Rostlin 8 (2-3): 58-61.

RIVIER, A. 1932. Quelques notations des rouilles du blé. Rév. Path. Vég. et Ent. Agr. 19: 191-201.

ROBERTSON, D. W., O. H. COLEMAN, J. F. BRANDON, H. FELLOWS, and J. J. CURTIS. 1942. Rate and date of seeding Kanred winter wheat and the relation of seeding date to dry-land foot rot at Akron, Col. Jour. Agr. Res. 64: 339-356.

ROEBUCK, A., and P. S. BROWN. 1923. Correlation between loss of leaf and damage to crop in late attacks on wheat. Ann. Appl. Biol. 10: 326-334.

RUSAKOV, L. F. 1926. [On the question of estimating the damage from cereal rusts.] Zashch. Rast. ot Vredit. 2: 574-580.

______. 1927. [A combination scale for estimating the development of rusts.] Bolezni Rastenii (Morbi Plantarum) 16: 179-185.

______. 1929a. [An attempt to classify winter-sown wheats according to the degree of their infection with brown rust.] Bolezni Rastenii (Morbi Plantarum) 18: 54-65.

______. 1929b. [Methods of appraising cereal rusts and their harmfulness in variety tests.] Trudy Vses. Sezda po Genet. i Seleks., Jan. 10, 1929, 5: 135-145.

______. 1929c. [Cereal rusts at the Rostov-Nakhitchevan Agricultural Experiment Station in 1927.] [No. Cauc. Reg. Agr. Exp. Sta.], Rostov-on-Don, Bull. 288: 1-24.

______. 1929d. [Rusts of cereals at the Yeisk Agricultural Experiment Station in 1927.] Zashch. Rast. (Pl. Prot.) 1929: 103-127.

RUSSELL, R. C., and B. J. SALLANS. 1940. The effect of phosphatic fertilizers on common root rot. Sci. Agr. 21:44-51.

RUZINOV, P. G. 1934. [Investigation of the degree of injury caused by certain cereal diseases in the field.] Zashch. Rast. (Pl. Prot.), 4: 5-30.

SABROSKY, Mrs. L. K. 1946. Use of sampling procedures in extension work. Mimeogr. Presented to Cornell Ext. Club, Cornell Univ., Dec. 2, 1946. 10 pp.

SALLANS, B. J. 1935. Study of the root rot problem of wheat and barley caused by Helminthosporium sativum in Saskatchewan. Canada Dept. Agr. Progress Rept. Dom. Bot. for 1931-34: 24-25.

______. 1948. Interrelations of common root rot and other factors with wheat yields in Saskatchewan. Sci. Agr. 28: 6-20.

______, and R. J. LEDINGHAM. 1943. An outbreak of common root rot in Southwestern Saskatchewan in 1942. Sci. Agr. 23: 589-597.

SALMON, S. C. 1930. The reaction of alfalfa varieties to bacterial wilt. Jour. Am. Soc. Agron. 22: 802-810.

______, and H. H. LAUDE. 1932. Twenty years of testing varieties and strains of winter wheat at the Kansas Agricultural Experiment Station. Kansas Agr. Exp. Sta. Tech. Bull. 30. 73 pp.

SǍVULESCU, T., and RAYSS. 1935. 6th Intern. Bot. Congr., Amsterdam, 1935. II: 208.

SAYRE, J. D., V. H. MORRIS, and F. D. RICHEY. 1931. The effect of preventing fruiting and of reducing the leaf area on the accumulation of sugars in the corn stem. Jour. Am. Soc. Agron. 23: 751-753.

SCHLEIDEN, M. J. 1850. Die Physiologie der Pflanzen und Tiere und Theorie der Pflanzenkultur 3: 474-475. Braunschweig.

SCHLUMBERGER, O. 1927. Über die Möglichkeit einer Versicherung gegen Schäden durch Pflanzenkrankheiten. Illus. Landw. Zeit. 47: 75-77.

SCHULTZ, E. S., and R. BONDE. 1944. The effect of latent mosaic (virus X) on yield of potatoes in Maine. Am. Pot. Jour. 21: 278-283.

______________, ______________, and W. P. RALEIGH. 1934. Isolated tuber-unit seed plots for the control of potato virus diseases in northern Maine. Maine Agr. Exp. Sta., Bull. 370: 1-32.

______________, and D. FOLSOM. 1921. Leaf roll, net necrosis, and spindling sprout of the Irish potato. Jour. Agr. Res. 21: 47-80.

______________, and ____________. 1923. Transmission, variation, and control of certain degeneration diseases of Irish potatoes. Jour. Agr. Res. 25: 43-117.

SCHULTZ, H. 1938. The Theory and Measurement of Demand. Univ. Chi. Press, Chicago. 817 pp.

SCHUSTER, C. E. 1933. Leaf area and shoot growth in relation to size and filling of filberts. Proc. Am. Soc. Hort. Sci. 30: 392-395.

SCOTT, J. R. 1941. The effects of mosaic diseases on potatoes. Scot. Jour. Agr. 23: 258-264.

SEMENIUK, G. 1944. Seedling infection of dent maize by Sclerotium bataticola Taub. Phytopath. 34: 838-843.

SEMENIUK, W., and J. G. ROSS. 1942. Relation of loose smut to yield of barley. Canada Jour. Res., C, 20: 491-500.

SHCHEGLOVA, O. A., and I. V. CHERNISHEVA. 1933. [Influence of mechanical reduction of leaf area on plant development, dry weight, and grain yield in spring wheat and barley.] Trudy po Zashch. Rast., Ser. 3, 3: 73-111.

SHEAR, C. L. 1918. Pathological aspects of the Federal fruit and vegetable inspection service. Phytopath. 8: 155-160.

SHEVCHENKO, V. 1933. [Experimental study of the influence of artificial reduction of the assimilatory surface of cereal leaves on the yields produced.] Trudy po Zasch. Rast., Ser. 3, 3: 44-60.

SMITH, A. L. 1941. The reaction of cotton varieties to Fusarium wilt and root-knot nematode. Phytopath. 31: 1099-1107.

____________, and A. L. TAYLOR. 1947. Field methods of testing for root-knot infestation. Phytopath. 37: 85-93.

SMITH, F. L. 1936. The effect of corn smut on the yield of grain in the San Joaquin Valley of California. Jour. Am. Soc. Agron. 28: 257-265.

SMITH, H. S., E. O. ESSIG, H. S. FAWCETT, G. M. PETERSON, H. J. QUAYLE, R. E. SMITH, and H. R. TOLLEY. 1933. The efficacy and economic effects of plant quarantines in California. Univ. California Bull. 553. 276 pp.

SMITH, K. M. 1933. Economic importance. In Recent Advances in the Study of Plant Viruses. P. Blakiston's Sons and Co., Philadelphia. 7-11.

____________, 1946. Virus Diseases of Farm and Garden Crops. Littlebury & co., Ltd., Worcester, England : 35.

____________, and R. MARKHAM. 1945. Importance of potato virus X in the growing of potatoes. Nature 155: 38-39.

SMITH, P. G., and J. C. WALKER. 1941. Certain environal and nutritional factors affecting Aphanomyces root rot of garden pea. Jour. Agr. Res. 63: 1-20.

SMITH, T. E., E. E. CLAYTON, and E. G. MOSS. 1945. Flue-cured tobacco resistant to bacterial (Granville) wilt. U. S. Dept. Agr., Circ. 727. 7 pp.

SORAUER, P. 1908. Manual of Plant Diseases, Vol. 1 (Dorrance translation): 20-21.

____________. 1909. Vorarbeiten für eine internationale Statistik der Getreideroste, Ztschr. f. Pflkr. 193-286.

SPRAGUE, H. B., and N. F. FARIS. 1931. The effect of uniformity of spacing seed on the development and yield of barley. Jour. Am. Soc. Agron. 23: 516-533.

STANILAND, L. N. 1946. Simple laboratory and field apparatus for the production of accurate line drawings to scale. Ann. Appl. Biol. 33: 170-177.

STEVENS, N. E., 1933. Plant pathology and the consumer. Sci. Month. 37: 325-329.

STEVENS, N. E. 1934a. Losses from potato late blight in 1885 and 1886. Phytopath. 24: 76-78.

______________. 1934b. Records of agricultural projects known to have failed through plant diseases. Plant Disease Reptr. 18: 7-16, 23, 40.

______________. 1935. An attempted analysis of the economic effects of cranberry diseases. Plant Disease Reptr. 19: 112-128.

______________. 1938. Problems involved in the control of plant diseases and insects. Jour. Econ. Entom. 31: 39-44.

______________. 1939. Disease, damage and pollination types in "grains". Science, N. S. 89: 339-340.

______________. 1940a. Losses from bunt of wheat in the United States. Phytopath. 30: 449-451.

______________. 1940b. Recent trends in plant disease control. Trans: Illinois State Acad. Sci. 33: 66-67.

______________. 1941b. Botanical research by unfashionable technics. Science 93: 172-176.

______________. 1943. Relation of weather to the keeping quality of Massachusetts cranberries. Massachusetts Agr. Exp. Sta., Bull. 402: 68-83.

______________. 1944. Further observations on alkaline flooding water in cranberry growing. Trans. Wisconsin Acad. Sci., Arts and Lett. 36: 395-398.

______________. 1945. Research and plant disease surveys. Plant Disease Reptr. Suppl. 152: 6-12.

______________, and C. M. HAENSELER. 1941. Incidence of bacterial wilt of sweet corn, 1935-1940. Forecasts and performance. Plant Disease Reptr. 25: 152-157.

______________, and J. I. WOOD. 1935. Losses from corn ear rots in the United States. Phytopath. 25: 281-283.

STEVENSON, E. C. 1947. The effect of seedling diseases of castor beans on the subsequent plant development and yield. Phytopath. 37: 184-188.

STEWART, F. C. 1919. Missing hills in potato fields: their effect upon the yield. New York Agr. Exp. Sta. (Geneva), Bull. 459: 45-69.

______________. 1921. Further studies on the effect of missing hills in potato fields and on the variation in the yield of plants from halves of the same seed tuber. New York Agr. Exp. Sta. (Geneva), Bull. 489: 1-52.

STONE, W. E. 1936. Growth, chemical composition, and efficiency of normal and mosaic potato plants in the field. Jour. Agr. Res. 52: 295-309.

STRAKHOV, T. D. 1925. [Ukrainian network of observation points. Instructions on the organization and appraisal of diseases of field and horticultural crops.] Kharkov. In YACHEVSKI, 1929.

SUKHATME, P. V. 1947. Use of small-size plots in yield surveys. Nature 160: 542.

SUMMERS, E. M., E. W. BRANDES, and R. D. RANDS. 1948. Mosaic of sugar cane in the United States with special reference to strains of the virus. U. S. Dept. Agr. Tech Bull. 955. 124 pp.

SUMMERS, J. N., and A. F. BURGESS. 1933. A method of determining losses to forests caused by defoliation. Jour. Econ. Entom. 26: 51-54.

SUNESON, C. A., 1946. Effect of barley stripe, Helminthosporium gramineum Rab., on yield. Jour. Am. Soc. Agron. 38: 954-955.

SWAIN, R. B., R. F. OLSEN, G. R. PHILLIPS, and W. S. FIELDS. 1946. Report on the special survey for insect pests and plant diseases in the vicinity of ports of entry, June 1943 - June 1945. Unnumbered mimeogr. publ., U. S. Dept. Agr., Bur. Ent. Pl. Quar.

SWANSON, A. F. 1941. Relation of leaf area to grain yield of sorghum. Jour. Am. Soc. Agron. 33: 908-914.

TAUBENHAUS, J. J., and W. N. EZEKIEL. 1931. Cotton root rot and its control. Texas Agr. Exp. Sta., Bull. 423. 39 pp.

TAYLOR, A. L. 1941. Unpubl. letters to Cooperators in the Root-knot Resistance Tests. Georgia Agr. Exp. Sta., Tifton, Georgia April 30 and Aug. 1, 1941.

TEHON, L. R. 1927. Epidemic diseases of grain crops in Illinois, 1922-1826. The measure of their prevalence and destructiveness and an interpretation of weather relations based on wheat leaf rust data. Illinois Nat. Hist. Surv. 17: 1-96.

______________, and G. L. STOUT. 1930. Epidemic diseases of fruit trees in Illinois, 1922-1928. Bull. Illinois Dept. Registr. and Educ., Div. Nat. Hist. Surv. 17, Art. 3: 415-502.

THUNG, T. H. 1940. [Phytopathological observations] ex Jaarverslag 1938-1939. Meded. Proefst. vorstenl. Tab. 88: 24-28.

______________. 1947. Potato diseases and hybridization. Phytopath. 37: 373-381.

TIDD, J. S. 1944. California citrus psorosis survey. Plant Disease Reptr. 28: 638-640.

TOUMARINSON, C. S. 1934. [On the physiological basis of scales for estimating the injuriousness of rust] Bull. Pl. Prot. Leningr., Ser. II. (Phytopath.), 1934: 35-56.

TOWNSEND, G. R. 1942. Spraying and dusting for the control of celery early blight in the Everglades. Florida Agr. Exp. Sta., Bull. 366: 3-26.

______________, and J. W. HEUBERGER. 1943. Methods for estimating losses caused by diseases in fungicide experiments. Plant Disease Reptr. 27: 340-343.

TRAVERSO, G. B., 1923. L'organizzazione dei Servizi fitopatologici in Italia. Atti XVI Congr. naz. Unione delle Cattedre ambulanti di Agricoltura italiane, 1923. (Rev. Appl. Mycol. 2: 478-480.

TRUMBOWER, J. A. 1934. Control of elm leaf spots in nurseries. Phytopath. 24: 62-73.

TUCKER, C. M. 1927. Pigeon pea anthracnose. Jour. Agr. Res. 34: 589-596.

TUTHILL, C. S., and P. DECKER. 1941. Losses in yield caused by leaf roll of potatoes. Am. Pot. Jour. 18: 136-139.

ULLSTRUP, A. J., C. ELLIOTT, and P. E. HOPPE. 1945. Report of the committee on methods for reporting corn disease ratings. Mimeog., unnumbered publ. of U. S. Dept. Agr., Div. Cereal Crops and Dis. 5 pp.

VALGREN, V. N. 1922. Crop insurance: risks, losses, and principles of protection. U. S. Dept. Agr., Bull. 1043: 1-27.

VALLEAU, W. D., and E. M. JOHNSON. 1927. The effect of a strain of tobacco mosaic on the yield and quality of burley tobacco. Phytopath. 17: 523-528.

VAN EVERDINGEN, E. 1926. Het verband tusschen de weergesteldheid en de Aardappelziekte (*Phytophthora infestans*). Tijdschr. over Plantenziekten 32: 129-140.

VASUDEVA, R. S. 1946. Virus diseases of potatoes in India; masking of mosaic symptoms and yield in relation to mosaic. Indiana Farming 7: 170-173.

VAVILOV, N. I. 1913. [Studies on the question of differences in resistance of cereals to parasitic fungi] Trudy Selek. Stan., Moskov Selskokhoz. Inst. 1: 1-108.

______________. 1919. [Immunity of plants to infectious diseases] Ann. Acad. Agr. Petrov, 1918. 239 pp.

______________. 1935. Scales of varietal resistance to infectious diseases. In Selected Writings of N. I. Vavilov, Chester translation, Chronica Botanica Co., Waltham, Massachusetts, 1949.

VESTAL, E. F. 1944. A simplified method of securing data from known sources: A study in sampling methods. Plant Disease Reptr. 28: 1164-1167.

VYVYAN, M. C., and H. EVANS. 1932. The leaf relations of fruit trees. I. A morphological analysis of the distribution of leaf surface on two nine-year-old apple trees (Laxton Superb.). Jour. Pom. and Hort. Sci. 10: 228-270.

WALDRON, L. R. 1928. Results from cooperative rod-row wheat trials in 1927. Jour. Am. Soc. Agron. 20: 500-510.

______________. 1936. The effect of leaf rust accompanied by heat upon yield, kernel weight, bushel weight, and protein content of hard red spring wheat. Jour. Agr. Res. 53: 399-415.

WALKER, J. C., and W. W. HARE. 1943. Pea diseases in Wisconsin in 1942. Wisconsin Agr. Exp. Sta., Res. Bull. 145: 1-32.

______________, and J. P. JOLIVETTE. 1943. Productivity of mosaic-resistant Refugee beans. Phytopath. 33: 778-788.

WALLACE, P. P. 1945. Certain effects of defoliation of deciduous trees. Connecticut Agr. Exp. Sta., Bull. 488: 358-373.

WARE, J. O., and V. H. YOUNG. 1934. Control of cotton wilt and "rust". Arkansas Agr. Exp. Sta., Bull. 308.

WATSON, M. A., D. J. WATSON, and R. HULL. 1946. Factors affecting the loss of yield of sugar beet caused by beet yellows virus. Jour. Agr. Sci. [Eng.] 36: 151-166.

WEIHING, R. M., D. W. ROBERTSON, and O. H. COLEMAN. 1938. Survival of several alfalfa varieties seeded on irrigated land infested with bacterial wilt. Colorado Agr. Exp. Sta., Tech. Bull. 23.

WEINBERGER, J. H. 1931. The relation of leaf area to size and quality of peaches. Proc. Am. Soc. Hort. Sci. 28: 18-22.

______________, and F. P. CULLINAN. 1932. Further studies on the relation between leaf area and size of fruit, chemical composition, and fruit bud formation in Elberta peaches. Proc. Am. Soc. Hort. Sci. 29: 23-27.

WEIR, JAMES R. 1918. Forest diesease surveys. U. S. Dept. Agr., Bull. 658: 1-23.

WEISS, H. B. 1940. Money losses due to destructive insects. Jour. New York Entom. Soc. 48: 195-199.

WELLHAUSEN, E. J. 1942. Leaf blight of corn in West Virginia. Plant Disease Reptr. 26: 494-495.

WELLMAN, F. L. 1939. A technique for studying host resistance and pathogenicity in tomato Fusarium wilt. Phytopath. 29: 945-956.

WERNER, H. O. 1925. The spindle-tuber disease. Nebraska Agr. Exp. Sta., Bull. 207. 21 pp.

WHIPPLE, O. B. 1919. Degeneration in potatoes. Montana Agr. Exp. Sta., Bull. 130. 29 pp.

WHITE, R. M. 1946. Preliminary observations on some effects of artificial defoliation of wheat plants. Sci. Agr. 26: 225-229.

WHITEHEAD, F. E., and F. A. FENTON. 1940. An airplane survey of green bug [Toxoptera graminum] injury in Oklahoma. Jour. Econ. Ent. 33: 762-764.

WHITEHEAD, T. 1924. Potato leaf-roll and degeneration in yield. Ann. Appl. Biol. 11: 31-41.

______________, J. F. CURRIE. 1931. The susceptibility of certain potato varieties to leaf-roll and mosaic infection. Ann. Appl. Biol. 18: 508-520.

WIANT, J. S., and G. H. STARR. 1936. Field studies on the bacterial wilt of alfalfa. Wyoming Agr. Exp. Sta., Bull. 214. 19 pp.

WILLARD, C. J. 1931. The correlation between stand and yield of alfalfa and sweetclover. Jour. Agr. Res. 43: 461-464.

WILSON, J. D. 1944. The control of celery blights with Bordeaux, the fixed coppers with and without sulphur, and fermate. Ohio Agr. Exp. Sta., Bimonth. Bull. 29: 95-98.

WINKLER, A. J. 1930. The relation of number of leaves to size and quality of table grapes. Proc. Am. Soc. Hort. Sci. 27: 158-160.

WITHROW, R. B. 1935. A photoelectric device for the rapid measurement of leaf area. Jour. Agr. Res. 50: 637-643.

WOLF, F. A., and E. G. MOSS. 1933. Effect of mosaic of flue-cured tobacco on yield and quality. Phytopath. 23: 834-836.

WOOD, J. I. 1935. Estimates of crop losses from diseases in the United States - 1931, 1932, and 1933. Plant Disease Reptr. Suppl. 87: 1.

__________, and N. W. NANCE. 1938. Diseases of plants in the United States in 1937. Leaf rust (Puccinia rubigo-vera tritici). Plant Disease Reptr. Suppl. 110: 184-188.

WYCKOFF, S. N., C. HARTLEY, and L. W. ORR. 1947. Protection against forest insects and diseases in the United States. U. S. Dept. Agr., Forest Serv., Reappraisal Rept. 5. 39 pp.

YACHEVSKI (JACZEWSKI), A. A. 1909. [Rusts of grains in Russia.] Dept. Zemled. Tr. Buro Mikol. i Fitopat., Sib., St. Petersburg. 187 pp.

__________________________. 1929. [A guide to phytopathological observations.] A. A. Yachevski Mycological Lab., Leningrad. 237 pp.

YARWOOD, C. E. 1943. Onion downy mildew. Hilgardia 14: 595-691.

______________. 1945. Copper sulphate as an eradicant spray for powdery mildews. Phytopath. 35: 895-909.

______________. 1946a. Increased yield and disease resistance of giant hill potatoes. Am. Pot. Jour. 23: 352-369.

______________. 1946b. Isolation of Thielaviopsis basicola from soil by means of carrot discs. Mycologia 38: 346-348.

YOUNG, P. A., and H. E. MORRIS. 1930. Researches on potato-virus diseases in Montana. Montana Agr. Exp. Sta., Bull. 231. 51 pp.

ZILLGITT, W. M., and S. R. GEVORKIANTZ. 1948. Estimating cull in northern hardwoods with special reference to sugar maple. Jour. Forestry 46: 588-594.