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The Threat of Exotic Plant Pathogens to Agriculture in the United States

The history of plant pathology records numerous examples of pathogens that, when introduced into areas where they were not previously found, rapidly spread and caused epidemics, with grave economic and social consequences.

The "genetic vulnerability" of many of the major crops that make up the world's primary food supply is acknowledged by agricultural scientists. Uniform plantings of corn, soybean, wheat, or other crops could suffer disastrous losses if virulent, aggressive pathogens should become established. The southern corn leaf blight epidemic of 1970 in the United States dramatically highlighted this point.

Because of the potential for damage by introduced pathogens, the United States, along with most countries of the world, has formulated plant quarantine regulations governing the importation of living organisms, agricultural products, and other articles of international commerce that may serve as "vectors" of plant pathogens. The Plant Protection and Quarantine (PPQ) program of the Animal and Plant Health Inspection Service (APHIS) of the U.S. Department of Agriculture (USDA) is responsible for developing and implementing regulations aimed at excluding alien plant pathogens from the United States.

Quarantines can never be totally effective, but they may serve to delay the introduction and establishment of an alien species. Delay is valuable if the time gained is used to obtain information about a pathogen and the disease it causes, information that can be used to prevent or mitigate harmful consequences should the disease become established. In addition, delay in the appearance of a damaging exotic disease allows continued normal production of the crop.

Because investigation of all pathogens currently exogenous to the United States is not feasible, effective methods for determining just which ones pose the greatest threats to our economy are needed. At present, a rational basis for predicting the establishment of a foreign pathogen in a new geographic area does not exist.

Identifying Dangerous Exotics

As early as 1929, the American Phytopathological Society (APS) Committee on Investigation of Foreign Pests and Plant Diseases (1) recommended the Society inform the proper federal authorities that dangerous parasites from other parts of the world would inevitably slip by quarantine and become established. They urged federal authorities to provide for comprehensive investigation in their native habitat of insects and diseases "which, because of geographical, crop, or commercial conditions, are likely to be introduced here" and thus acquire the information required to prevent or delay their entry, or in the case of accidental introduction, to at least provide effective and immediate control. The proposed research subjects were: 1) diseases of corn, particularly "mosaic of Hawaii"; 2) Fiji disease of sugarcane in the Philippines and South Sea areas; 3) diseases of wheat, particularly stripe rust in Europe; 4) oriental citrus diseases, concentrating on black spot caused by *Phoma citricarpa*; 5) larch canker; 6) elm diseases of Europe; 7) soybean diseases in the Orient and Manchuria; 8) certain apple diseases of importance in northern Japan, ie, *Diaporthe mali, Sclerotium mali,* and *Valsa mali*; and 9) *Botrytis liliorum* in Japan.

The warning about the elm diseases of Europe proved prophetic; in the early 1930s, the devastating Dutch elm disease became established in the eastern United States. The suggestion to concentrate studies in Europe on stripe rust of wheat presumably was in recognition of probable racial differences in the pathogen population, since stripe rust of wheat had been reported in California in 1921 and several times thereafter in various western states prior to 1929. Severe epidemics have occurred periodically in the Pacific Northwest since 1959.

Urgent concerns expressed in 1936 (1) included: 1) the need for a more adequate detection service for observation of questionable plant introductions, 2) the need to test U.S. plants under foreign conditions to determine their reactions to foreign diseases not yet introduced into the United States, 3) the need to establish specialists in foreign countries to obtain specific information on foreign diseases, 4) the need to exclude different biological races of parasites already present in the United States, and 5) the need for safety measures when introducing living cultures or viable specimens of parasites from abroad.

McCubbin (7) pointed out in 1936 that the logical way to evaluate injurious plant diseases would be to assemble a comprehensive body of information on the foreign parasite. Unfortunately, this was not possible because necessary data were lacking. The existing literature was scant and often more suited to mycological purposes than to appraisal of disease threats from a quarantine standpoint.

The maps published by the Commonwealth Mycological Institute of the United Kingdom (5) represent the only concerted effort to document and update the world distribution of plant diseases. These maps, however, do not include host distribution or relevant ecological information.

Weltzien (15) reasoned that if the geographic distributions of pathogen and host were known and sufficient information on their ecological requirements was available, disease occurrence in

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previously uncontaminated areas could be predicted. He stressed that errors can easily be made when interpreting disease distribution maps if the geographic distribution of the host is not known. Areas of differing disease intensity and host damage also must be accurately mapped. Weltzien suggested that three zones be recognized: 1) the area of main damage, where epidemics occur whenever a susceptible crop is grown without protection; 2) the area of marginal damage, where epidemics occur irregularly and cause significant losses in some seasons only; and 3) the area of sporadic attack, where damaging disease rarely occurs.

Genetic changes in pathogen, host, or both could affect validity of prognosis. Weltzien states that breeding for resistance or developing physiologic races would not alter the boundaries of the climatic regions favorable for a specific disease but rather would affect control techniques within the existing areas of main and marginal damage. The appearance of new ecological races of pathogens might require changes in prognosis and in zonation of disease areas.

Earlier, Reichert and Palti (12) suggested a pathogeographic approach to predicting plant disease occurrence. They distinguished between the prediction of disease occurrence and the prediction of disease outbreaks. Based on the records of world distribution of pathogen and host and on their ecological characteristics, the identification of dangerous diseases for defined geographic regions was believed feasible. The principal limitation in the use of their system, the authors felt, was the scarcity of accurate data accompanying disease records. The needed data, they stated, should include "compilation of lists of records of the occurrence of pathogens, with precise indications of habitat, specifically stating elevation, topography, soil type and wetness, shade, light and aeration conditions (e.g. density of vegetation), as well as cultural practices." Reichert and Palti grouped selected diseases into those capable and those not capable of surviving unfavorable seasons in the area in question. Moisture and temperature conditions of air and soil were the primary assignment criteria.

Thurston (14) listed selected diseases he considered to have high, intermediate, or limited potential of becoming internationally important, emphasizing tropical diseases that in 1973 were limited to a few countries or a continent. To be highly threatening, a disease should have "the ability to spread rapidly, cause serious losses, and be difficult to control." Diseases are judged to have intermediate threat potential if they clearly are unable to spread rapidly to other countries or continents or if no efficient, economical control measures are available. Diseases of limited potential are capable of causing serious crop losses but either spread very slowly or can be efficiently and economically controlled. Thurston pointed out that judgments on the potential of the various pathogens to cause serious losses require sound information that is still generally lacking.

Of the five diseases Thurston listed as highly threatening (two fungal, two bacterial, and one viral), one is known to have appeared in a new area. Bacterial leaf blight of rice, caused by *Xanthomonas campestris* pv. *oryzae* (6), was identified in Colombia in 1977 but so far has failed to cause the damage that was anticipated.

In 1973, a USDA Import Inspection Task Force, chaired by R. C. McGregor, attempted to define and quantify the risks from entry of exotic agricultural pests and diseases perceived to be major threats to the environment and to agriculture in the United States (8). A mathematical model was developed to identify the most serious foreign organisms and to rank them in order of expected impact. The available records of nearly 2,000 foreign pathogens were examined, and 551 were chosen as potential risks to U.S. agriculture. This initial screening was influenced to a major extent by the economic value of the hosts.

For each organism selected, specific information was assembled and used to develop a ranking value. The equation for computing the ranking value was $EEI = P \times E$, where EEI = expected economic impact, P = probability of the pest becoming established in the United States during the next year, and E = economic impact if the organism becomes established. P was based on the volume of vector material imported into the United States, the "hitchhiking" potential of the organism, and the ease of establishment of the organism after arrival. E was calculated from the amount of host(s) grown, the ecological range of the foreign organism as a percentage of the range of the host, the loss in yield when "normal" controls are used, the added cost to control the new pathogen, and the added cost of increasing growing area to offset losses caused by the new pathogen.

Because information was lacking on rates of spread of the pathogens in their endemic locations, this dynamic aspect could not be incorporated into the model. No attempt to include social and environmental impacts was made. Further, the model assumed the absence of quarantine.

Diseases of forest trees consistently ranked very high because of the economic criteria used in the model. Long-term economic losses would be incurred because of the large areas involved and the long replacement times required (the salvage value of diseased trees was not considered). Certainly, the impact of the virtual loss of the American chestnut caused by the introduction of *Endothia parasitica* can hardly be overestimated. On the other hand, the loss of a major annual food crop might result in more economic disruption than the loss over a long period of a tree species.

Seven exotic plant pathogens were estimated to have a 90% probability of establishment within 8 years. These organisms and their rankings were: *Rosellinia radiciperda*, 2; *Heterodera latipons*, 32; *Septoria maydis*, 55; *Synchytrium dolichi*, 57; *Synchytrium umbilicatum*, 59; *Corynebacterium tritici*, 61; and *Pythium volutum*, 76. None had been reported within the United States or had been intercepted by PPQ inspectors as recently as February 1983.

APHIS listed 20 plant pathogen introductions during 1972–1981 (*personal communication*). Of the 20, *Heterodera avenae*, *H. zeae*, *Puccinia melanocephala*, and *Ustilago scitaminea* were listed in the McGregor report as being of concern but were not among the 100 most serious. The remaining 16 were not included in the report because of the low economic value of their respective host crop.

Where Are Potential Threats?

Eight primary centers of origin, all in mountainous areas in the tropics and subtropics, have been identified for our major cultivated crops (13). In these centers, ancestral forms diversified and cultivated forms began to evolve. As the evolving plants moved, mostly with the aid of man, into new areas having different environmental conditions, secondary and tertiary centers of diversity developed.

Primary and secondary centers for major agricultural crop plants have been extensively investigated, but less scientific attention has been directed to centers of origin and evolution of the pathogens that attack them. In the centers of host origin and diversity, however, new strains of pathogens appeared and coevolved with their hosts (4).

Centers of origin and diversity have provided agriculture with plants having valuable genes for resistance to many diseases, but these centers also contain strains of pathogens possessing an array of genes for virulence. These pathogenic strains could be especially devastating on modern cultivated forms of the host that may have been grown for long periods in areas remote from the center of origin and free from a particular pathogen.

Currently, teams of scientists visit these centers of origin to collect ancestors of cultivated plants to provide gene diversity for germ plasm banks and also to collect plant pathogens as agents for the biocontrol of noxious weeds and insects. This activity provides excellent opportunities for identifying "new" diseases and "new" pathogenic strains of known pathogens, thus alerting pathologists to potential threats. Greater collecting activity also increases the chances of inadvertent introduction of undesirable organisms if stringent procedures to exclude them are not established and followed. Centers of origin and diversity of crop plants are considered to be sources of potential threats primarily because of the diversity of pathotypes that have coevolved with hosts ancestral to modern crop plants.

Another likely source of potential threats may be those areas of the world where a heavy concentration of a given host plant is grown. Here large populations of a given pathogen capable of attacking that crop can also develop. This may increase the number of forms of the pathogen with enhanced or broader virulence that arise through mutation, recombination, or parasexual processes. Such regions are also likely to be exporters of considerable volumes of plant materials, thus increasing the probability that pathogens would also be exported.

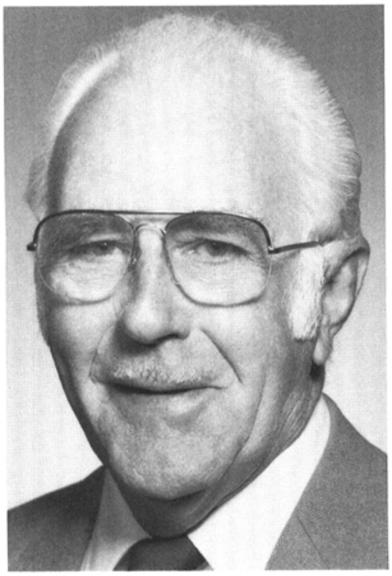
Pathogens have a higher probability for establishment on compatible host plants in an area climatically similar to that of their home region than in a region differing in key environmental factors. Thus, regional agroclimatic analogues, such as those compiled by Nuttonson (11), are helpful in directing attention to specific foreign areas likely to harbor pathogens with a high potential for successful establishment in specific areas of the United States.

In view of our limited knowledge about the maximum and minimum values of factors controlling infection, growth, and development of many foreign pathogens, it would be unwise to ignore virulent pathogens in areas with climates dissimilar to those in the United States. Conceivably, a pathogen thought to be limited to the tropics might function quite efficiently when transported across physical barriers and introduced into the temperate zone. In this hypothetical case, establishment of the pathogen as a permanent member of the agroecosystem would hinge greatly on its ability to survive or escape the temperate zone winter and produce initial inoculum during the following growing season. Further, we cannot overlook the fact that mountainous areas in tropical and subtropical regions provide vertically arrayed econiches of great variety, some of which have counterparts in the temperate zone.

Which Pose Greatest Threat?

Among the agents causing diseases in plants, the fungi appear to present the greatest potential threat. Field crop foliar diseases that could explode in one or two growing seasons to cause losses over extensive areas would demand the quickest response.

The rusts and downy mildews are good examples of "explosive" diseases. In general, they do not require "unusual" growing seasons to become epidemic—normal conditions for growing a good crop are suited to rapid disease



C. H. Kingsolver

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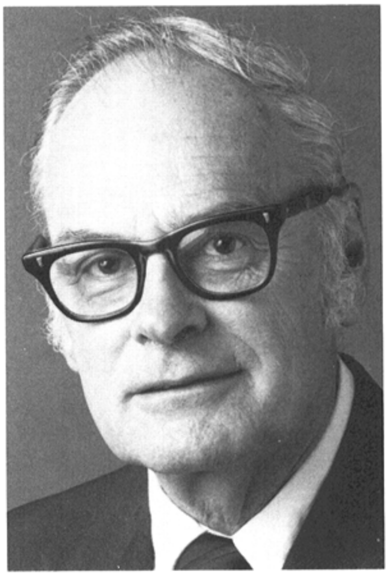

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development and spread. Diseases of forest and shade trees characteristically spread much more slowly than foliar diseases of field crops, as do soilborne diseases, nematode-caused diseases, and virus-caused diseases. Bacteria rank next to fungi as potential threats requiring quick response.

Designation of certain exotic diseases that appear to threaten agriculture in the United States does not, of course, reduce our crop vulnerability. Further steps must be taken. These include development of detailed information required for vulnerability assessment, accumulation of data permitting formulation of control strategies in advance of the appearance of a pathogen, creation of a reliable early detection system, and development of a rapid emergency response capability.

Vulnerability assessment. For an alien pathogen designated as having high threat potential, the next question is: What damage would that pathogen, if introduced, be capable of inflicting on cultivars of its host in the commercial fields of the United States? Providing answers to that question comprises crop vulnerability assessment.

One of the two approaches to vulnerability assessment is to take domestic cultivars, breeding lines, and germ plasm to regions where the pathogen is endemic and then study disease development and ensuing crop loss there. The other is to import aggressive and virulent isolates of the pathogen and study them on domestic materials under controlled conditions in pathogen containment facilities. Because each approach has distinct advantages and disadvantages, they should be employed in complementary fashion.

Working in endemic areas permits field epidemiological studies with large host populations. If the regions are also climatically analogous to the growing areas in the United States, the data can be used in analytical and simulation models to help quantify the vulnerability assessment of our domestic crop.

Conducting research in foreign locations is not always feasible because of political, institutional, or other reasons. China, for example, is of great interest as the origin of cultivated soybeans and quite possibly of *Phakopsora pachyrhizi*, the cause of soybean rust. Only recently, however, have scientists from the United States been able to engage in cooperative research in that country. Other regions of interest are currently not freely accessible.

Facilities and technical support are available at many foreign locations, but in some areas they are inadequate to accomplish the quantitative studies required. Research centers such as the International Maize and Wheat Improvement Center (CIMMYT) in Mexico, the International Rice Research Institute (IRRI) in the Philippines, and the Asian Vegetable Research and Development Center (AVRDC) in Taiwan have highly competent staffs and excellent facilities. Information contributing to vulnerability assessment could be obtained at these locations if cooperative programs of mutual interest to both center and U.S. scientists were to be established. The Plant Disease Research Laboratory (PDRL) at Frederick, Maryland, has used contractual agreements with AVRDC and with the universities of Sydney and Queensland in Australia to study the epidemiology of soybean rust in the field.

Research on potentially dangerous exotic pathogens outside their endemic areas requires specially designed and operated pathogen containment facilities that are expensive to construct and to operate. Also, adherence to a stringent operational protocol to ensure containment of exotic pathogens often makes experimental procedures more time-consuming and less convenient for the researchers.

Studies within containment facilities are done in growth chambers and greenhouses. Nevertheless, well-designed and properly interpreted experiments yield data relevant to vulnerability assessment of a given crop—host range of the pathogen, virulences of pathotypes, resistance in host germ plasm, environmental requirements for infection, etc. The ability to simultaneously compare isolates of pathogens from geographic areas throughout the world, under controlled and reproducible conditions, is advantageous. This has been done at PDRL with *P. pachyrhizi* (3), foreign cultures of *Puccinia polysora* on corn (9), and various alien species and strains of the organisms causing downy mildews in corn and sorghum (2).

Early detection. The earliest possible detection of a disease with potential to spread and cause serious damage to a U.S. crop is of paramount importance for successful implementation of eradication or control procedures. *Helminthosporium maydis* race T caused widespread losses to the U.S. corn crop in 1970. Some 10 years earlier, researchers in the Philippines had published on the extreme susceptibility of corn lines with the cytoplasmic gene (Tcms) causing self-sterility (10). In the United States in the years just before 1970, corn varieties with this gene were widespread throughout the major production areas. Race T was undoubtedly present and widely distributed prior to 1970. Infections on corn were probably assumed to be those caused by *H. turcicum* or *H. maydis* race O, both endemic pathogens of relatively lesser concern. Was *H. maydis* race T a foreign introduction or did it develop here? The answer is relatively unimportant. What is important is that we had had advance warning that a form of *H. maydis* could cause severe damage on corn lines containing Tcms, regardless of other resistance genes present. Earlier detection of this variant within the United States and a prompt response might have substantially reduced the $1 billion loss attributed to the southern corn leaf blight epidemic in 1970.

To detect newcomers or sudden changes in endemic pathogens, current detailed information on the distribution of endemic pathogens is essential. These data must be continuously updated. The Plant Disease Survey, initiated in the 1930s and continued through the 1940s, represented a cooperative effort of the USDA and various states to collect and systematize records of disease occurrence.

In 1973, an ad hoc committee of APS urged the development of a plant disease detection and information program. In 1976, APHIS initiated a pilot test program in 10 states of the upper Mississippi River valley for early detection of new pests in this major crop production area. Monitoring plots for endemic as well as "new" diseases was an integral part of the effort. This program has been terminated.

In 1979, APHIS requested the help of the Intersociety Consortium for Crop Protection (ICCP) in defining information needs relating to foreign pests. In 1980, an ad hoc committee composed of members of ICCP's Plant Pest Survey and Detection Committee submitted a report on plant pest information needs to the deputy administrator of PPQ/APHIS/USDA. This group, as had other groups preceding it, stressed the necessity of systematizing information on both foreign and endemic pathogens to enable access and use. Modern data management systems should make the task less formidable, but major expenditures of time and funds would still be required.

Serious difficulties affect the establishment of a convenient and suitable data management system. One is the confusion in taxonomy and nomenclature of many pathogen groups. Another is the paucity of quantitative data on epidemic development and disease losses, due in part to the lack of standardized methods. The use of remote sensing from satellites or aircraft may, in the future, reduce some of the monitoring burden. Close international cooperation to assure standardized recording of data is vital.

The excellent program of monitoring stem rust in the United States, directed from the USDA Cereal Rust Laboratory at St. Paul, Minnesota, demonstrates that the many different races of the rust pathogens of important cereals can be detected early. Effective methodology has been developed, and a network of competent cooperators in Mexico, the United States, and Canada works closely with the staff at the Cereal Rust Laboratory.

At present, PPQ is acting as the lead agency in setting up a cooperative national pest survey and detection program. This will involve a national data storage and retrieval network, a data collection network, and a pest identification system. Standardized methodology will be developed, and emphasis will be on national coordination of programs formulated and carried out in individual states. Cooperation with appropriate private groups, such as the various commodity organizations, will be implemented. The program became active for a limited number of selected crops and pests in 1982.

Emergency response. Comprehensive emergency response systems exist for animal diseases but not for plant diseases. Some legislation relating to emergency control and eradication of specific plant pathogens has been enacted, but no broad flexible response systems are in place.

An action plan for each high-risk disease should be formulated, based on detailed vulnerability assessment data accumulated beforehand. Such a plan should include action options based on the size, severity, and location(s) of disease outbreaks and the maturity of the crop when the initial outbreak is detected. There must be a mechanism to implement the plan without delay. Lines of authority and responsibilities at local, state, and federal levels must be clearly understood. PPQ is the logical agency to coordinate this system.

A wide spectrum of emergency response actions can be envisioned. In some situations, eradication of crops in disease foci and immediately surrounding areas would be appropriate. Fungicidal application on a large scale might be required, possibly involving military equipment for aerial spraying or dusting. In general, rusts, mildews, most other leaf spotting diseases, and bacterial diseases can be protected against by either a copper or a dithiocarbamate material. To assure a timely and adequate supply, each class of chemical material should be stockpiled. Measures not economically feasible in commercial farming operations would be appropriate to prevent significant loss in a major food crop. If we can sufficiently flatten the disease progress curve, we will "break the back" of the epidemic. The difference between a 10% and a 20% loss of our annual corn crop—currently 235 million tons worth about $20.5 billion—is $2 billion. Development and implementation of plans for responses of this sort should be a high priority for U.S. agriculture.

Discussion

There is nearly unanimous agreement that some foreign diseases could seriously hurt agriculture in the United States if they were to get in. To predict which ones will get in, how soon, and how damaging they would become is a task most smart odds makers would avoid. Based on past attempts, the track record is not impressive. It is not our intention to overemphasize the uncertainties, but failing to recognize their existence serves no constructive purpose.

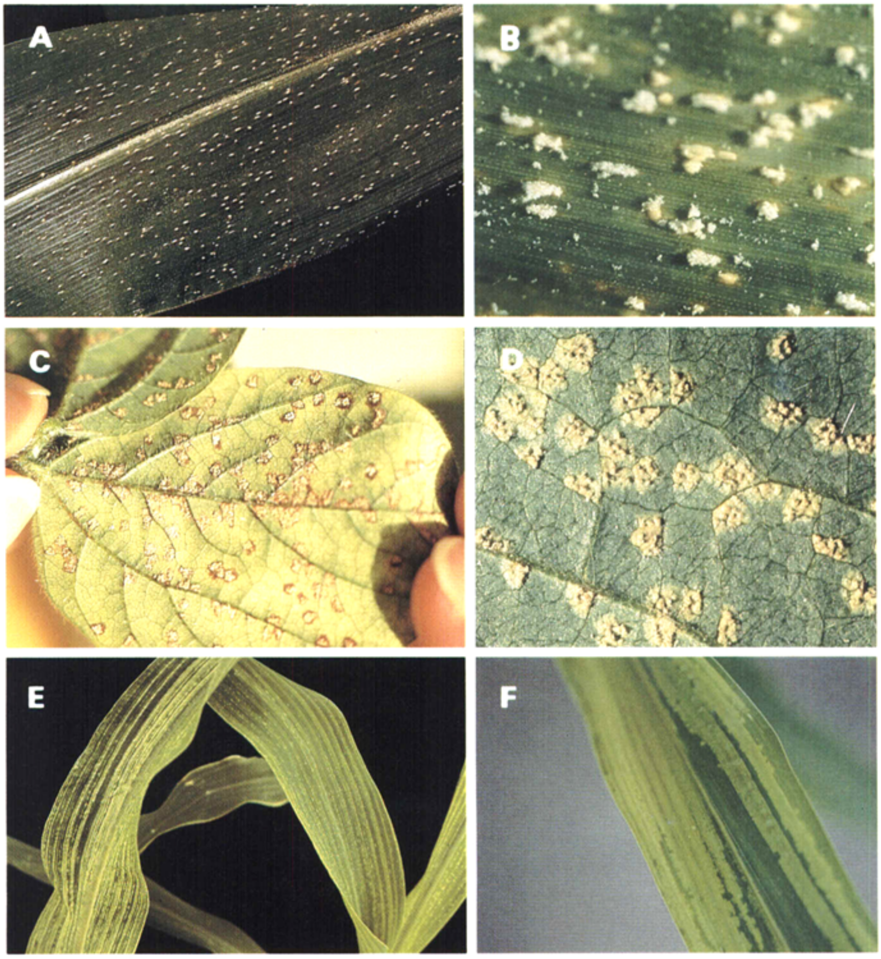
The paucity of hard data is a major factor limiting validity of assessments. Lack of standardized methodology and data recording further limits the general usefulness of many published studies. A global, internationally coordinated system of data accumulation, storage, and retrieval for each major crop is vital to increase the validity of vulnerability assessments.

An ideal way to reduce crop vulnerability to a foreign pathogen would be incorporation of durable resistance into agronomically desirable and high-yielding commercial varieties. Alternatively, breeding lines with suitable resistance factors could be developed and maintained, ready for quick use when the disease appears. Vulnerability assessment activities should normally provide information contributing toward this objective. Studies within the containment facilities at PDRL, for example, have identified sources of usable resistance to soybean rust (3).

Primary food crops in the continental United States were derived initially from foreign sources. Some believe that most of the pathogens that can seriously attack these crops have already been introduced, most by man's activities. What records there are show no increase in the rate of introductions during the period from World War II to the present, a time of greatly increased speed and volume of movement of goods and people among virtually all regions of the world.

As new geographic areas supply agricultural commodities to the United States, new source regions and pathways develop for groups of pathogens currently not represented in our agroecosystems. We, in turn, represent a source of potentially dangerous pathogens for new trading partners as we export agricultural commodities to them. Expansion of crops into new territory, as in the greatly enlarged soybean production program of Brazil in recent years, creates opportunities for new diseases to appear.

Even if it were true that essentially all foreign pathogens that could establish themselves on American crops had already done so, there remains the



Some plant diseases exotic to the continental United States: (A) Tropical rust on corn, caused by *Physopella zeae*. (B) Close-up of tropical rust pustules. (C) Soybean rust on lower leaf surface of soybean, caused by *Phakopsora pachyrhizi*. (D) Close-up of soybean rust lesions, showing individual uredia within lesion areas. (E) Maize streak on corn, caused by maize streak virus. (F) Downy mildew on corn, caused by a Thailand isolate of *Peronosclerospora sorghi*.

question of future changes among the pathogens. Most of these microorganisms are capable of as much hybrid variation and mutation as their hosts. That new pathogens will continue to arise is undisputed, but any estimate of the rate of such appearances on a global scale, even for a single host-pathogen combination, is not feasible.

Remaining prepared and alert is easier for frequently recurring emergencies, such as fires and auto accidents, than for dangers that are realized infrequently and irregularly. The research priority and effort assigned to reducing the vulnerability of our crops to exotic pathogens will depend on the firmness of our collective belief that: 1) the threat is real, 2) significant damage will occur when the vulnerability is manifested in the absence of advance preparation, and 3) effective response systems can be devised in advance that will prevent or appreciably reduce the harmful consequences of an introduction.

The cost of efforts to reduce probable future losses can be likened to an insurance premium. It might be argued that each year that passes without the calamity occurring represents a "waste" of the annual premium cost, but few individuals would advocate cancellation of the policy. In view of the enormous economic and nutritional importance of America's major crops, both at home and throughout the world, it would seem prudent to develop and maintain a continuing vulnerability assessment and response system.

Next month: The authors describe the Plant Disease Research Laboratory's plant pathogen containment facility at Frederick, Maryland, where necessary investigations can be conducted safely with plant pathogens of any type from any area at any time.

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