THE PROMISE OF MODERN BOTANY FOR MAN'S WELFARE THROUGH PLANT PROTECTION*

BOTANY is the most important of all sciences, and plant pathology is one of its most essential branches. The statement is hyperbolic, of course, but it is not mere bombast. For man still is basically dependent on plants for subsistence. Plants are the sole creators of food and clothing materials; man and other animals are merely cultivators, transformers, processors or purveyors. When we consider the manifold additional uses of plants and plant products, including their service in building and conserving soil, in controlling floods and in increasing the esthetic enjoyment of life, the assertion in the first sentence could at least be defended in argument. At any rate it is well to remind ourselves occasionally that human subsistence is dependent on plants and that the number of people that can exist in the world is limited by its agricultural and aquicultural potentialities.

If plants are essential, it follows that their protection also is of paramount importance. Plants need protection against unfavourable soil and weather, against certain industrial by-products, against insect pests, against diseases caused by bacteria, fungi, eel-worms and other living organisms, and against filterable viruses. Crop plants may be severely damaged or commercially ruined by any of the above causes. It would be desirable but hardly feasible within reasonable limits, to discuss the devastation caused by all these factors. Therefore, this discussion is restricted principally to plant diseases caused by plant parasites, except in so far as other factors must be taken into consideration in controlling them.

Ever since the dawn of recorded history plant diseases and insect pests have been among the greatest hazards in the production of crop plants, and they still are. It has been estimated that insect pests cost the people of the United States approximately a billion dollars annually, and plant diseases are about as costly. Plant pathologists and entomologists often are ridiculed for their allegedly extravagant estimates of damage caused by diseases and pests. But any one who has seen the devastation caused by epidemics of black stem rust of wheat and other small grains, by late blight of potatoes, by grasshoppers and by many other diseases and insects must be profoundly impressed with the magnitude of the financial losses, the tragic consequences

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to farmers and the far-reaching sociologic and even political implications of such crop catastrophes.

While the control of insect pests is not primarily a botanical problem, the relation of insects to many plant diseases is so important that a discussion of plant protection would not be complete without at least brief reference to it. Insects are the principal or only agents of dissemination and inoculation of many plant pathogens. In popular language, insects are tremendously important in spreading plant diseases. They are responsible for the spread of some of the most destructive virus diseases, such as curly-top of sugar-beets, aster yellows, sugar-cane mosaic, raspberry mosaic and many others. They also are largely or wholly responsible for the dissemination and inoculation of the bacteria or fungi that cause rots of potatoes and other vegetables, pear blight, the Dutch elm disease, wilt of cucumbers and related plants, and certain wood stains and rots of felled timber. So important are insects in connection with many plant diseases that disease control becomes a joint entomological and botanical problem. And the protection of crop plants against many insect pests themselves may well be accomplished by botanists through the breeding of resistant varieties. This method of controlling insects has not been used extensively, but there is evidence that it may become very important. Modern botany can promise much for the control of certain insects, but close co-operation between entomologists and botanists can promise still more.

How important is it to protect plants against diseases? Far more important than often is supposed. In a Mayo Foundation lecture several years ago Professor Whetzel pointed out that one-third of the sweet potato crop of the United States is destroyed annually by diseases in the field or in the storage house, "one bean in every dozen, one apple in every seven, one peach in every eight, one bushel of Irish potatoes in every twelve, and one bushel of wheat in every ten, are destroyed annually by diseases in these crops." It is stated further that certain potato growers in Pennsylvania have increased acre yields of potatoes between 300 and 500 bushels over the average of the state by using disease-free seed and by spraying. In Minnesota, a number of years ago, yields of potatoes were increased by 160 bushels an acre in demonstration plots through the use of disease-free seed. Yields of wheat have been almost doubled in experimental plots dusted with sulphur to control rust. The terrific stem rust epidemic of 1935 destroyed 12 per cent. of the wheat in Kansas, 15 per cent. of that in Nebraska, about 30 per cent. of that in South Dakota and about 60 per cent. of that in Minnesota and North Dakota. The total toll taken by rust in that one year was more than 125,000,000 bushels. The terrible devastation over thousands of square miles can scarcely be realized by any one who has not seen it himself. And epidemics of other diseases can be equally destructive over considerable areas. Thousands of acres of sugar-beets are periodically abandoned because of the ravages of the curly-top disease; the chestnut blight has practically destroyed the chestnuts of

the United States ; and the Dutch elm disease is now menacing one of our finest shade trees. And these are only a few examples. Surely the protection of plants against diseases is of national concern.

Fundamental to crop protection is better crop adaptation. Just as nature has selected ecotypes of native plants, that is, strains particularly suited to certain soil and climatic conditions, just so must the crop ecologists or breeders select strains of crop plants that are particularly suited to certain environmental conditions. For drought, excessive summer heat and winter cold are grave hazards for crop plants. Their destructive effects are both direct and indirect. Several million acres of winter wheat are abandoned each year because of winter injury ; about 15,000,000 acres, or one-third of the total planted, having been abandoned in 1933 ; fruit trees are periodically killed or severely injured by cold, and during the drought years of 1933 and 1934 about a billion bushels of corn were destroyed by heat and drought. The weather cannot be controlled, but its destructive effects can be reduced by developing adapted varieties and by the use of suitable cultural practices. Much has already been accomplished. The substitution of Crimean wheats for Mediterranean types in the Southern Great Plains area has greatly reduced losses from unfavourable weather ; the development of Minturki wheat has made winter-wheat growing safer on the northern fringe of the winter-wheat region ; the development of Ceres wheat has reduced somewhat heat and drought injury in the northern spring-wheat region ; the development of early maturing varieties of wheat and corn has reduced danger of damage by early frosts ; and the development of stiff-straw varieties of small grains has reduced the danger of lodging on soils where it was common. But far more can and should be done. When we consider the terrific losses of recent years, the need for varieties still better adapted to resist unfavourable weather and soil conditions is apparent. And past progress indicates the possibility of greater accomplishment for the future. But superior varieties are not plucked out of a hat by tricks of legerdemain ; they are the result of long and painstaking and laborious sorting and breeding and testing. The breeding of better adapted varieties is not a pastime for botanists in their spare moments. It requires time, labour, skill and adequate facilities.

Crop adaptation also is an aid in controlling some plant diseases caused by pathogens, particularly those that attack weakened plants. For unsuitable environment often predisposes plants to insidious but destructive diseases. Certain root rots of cereals, for example, are most destructive to plants weakened by unfavourable environment. Canker fungi and wood rots are likely to attack fruit trees that have suffered winter injury. There even is evidence that resistance to stem rust may be lowered when normally resistant wheat varieties are grown under environmental conditions to which they are unsuited. It is becoming increasingly evident that plant disease resistance is a variable character that is governed not only by genetic factors but also

by environment; hence, the importance of having varieties well adapted to local soil and climatic conditions. While this is especially true of long-time perennial crops, it is true also of annual crops. Some European countries have long recognized the necessity of breeding locally adapted varieties, and there appears to be increasing appreciation of its importance in the United States. The desire for standardization, however, sometimes has resulted in growing varieties under conditions to which they are not suited. The breeder of locally adapted varieties can contribute significantly to plant protection.

A primary obligation of botanical science is to help promote what may be termed plant public health. And one way of accomplishing it is by preventing the promiscuous interchange of dangerous plant pathogens between regions and countries. This requires more knowledge, better techniques and better social attitudes. There are those, of course, who are opposed to plant quarantines on the ground that they are unnecessary or ineffective But surely one can scarcely contemplate with serenity the devastation caused by chestnut blight, the total cost of citrus canker in Florida and other Gulf States, the economic importance of white pine blister rust, and the menace of the Dutch elm disease to our finest shade tree. These diseases are caused by pathogens that were brought into the country by man and could have been excluded by quarantines. And they are only a few of the total, to say nothing of introduced insect pests. When one reviews the history of many of the most destructive diseases, it is astounding to find how many of them have attained their present status through the activity of man himself. Many of them originally were restricted in importance and geographic distribution; they could not have crossed natural barriers such as high mountain ranges, oceans, and even crop barriers, by natural means. But man, because of ignorance, apathy, carelessness or lack of foresight, did what nature could not do. He carried them to the far corners of the earth, where they often have persisted in their most pernicious form.

There is great potential danger in transporting propagative parts of plants from one part of the world to another, because a disease may be far more destructive in a new region than in one where it has long existed. The varieties grown in the new region may be far more susceptible than in the region where the disease has long been prevalent, or the weather and soil conditions may be more favourable. Because a disease is relatively unimportant in one region is no guarantee that it will be unimportant in all regions. The chestnut blight is far more destructive in North America than in its original home in the Orient because the American chestnut is very much more susceptible to it than oriental species. Citrus canker was not recognized as a destructive disease until it found extremely favourable conditions in its new home in Florida. Plant breeders repeatedly have developed disease-resistant varieties of crop plants, only to see them succumb to new parasitic

races of the same pathogen which may have been introduced from other regions. The danger of introducing new strains of a pathogen is well illustrated by the fact that Anthony oats is fairly resistant to stem rust in the United States but completely susceptible in certain areas of Northern Europe, merely because different races of the stem rust fungus prevail there. There are similar situations with respect to other rusts, smuts and other destructive pathogens. Surely there is ample evidence that quarantines are desirable if they can be made effective.

Can quarantines be effective? The question cannot be answered categorically. Obviously, the success of any quarantine will depend on the method of dissemination of the pathogen involved, on the nature of the barriers between the area where the disease occurs and the area to be protected and on the adequacy of the quarantine organization. Obviously there should be a scientific basis for every quarantine. This often has been lacking, and things have been done, that need not have been done, and things have not been done that should have been done. The quarantine on Maine potatoes, about twenty years ago, because of powdery scab was costly, but it was neither effective nor necessary, because the disease already was present in one region that the quarantine was designed to protect and could not develop destructively in another because of unsuitable environment. It was a mistake. But whose fault was it? Not the quarantine organisation's! Their action seemed justified on the basis of the available information, but there was not enough information available. The fault was with those who failed to provide for adequate plant disease surveys. And one reason clearly was the difficulty of overcoming the inertia or resistance of many people who refused to consider seriously what might happen but only what had happened. There is serious danger in having thoughts rooted too deeply in the immediate present or in the past.

Practical botanical science must project itself more into the future; and to do so it must not be too practical. For science surely as the obligation to forecast the future, not only to explain the past and present. Observations and researches should be made to find out where potential as well as present danger lurks. This can be done only by studying diseases over as wide a territory as is necessary, whether domestic or foreign. Domestic plant disease surveys are essential from a number of standpoints. Unfortunately, however, their value often is not recognised. It is pertinent to ask how plant pathologists can be expected to meet new situations, to interpret old ones and to prepare for future emergencies if they do not have opportunity to make adequate studies of diseases as they exist and factors influencing their distribution and development. Plant diseases survey studies, ecologic studies, are among the most important in the whole realm of plant protection, and yet we often are so myopic as not to appreciate their value and provide for their support.

In addition to domestic plant disease surveys every country should interest itself in the diseases of other countries, especially those that grow the same kinds of crops. Information should be obtained regarding the methods of effective dissemination and the effects of the parasitic races of the foreign pathogen on the crop varieties and under environmental conditions similar to those of the country to be protected. Only when such information is available can the most adequate and intelligent quarantine action be taken. When we consider our own experience with chestnut blight, citrus canker, white pine blister rust and the Dutch elm disease, and the experience of many foreign countries with other diseases, we can scarcely avoid the conclusion that quarantines are essential; and, when we consider certain other cases, we must admit that unfortunate mistakes have been made in their application. The remedy, however, is not wholesale condemnation, but improvement through the results of research. And the research must precede practice, not lag behind it and do the second guessing.

The principles that apply to quarantines apply equally to eradication campaigns. Unfortunately, even some botanists still maintain a scornful or sceptical attitude toward large-scale eradication as a control measure. This was true also of many medical men when medical science entered the field of public health. If it is considered demeaning for botanists to assume leadership in plant public health measures, at least no one needs demean himself unless he chooses. Every scientist has a right to his scepticism, but he also has the obligation to study each situation honestly and thoroughly before pronouncing destructive *dicta ex cathedra*.

Some eradication campaigns have succeeded; others have failed. Some have been modified with respect to aim and scope; others were carried out as originally conceived. The difficulty is that emergency or public demand precipitated some of them before scientists were ready to supply the best techniques or accurately to predict the probable outcome. The chestnut blight eradication campaign failed; the citrus canker eradication campaign in Florida was conspicuously successful. The white pine blister rust campaign was not successful in completely eradicating the disease from the United States, but it has been eminently successful in controlling the disease for practical purposes in New England and the Lake States. The barberry eradication campaign has been successful in eliminating a tremendous number of annual local and regional epidemics of stem rust throughout the eradication area and in causing a downward trend in average annual rust losses. It has not resulted in complete elimination of general epidemics, but has reduced their frequency and is a practical control measure in the more eastern states of the area. Furthermore, the indirect benefits are almost incalculable. The existence of parasitic races of stem rust is one of the greatest handicaps to the development and maintenance of rust-resistant varieties. Varieties have been distributed as rust resistant, have retained their resistance for some time, and then have become susceptible because of the appearance of new or

hitherto unimportant parasitic races. Researches on the genetics of the stem rust fungus show that these new races are produced principally, if not almost exclusively by hybridization on the common barberry. Almost 150 of these parasitic races are known, and there is definite evidence that new ones are produced and perpetuated through the agency of the barberry. From the standpoint alone of preventing the future development of new races and reducing the number now in existence, the barberry eradication campaign is worth-while. The most recent experience with parasitic races was in the crop season of 1935, when Ceres wheat, hitherto moderately to highly resistant to stem rust, succumbed to its ravages because of a combination of factors, including the prevalence of a relatively new physiologic race to which it is very susceptible under certain conditions. Is it too much to expect that some of the wider implications of such control measures as barberry eradication should be understood and appreciated ?

Both white pine blister rust eradication and barberry eradication often are criticized because of changes in objective, method or, in some cases, unguarded statements regarding probable results. Unfortunately, it is impossible here to discuss fully the merits of the questions involved. However, both campaigns have paid for themselves many fold. Before condemning them because they do not eliminate the diseases completely, it would be well to picture what would have happened had they not been undertaken. Surely it should not be difficult to appreciate the value of a disease control measure that contributes significantly to the alleviation of a situation, even if it is not perfect or if it must be used in conjunction with other methods. The fact that techniques were modified or simplified and that the work could often have been done more economically and effectively had all necessary facts been available at the beginning merely strengthens the argument that research should not only accompany but also precede control measures. A highly significant contribution of modern botany to man's welfare will be to provide a technical service to accompany every control program and, particularly, to accumulate through research a reservoir of facts to be available as soon as necessity arises, not years afterward.

Botanical science can and should function far more effectively in future than in the past in protecting long-time pasture and forage crops against short and unprofitable life because of the inroads of insidious diseases. The increasing emphasis on grassland and forest creates new problems. Obviously, direct control of diseases often is difficult or impossible with such plants and mistakes cannot be rectified so easily as with annual crops. If a mistake is made with annual crops, it can be avoided the next year. But when pastures are established or forests planted, they constitute a long-time investment and changes to rectify mistakes are expensive. Therefore there must be adequate research in order that the mistakes may be prevented, that the most suitable kinds of plants be provided and proper cultural practices devised.

Considerable is known about diseases of individual grasses and forage crops, but too little is known about the relative value of different strains, the relation of pure and mixed stands to the development of diseases, about the relation of soil type, site and fertilization to yields and longevity. And in many cases still less is known about the relative disease resistance of strains or biotypes within a species. At the Welsh Plant Breeding Station, Aberystwyth, the writer saw, a number of years ago, a large number of strains of orchard grass, *Dactylis glomerata*, which had been selected in the vicinity and propagated vegetatively. Not only did they differ greatly in growth habit and other important characters, but some of them were virtually immune from yellow stripe rust, while others were completely susceptible. Obviously, such selection work and the incorporation of the results into agronomic practice is extremely valuable. The ecology and pathology of grasslands must be studied thoroughly if costly mistakes are to be avoided. They can and should be avoided, but botanical science must be put to work on the problems if they are.

Better protection of forest trees against diseases and deterioration due to wood rots is imperative if the land devoted to forests is to be used to best advantage. Necessarily, improvement must be attained through incorporation into silvicultural practice and forest management of the results of research. It is known, for example, that Armillaria root rot causes heavy damage to many of the most valuable tree species. But what is the relation of pure or mixed stands, density of stand, site and other factors to its development? This information should be utilized when the plantings are made. Likewise, the relation of similar factors to the development of canker diseases and wood rots must be learned and appropriate measure taken. In Northern Europe it has been shown that larch canker is likely to be much more destructive in pure stands than in mixed ones, and this fact is taken advantage of in practice. With the increasing emphasis on managed forests in the United States, similar facts should be taken into consideration. Thinning operations, cutting methods and cutting cycles must be arranged with due regard to the protection and performance of permanent forests and woodlands. The art of growing healthy trees must be based more and more on scientific principles, but the scientist who discovers them and recommends their application also must learn more about the art of growing trees—not only in pots in the greenhouse, but in the woods. And he must learn more about the pathogens of the trees—not only on nutrient agar, but on the trees themselves. What is known, for example, about the relative resistance of biotypes within tree species? Almost nothing. But yet there are such biotypes, differing profoundly in growth characters and in disease resistance. On a private estate in Germany, for example, the writer recently saw plantings made from different seed lots of Scotch pine. The plants were growing under comparable conditions, but yet plants from different seed lots differed strikingly in rate of growth, growth habit and resistance to the leaf-cast disease. The trees in some of the plots were almost completely defoliated by the leaf-cast disease,

while those in others were virtually immune. It was a beautiful demonstration of the existence of races or strains within a tree species. The importance of the application of genetic principles, particularly with respect to the selection of planting stocks, can hardly be overestimated. And even scientific breeding of trees is not a mere dream ; a beginning has been made, and the possible value has been shown. The forests of the future can and will be far better than those of the present if science is given greater opportunity to function in their establishment and maintenance.

In the future far more will be done than in the past toward protecting crop plants against soil-borne diseases through cultural practices, including soil fertilization, time of sowing and rotation. The discovery that corn is predisposed to root and stalk rots by lack of sufficient phosphorus and potash ; the discovery that early sowing of flax is likely to prevent serious injury by Fusarium wilt, the discovery that damage from fusarial head blight of wheat and barley can be greatly reduced by not sowing them on corn land suggest the possibilities of accomplishment in this direction. But there still is a vast field for exploration and a rich reward in results of practical value in this phase of crop protection. How little is known, for example, about control of diseases caused by so polyphagous a species as *Rhizoctonia solani* ? And yet there are definite indications that study of physiologic specialization in this species will yield results that can be applied with great profit in growing such important crops as sugar-beets, potatoes, tomatoes and other vegetables.

Investigations of antibiosis hold great potential promise for the future. It is known that some microorganisms have a tendency to inhabit or prevent the growth of others, including plant pathogens. Certain bacteria are known, for example, that prevent the development of smut fungi. Certain fungi are known that prevent the development of Rhizoctonia and other generalized parasites. It is one of the commonest observations in cultural work that fungi growing together may have no effect on each other, may stimulate each other, may be mutually antagonistic, or one may prevent the development of the other. This phenomenon has been studied in the past principally because of its scientific interest, but in future it should be studied also because of its potential practical importance. A beginning has been made, and promising results have been obtained. From these results it seems certain that the information obtained can be applied, at least on a small scale, to the protection of valuable ornamentals, and possibly of fruit trees. There even is promise that it can be used on a large scale in helping to devise cropping systems that will enable antibiotic organisms to function significantly in controlling such destructive and refractory diseases as potato scab, root rots of cereals and probably many others.

Chemical immunization of plants has been attempted so often and with such indifferent results that many plant scientists have concluded that it is impracticable. But recent results obtained by Hassebrouk in Germany show that it is definitely possible and possibly practicable.

Past progress in the control of diseases by fungicides, in co-operation with chemists, points the way to extensive progress in the future. The step from copper sulphate and formaldehyde to the best organic mercury dusts was scarcely dreamed of twenty-five years ago. And yet these most recent fungicides have largely eliminated the danger of seed injury, are much easier to apply, and they control certain diseases that resisted control entirely by the old fungicides. Then, too, there will be tremendous progress with respect to the specific applications of fungicides. The investigations at Cornell University showing that in some localities potato yields are increased greatly by increasing the proportion of copper sulphate to lime in the bordeaux spray, while the reverse is true in other localities, show how little we know and how much can be accomplished by precise investigations of fungicides and their effects. There is tremendous need for information regarding effects of different fungicides on different crop plants, on different pathogens and under different conditions. It is to be hoped that the " squirt gun days " of plant protection are on the way out ; but they will linger on until there is wider appreciation of the necessity for investigations made on an adequate scale and with the required degree of precision.

There is great promise in the control of plant diseases through the development and use of resistant varieties. Indeed, some diseases cannot be controlled economically by any other means. Flax wilt, wilt of peas, tomato wilt, asparagus rust, cabbage yellows and some rusts of cereals are now being more or less completely controlled by growing resistant varieties. But a vast amount of laborious work and research is required to insure sound and substantial progress in breeding resistant varieties. It is not always easy to combine disease resistance with other required characters. Neither is it always easy to combine in one variety resistance to all the important diseases in the region. And even if a new variety is resistant, it may prove very susceptible to hitherto unimportant diseases. Nor does a variety necessarily remain resistant permanently.

The difficulty of combining all desirable characters in one variety and of foreseeing what is likely to happen can be illustrated by experiences in barley breeding. About 25 years ago there came a demand for smooth-awn barley, for reasons that any one who has shocked or threshed barley will understand. Accordingly, crosses were made between the variety Lion, which had little but its smooth awns to recommend it, and Manchuria, a good barley except for its sawtooth awns. What appeared to be good, smooth-awn hybrids were developed from this cross, but after they had been grown for some time, they proved to be poor yielders. In seeking the reason, it was found that they were very susceptible to the spot-blotch and root-rot disease caused by a fungus with the euphonious name of *Helminthosporium sativum*. Work was then started by plant breeders and plant pathologists at the Minnesota Experiment Station in attempts to produce varieties with

smooth awns, stiff straw, good quality, yielding ability and resistance to spot blotch. Within a few years two varieties, Velvet and Glabron, were developed and distributed. Several years later, however, it was found that they were extremely susceptible to loose smut, head-blight and to some parasitic races of the barley stripe organism.

Because of the nature of these diseases themselves, it would have been difficult to foresee this development. Loose smut causes abundant infection only when there is moisture during the flowering period of barley. Furthermore, the infection does not become apparent until a year after it has taken place. And at the time when the breeding work was done, no method was known, without absolutely prohibitive labour costs, of artificially inducing an epidemic in order that the relative resistance of hundreds of hybrid lines could be learned. Such a method has been devised within the last few years, however, and will be of great aid in future work. As concerns head-blight, it was not known, even by the most competent pathologists, that it could cause such terrific epidemics in barley ; it was considered primarily a disease of wheat. Then, too, epidemics usually develop only when there is warm, moist weather during the earlier development of the barley kernel. And epidemics did not develop during the years when the varieties were being produced. Perhaps the breeders should be criticized for not having furnished the right kind of weather. They do now. By growing hybrid lines to be tested under huge tents, watering frequently to maintain high humidity and spraying the plants frequently with a suspension of the blight spores in water, artificial epidemics are produced so that the relative susceptibility of varieties and hybrid lines can be determined. But this method was a gradual evolution, involving extensive studies by the Wisconsin and Minnesota agricultural experiment stations and the United States Department of Agriculture of the head-blight pathogen and the factors affecting its development. Even after preliminary, empirical experiments had shown that plants under small muslin cages were more likely to become heavily infected with head-blight than those outside, what would a guardian of purse-strings have said to a request for funds to construct tents under which to breed barley ? The realization that weather had to be made to order in an investigation of this kind was a slow evolution, just as were the necessary principles on which the breeding procedure must be based. And, unfortunately, many of these principles were learned during the breeding work, or even after it had been done ; they were needed beforehand. Surely, if we learn at all from past experience, it must be evident that research should precede practice and guide it.

Nevertheless, head-blight has been very destructive in many regions in recent years, as it not only reduces yields greatly but may also make the barley unfit as feed for pigs, because it makes them violently sick. Therefore the development of resistant varieties is urgent. But no varieties of barley

now known in this country seem to be sufficiently resistant. Obviously, then, a search must be made in other countries, an important job for plant explorers. And possibly it may be well to remind ourselves that plant explorers who search for plants in many distant lands are not looking only for the curious and bizarre but often for plant varieties that are essential to the solution of just such problems as the barley-blight problem. Their work usually is hard and often hazardous, but it is essential. They must find resistant varieties, which often are inferior in other respects. Then the breeder must cross them with otherwise good varieties and attempt to get the desired combination of characters in hybrids.

The complexities of some breeding programs are well illustrated also by experience with wheat. About 1907 the United States Department of Agriculture and the Minnesota Agricultural Experiment Station embarked on a program of developing stem-rust resistant wheats. Bread wheat varieties were susceptible, but many durum or macaroni wheat varieties seemed resistant ; therefore crosses were made between durum and common wheats in the hope of combining the bread wheat character with the rust resistance of the durums. Many of the most resistant hybrid lines were so susceptible to root-rot that they were discarded, or the root-rot automatically eliminated them. It also was found that there was linkage between the durum character and rust resistance ; those hybrids that were rust-resistant also had the quality of durum wheats and not of bread wheats. This was discouraging, and some thought that it would be impossible to combine rust resistance with other desired qualities. Advances in knowledge of plant genetics, however, indicated that there might be " crossing over," that there might appear an occasional hybrid in which the bond between durum quality and rust resistance was broken. The obvious procedure was to grow large populations of hybrid lines. This was done, and finally a few plants in one line out of about 1,000, from a cross between Marquis and Iumillo durum, were found which combined the desired characters of rust resistance with bread wheat characters. From one of these plants the variety Marquillo was developed. However, flour made from Marquillo is so likely to be off colour that it is no longer recommended and has been replaced by better varieties.

One of these better varieties is Ceres. The first step in its production was the development of the variety Kota, which originated from some resistant plants of bread wheat found in fields of durum. These plants were selected, propagated, tested, and the progeny finally distributed. Kota appeared very resistant to stem rust but soon proved to be so susceptible to orange leaf rust, to loose smut and to stinking smut that it fell into disfavour. In addition, it had very weak straw and was therefore likely to lodge badly. It was then crossed, at the North Dakota Experiment Station, with Marquis, at that time the standard bread wheat of the spring wheat region. One of the hybrid lines was developed into the variety called Ceres. Ceres has far stiffer

straw than Kota, is in general better wheat, and appeared to be equally resistant to stem rust, and certainly no more susceptible to the smuts and leaf rust than the Kota parent. It was moderately to highly resistant to stem rust and withstood a number of rather severe epidemics very well, but it succumbed completely to the terrific epidemic of 1935 because of a combination of factors that were unfavourable to its development and extremely favourable to the development of certain parasitic races of stem rust.

Better rust-resistant varieties than Marquillo, Kota and Ceres are either made or in the making. All three have rusted heavily under some conditions and have other defects. The production of Marquillo had shown the possibility of obtaining resistant bread wheat types from crosses between durums and bread wheats. But this variety is susceptible to root-rots, its flour is low in colour score, and it is not always so resistant as is desirable. For these reasons one of its sister selections was crossed with a selection from a cross between Marquis and Kanred, a hard red winter wheat, which is immune from a considerable number of parasitic races of stem rust. This double cross (Marquis × Iumillo) × (Marquis × Kanred), has resulted in the production of the variety Thatcher, which obtained one type of resistance from Iumillo, another from Kanred, and has the spring habit and high quality of Marquis. So far Thatcher has been moderately to highly resistant to stem rust, but there are indications that it may become heavily rusted under some conditions. Furthermore, it is quite susceptible to orange leaf rust. Therefore it and other selections and varieties have been crossed with Hope and H44, two varieties produced by McFadden as a result of crossing Marquis with Jaroslav emmer, which is resistant to stem rust, stinking smut and several other diseases. As in the case of bread wheat-durum crosses, only a few hybrid lines combined bread wheat characters with the resistance of the emmer parent. But Hope and H44 did. Although they are not good wheats, they have been used extensively in recent years as resistant parents in crosses with better wheats. But another complication has arisen. Both Hope and H44 are very much more susceptible to the black chaff disease than the varieties now grown. This, then, introduces another new problem, especially since there appears to be linkage between the resistance to rust and susceptibility to black chaff. That is, rust-resistant segregates from crosses with Hope or H44 as one of the parents are susceptible to black chaff. Possibly this linkage can be broken, or possibly the disease will not be very important. That remains to be seen. Certain it is that many of the hybrids between Hope or H44 and other varieties usually are almost immune from stem rust. But will they remain so under all conditions ?

Hope wheat has rusted heavily, not only in experimental tests in the green-house, but also under natural conditions in the field, as shown by Abbott in Peru. And why should it not ? Disease resistance, like any other plant character, varies more or less with environmental conditions. The practical

question is, how much will it vary under the range of conditions in which the variety is likely to be grown ? Hope has varied from virtual immunity to virtually complete susceptibility. Seedling plants are highly resistant to many parasitic races but completely susceptible to some. As the plants grow older, however, they are likely to be resistant to all races, because of a combination of characters which make it difficult for the rust to enter and to develop well even if it does succeed in entering. Then why does Hope sometimes rust heavily ? The question has been answered, to a considerable extent at least, by investigations made by Helen Hart. Stem rust does not enter Hope as easily as some varieties because the stomata have a tendency to remain closed much of the time. It takes considerable light to make them open. Therefore if there is moisture on the plant long enough to enable the spores to germinate while the stomata are open, the rust enters. The important thing is to have light and moisture for considerable periods of time. Obviously, this combination is not likely to occur often. While light is required for entrance of the rust, it develops well after entrance only under reduced light intensity, its development being sharply checked in full sunlight, just the opposite of the case with most varieties. Clearly, then, Hope will become heavily rusted only when a rather unusual combination of conditions prevails. There must be abundant inoculum of one or more virulent physiologic races, there must be light for considerable periods while the plants are wet to permit entrance of the rust, followed by lowered light intensity to permit the rust to develop. These conditions must be repeated several times in order that an epidemic may develop. Therefore Hope is not likely to become heavily rusted very often, but it has been heavily rusted and no doubt will be again. It is resistant under more conditions than most other resistant varieties and is therefore extremely valuable ; but it is not universally resistant, and this fact may as well be recognized now as later.

Even if the mechanism of resistance of varieties remained constant, their disease reaction might vary greatly because of the existence of parasitic races. Investigations during the past twenty years have shown that there are numerous parasitic races of the cereal rust fungi, the cereal smut fungi, those causing root-rots of cereals, and a host of others. In fact, it appears now that most species of parasitic fungi comprise races that may be alike in appearance but quite different in their parasitism. Approximately 150 such races of the wheat stem rust fungus are known. Consequently, some varieties are resistant in some years and in some localities and completely susceptible in others. The variety Kanred was distributed a number of years ago as a rust-immune hard red winter wheat. It was soon found, however, that it was completely susceptible to some parasitic races and that it may rust heavily when and where these races are present. The same is true of the durum wheats. Until about 1923 they were considered highly resistant to stem rust. However in that year, an epidemic developed on them,

and the same thing has happened in a number of subsequent years. Whether most durums rust, then, depends on the particular parasitic races present. And to complicate the matter still further, there is some evidence that a variety may be resistant to certain races at certain temperatures and susceptible at others. In other words, environmental factors determine whether certain races can attack a certain variety or not. This whole series of complications, together with genetic and pathological studies on the nature of rust resistance, led to the breeding of varieties with "adult" resistance. This simply means that older plants of some varieties, because of structural or physiologic peculiarities, are generally resistant to all parasitic races under natural conditions in the field, even though the seedlings may be susceptible. This, then, seemed to be the answer to the challenge of parasitic races. Unfortunately, however, "adult resistance" may vary, as already mentioned in connection with Hope wheat.

What has been said about stem rust is equally true of other diseases. The fact that there are so many parasitic races and that the resistance of varieties, even to single races, may vary merely shows the complexity of one of the most important problems in plant protection, the breeding of resistant varieties. The difficulties have not been magnified. Numerous examples could be given in support of this statement. Many varieties of wheat were resistant to stinking smut, only to become susceptible; some wilt-resistant varieties of flax have become susceptible; some smut-resistant varieties of sorghum have lost their resistance; certain mosaic-resistant varieties of sugar-cane are no longer resistant. Nature is not static; it is dynamic. The plant disease problem is not static; it changes. And why should it not change? The pathogens that cause disease change.

Extensive researches during recent years show conclusively that new parasitic races of pathogenic fungi arise through mutation, hybridization and probably through chance assortment of nuclei. That new races arise through mutation is perfectly clear from studies on certain smut fungi; that they apparently arise in several fungi through chance assortment nuclei seems likely from recent studies in California and elsewhere; that they arise commonly through hybridization in some of the ascomycetes and in the rusts and smuts is proved beyond question. Hybrids have been made between biotypes within a species, between different species and even between different genera. In fact, the union of lines of different sex is prerequisite to infection in the rusts and smuts. While we are breeding disease-resistant varieties of crop plants, nature is breeding new races of crop pathogens. Man probably can keep ahead of nature, but to do so he had better know what nature is doing to checkmate him. To proceed blindly in the dark is not likely to lead to greatest progress. Research must show the way.

It must be apparent, even from the few examples given, that obstacles to the development of resistant varieties are not necessarily insuperable; in many cases they are not, because they already have been overcome. In other cases they are still to be overcome. It is not desired to magnify difficulties and cast a pall of pessimism over breeding as a method of protecting plants. Quite the contrary. The fact is that breeding is the only hope of controlling some of the most destructive diseases. The need for resistant varieties is acute. What is desired to emphasize is the urgent necessity for an appreciation of the complexities inherent in many breeding problems, for fuller understanding of the needs in solving them, and for wider vision with respect to the scope of necessary researches and their results. In some cases suitable resistant varieties already are available, but in many others there are no commercially desirable ones. Plant exploration may be required; testing and sorting is necessary. The genetics of the crop plants must be studied; the number and parasitic capabilities of parasitic races of the pathogen must be learned; studies should be made to ascertain whether new races are arising; the nature and variation of resistance should be studied; and ecologic studies must be made of the host plants in relation to the disease. Only on the basis of such studies can serious mistakes and disappointments be avoided and permanent progress be made. For it is important to know not only what has happened but also what is likely to happen under certain conditions. Even so, it may be necessary to replace varieties periodically, as commercial requirements and natural situations change.

There has been great progress in plant protection, and the prospective accomplishments are still greater. Emancipation from empiricism will be one of the most significant. This will require more intimate knowledge of crop plants, elucidation of the nature of disease inciters, such as viruses, more detailed life history studies, finer analysis of the role of environmental factors in the development of disease, epidemiology studies to improve predictability of disease out-breaks, vast improvement in specific control measures and more precise knowledge regarding their application. Botanists of many persuasions must co-operate in these studies even more closely and sincerely than in the past.

"The price of a sound, comprehensive national life is in these times widespread and intelligent scientific research." This quotation from Angell is applicable to plant protection, as well as to problems in general. Botanical science can promise man better varieties of crop plants and can show how better to protect them against diseases and other hazards. But to accomplish this there must be provision for basic research, to discover facts and formulate principles; experimentation, to determine when, where and how they can be applied profitably; and education, to incorporate them into practice and capitalize on their value. We need not only fuller knowledge, improved skills, and better techniques, but also a deeper and more widely diffused sense

of obligation to science and to society and a determination to discharge it equally faithfully and honestly to both. This statement is platitudinous, of course. But, like many other platitudes, it often is ignored and can be emphasized with profit. And it is not mere parroting of a newly popularized slogan. Many investigators and most teachers were thoroughly imbued with the idea long before attention was focussed on it in recent years. What is lacking in many cases is not the spirit but the substance to enable science to serve society.

There must be much good research, but much of it must be good for something. Only when there is broader realization of the ultimate value of basic research, not only to clarify situations, but especially to provide a reservoir of facts and principles for future emergencies, will it be possible to proceed as intelligently and effectively as necessary in plant protection. If past experience teaches anything, it teaches that the most fundamental research often is the most practical in the end. Plant disease situations continually change, because crops and pathogens and conditions change. New problems continually arise. Only by elucidating principles and accumulating wisdom through research can we foresee possible future developments and prepare to meet them. Apathy and lack of comprehension, rather than antagonism, are the greatest obstacles to research and progress. Many people still have a child-like faith that science can perform miracles. A new disease or insect pest menaces an important crop. The formula is to provide money and demand a miracle. " Miracles of science " may be a good figure of speech, but most scientific miracles are the result of long and laborious search and research, repeated many times. We hear much about preparedness. Preparedness is essential in plant protection, but we had better prepare for the future before it arrives instead of after it is present or past. And preparedness must be based on research.