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Assessing the Risk and Potential Impact of an Exotic Plant Disease

The policy of the United States is to protect its agricultural capability against damage resulting from the introduction of foreign plant and animal pests without unnecessarily restricting the international movement of people or commodities. One of the primary missions of the USDA-ARS Foreign Disease–Weed Science Research Unit (FDWSRU) at Frederick, Maryland, is to carry out this policy, including identifying foreign pests of crops that are important in American agriculture and assessing the potential damage that those pests could cause if introduced into the United States. The mission is called "pest risk analysis" and consists of risk assessment (scientific estimation of the likelihood and magnitude of establishment of a given pest risk) and impact assessment (estimation of the consequences of establishment of the pest).

Risk analysis for foreign pests requires the availability of as much information as possible on the organism and its interactions with the environment. Obviously, foreign pests that are under quarantine cannot be tested in the field in the United States to obtain direct measures of their capacity to cause damage under U.S. conditions. This poses a dilemma in developing a quantitative assessment in the absence of adequate information and technology to fill the knowledge gaps (8).

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This dilemma is common for impact assessment in other biological disciplines (2,8) and limits most assessments to the qualitative state (1,9,17). A universally acknowledged body of theory and methodology in biological impact assessment needs to be developed (8).

Soybean rust, caused by *Phakopsora pachyrhizi* Syd. & P. Syd., is a major disease of soybean (*Glycine max* (L.) Merr.) in tropical and subtropical areas (5,21). Many countries have reported substantial yield losses to soybean rust (5), and the damage is increasing (21). Even though soybean rust has not been found in the United States, we must not ignore it, because more soybeans are produced in the United States than in any other country in the world. The history of plant pathology documents many cases of grave economic and social impacts from plant diseases caused by pathogens introduced into areas where they were not previously found.

During the last 15 years, the FDWSRU has used soybean rust as a model disease for risk and impact assessment. Our risk analysis of soybean rust is based on data from comprehensive research programs. At least 27 papers about this disease have been published by FDWSRU in respected journals. Our experiences and the methods we use can be applied to other plant diseases and to development of biological impact assessments in other disciplines. In this paper, we review the soybean rust research conducted during the past decade, describe approaches and methodology applied in the risk analysis, and discuss the implications for biological impact assessment in general.

The Project

Study of soybean rust at FDWSRU began in the early 1970s. In 1976, the first report of soybean rust in Puerto Rico accentuated the threat of this pathogen to U.S. soybean production, and our risk analysis at FDWSRU started that year. The project can be considered in two phases of information flow (Fig. 1). The first phase involved assessment of the source of the threat, the epidemiology, and the crop losses based on data from research in the containment facility and in field locations in Asia. The second phase involved analysis and integration of the information obtained and quantification, through modeling, of potential effects of the disease on soybean yield and economic returns in the United States.

Phase One: Assessment

Assessment in the containment facility. Outside their endemic areas, exotic pathogens can be studied safely only in containment. The FDWSRU's facility represents the highest level of containment for plant pathogen research (15). In this facility, we can safely and efficiently study plant pathogens of any type from any geographic area at any time. We can compare collections of pathogens from different parts of the world side by side under the same conditions (15). We designed our studies of soybean rust in the containment facility to answer two questions: Do soybean rust populations in different parts of the world represent different threats to the United States? And how would these populations respond to climate conditions in the United States?

To answer the first question, isolates from all over the world, including South America, Australia, Indonesia, India, and Taiwan, were grown simultaneously in separate areas of the containment facility for comparison. Bonde and Brown (3) found that spores of isolates from

Asia were morphologically indistinguishable from those of isolates from the Western Hemisphere except for a difference in the germ pore. Bromfield et al (7) showed that isolates from the Western Hemisphere were less virulent and less aggressive, producing lesions with no, one, or two uredia and extensive necrosis (RB type) (Fig. 2A), than isolates from Asia, which produced lesions with more than two uredia and without extensive necrosis (TAN type) (Fig. 2B). Melching et al (14) showed that an isolate from South America produced small, tan lesions with less sporulation than isolates from Asia. Bonde et al (4) compared the isozymes of the rust fungi and found no isozyme polymorphism among isolates from the same hemisphere but showed that isolates from different hemispheres have only 7% putative alleles in common (Fig. 2C). This indicates that the two populations of *P. pachyrhizi* are not closely related genetically. Because of its greater aggressiveness, the population from the Eastern Hemisphere appears to be the more important threat.

To understand the epidemiology of the pathogen, research in the containment facility (Fig. 2D and E) focused on determining the importance of each component or subcomponent in the disease cycle and quantifying its response to host and environmental variations. Spore germination, infection, latent period, lesion expansion, sporulation, and senescence of uredia have been thoroughly studied (Fig. 3), and effects of alternative hosts (20) and resistance (6) as well as spread of the pathogen (5) have been quantified. For example, in the containment facility Marchetti et al (12,13) and Melching et al (16) quantified the requirements of temperature and of dew period duration for soybean rust infection and concluded (12) that the two conditions are suitable for soybean rust infection in certain soybean production regions of the United States.

Local assessment. From the beginning, we recognized the importance of information on disease dynamics at the population level, which cannot be obtained from the containment facility. Before our project, few systematic field studies on the relationship between environment and soybean rust were available (22). A cooperative agreement between FDWSRU and the Asian Vegetable Research and Development Center (AVRDC), Taiwan, was established in 1979 to study soybean rust epidemics in the field. FDWSRU provided financial support and consultation, and AVRDC provided the facilities for field studies (Fig. 2F). AVRDC was an excellent site for field studies because: 1) soybean is grown year-round in Taiwan and rust epidemics vary greatly according to season (Fig. 4A) and 2) the climate in Taiwan is similar to that in some southern states of the United States.

Many epidemiological experiments have been conducted, and results have been documented by Tschanz (22) and Yang et al (28). One extensive sequential planting experiment contributed greatly to our understanding of rust disease epidemiology. Two soybean cultivars that differed in photoperiod sensitivity were planted weekly from December 1979 to October 1981, and rust severity and defoliation were assessed at weekly intervals for each planting (28). The weekly planting created a series of environmental windows, each having a unique weather and host growth condition resulting in various types of epidemics (Fig. 4B) (28). In terms of weather, the effects of seasonal differences in epidemics may be similar to the effects of geographic differences. For example, because rust occurred in the AVRDC plots throughout the year and because the climate in Taiwan is analogous with that in some areas of the United States, we may conclude the disease has the potential to occur in the United States.

Crop loss was assessed in another major study that provided information for modeling the impact of disease on yield. These experiments were conducted with six cultivars differing in rust resistance. Effects of disease on yield were measured at four levels: indirect yield components, direct yield components,

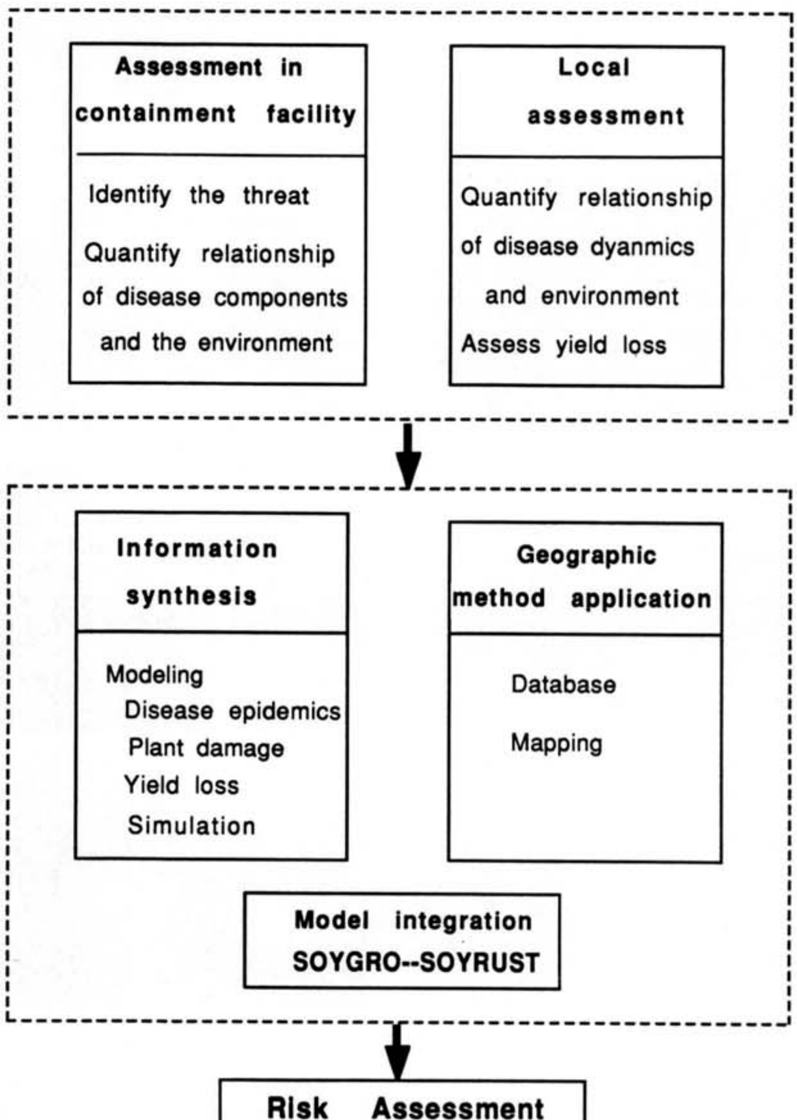

Fig. 1. Procedure followed at the USDA Foreign Disease-Weed Science Research Unit for assessing impact of soybean rust, caused by *Phakopsora pachyrhizi*, on soybean production in the United States.

plant yield, and plot yield. Although disease was correlated with many yield components as well as with plant growth processes such as shoot growth (29), the closest relationship between disease and crop response was in duration of green leaf area and plot yield (26). This indicated the best point for coupling a disease model with a soybean growth model. Studies also showed differences among cultivars in yield losses, perhaps because of differences in tolerance. Thus, we selected a model simulating plant growth at the process level so that disease effects would be reflected correctly.

Phase Two: Data Synthesis

Why a synthetic approach? Assessment is the process of tying together pieces of information in a rational way (8). We used the synthetic, modeling approach because we could project the way in which a soybean rust epidemic could proceed in the United States under a wide range of weather conditions. Our projections are based on a model reflecting the interactions of host, pathogen, and environment. Because of the difficult nature of foreign disease study, such a model must be developed from data collected by different people in different periods at different locations (25). The synthetic approach allows us to organize the information into a rational system (25). For instance, more than 16 scientists conducted the studies of soybean rust impact assessment over a 15-year period. Depending on individual experience and knowledge, each scientist evaluated results differently, showing the disease from different angles. New information was generated by reexamining the old data using updated knowledge in a holistic view.

Why a geographic approach? Risk analysis of a foreign pathogen impacts decision making at the national level. We need to know the disease potential nationwide. The United States is a vast country with wide diversities in soil, climate, crops, and alternative hosts. Therefore, an epidemic will differ from one region to another in severity and in effects on the economy (11).

Weltzien (23), who first developed the concept of geophytopathology, reasons that if geographic distributions of pathogen and host are known and if sufficient information on their ecological requirements is available, disease occurrence in a previously uncontaminated area can be predicted. A geographic approach is a methodology to characterize an ecosystem dynamically with geographic information and different mapping techniques. It is a powerful tool for program planners to use in predicting, surveying, and monitoring the movement of pests, and it may assist economists in evaluating the economic impact. Royer and Dowler (18,19) have extensively discussed application of this approach in risk analysis.

Modeling disease. Whether the geographic differences in conditions for rust development among the regions can be correctly reflected depends on the quality of disease models. Three types of rust development models, varying from empirical to mechanistic, were developed and compared with the data mentioned above. The first empirical model used days after inoculation as the predictor and explained only 28% of the disease variation among 73 epidemics of the sequential planting experiments. The second model used physiological days of pathogen and plant as predictors and determined up to 75% of the total variation in the data (28). The mechanistic disease simulation model SOYRUST (27) further improved disease prediction ($r^2 = 0.84$). SOYRUST, consisting of four rate variables driven by dew period and temperature and of six state variables, predicts disease development in daily increments.

Historical data were reanalyzed to develop the SOYRUST model (27). The effects of dew period and temperature on infection had been presented as two-dimensional graphs (12) or as tables (16). After reanalysis, a model was developed to estimate infection (Fig. 3B) (27)). Other component or subcomponent models, including latent period (Fig. 3C), lesion expansion (Fig. 3D), and infection period (Fig. 3E), were also developed by use of previously collected data. SOYRUST was extensively validated, including data not used in model development, and the results showed a very good fit between predicted and observed (Fig. 5) (27).

Disease-plant model. Integration of a disease model with a soybean growth simulation model was another method we used to improve the ability to detect geographic differences. The soybean growth model SOYGRO was developed at the University of Florida (24) and was modified by the International Benchmark Station Network for Agrotechnology Transfer (IBSNAT) at the University of Hawaii. The model, which represents the highest level of crop simulation today, simulates soybean plant growth at hourly intervals, using soil, weather, and cultivar variables as inputs,

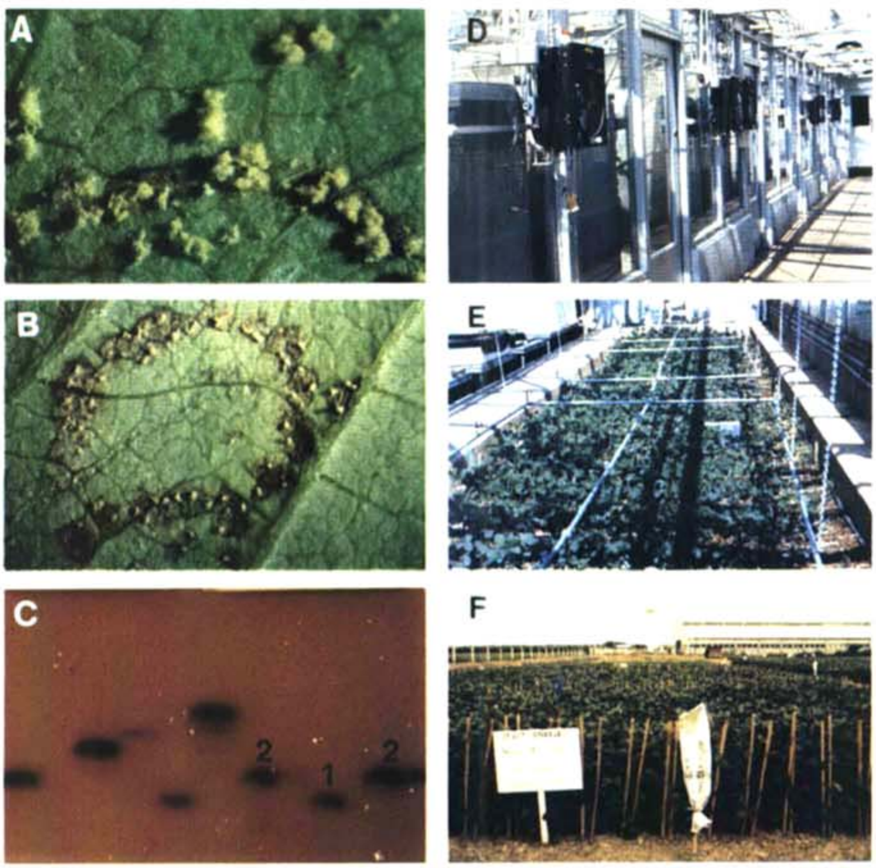

Fig. 2. (A) TAN reaction type (more than two uredia and no extensive necrosis) and (B) RB reaction type (no, one, or two uredia and extensive necrosis) of soybean rust lesions on lower leaf surface. (C) Isozyme differences in isolates from Asia (1) and the Western Hemisphere (2); other bands are for different pathogens used as controls (Bonde et al [4]). (D) Cubicle growing areas and (E) planting bed at Foreign Disease-Weed Science Research Unit containment facility where soybean rust is studied. (F) Experimental plot for study of soybean rust at Asian Vegetable Research and Development Center.

and provides daily output. It can be used to analyze the sensitivity of soybean growth and yield to planting density, cultivar, soil type, and weather. It has been extensively validated through many years and locations. The computer model is friendly and has been used by scientists in many institutes for different research purposes.

We can integrate SOYRUST as a subroutine of the plant growth model without changing the program structure of the main model because there is an interface for coupling foliar disease effects on plant growth in SOYGRO. Because soybean rust affects plant growth by reducing green leaf area (26,29), only leaf area in the growth model was considered directly affected. SOYRUST takes the variable of AREALF (leaf area cm^2/m^2) of SOYGRO as an input. It then calculates the diseased leaf area (DISLA) every day and passes the calculation as an output back to SOYGRO. DISLA has been built into SOYGRO as a variable determining plant photosynthesis for growth, and plant growth under the disease effects can be calculated. At the end of simulation, the model outputs disease progress during the season and predicted yields with and without the disease. Anyone familiar with FORTRAN language can readily use this simulation model.

Assessment. We selected some key locations in different geographic regions of the United States to assess the hazard of soybean rust. Locations were selected on the basis of importance to soybean production and availability of weather data. For this assessment we assumed: 1) the commercial cultivars grown at the location were susceptible to rust and 2) infection began at the initiation of soybean flowering (22). Weather data and soil type at each location were used as the input to run the integrated model.

Results of the simulation showed that yield losses could be considerable in some areas of the United States (Fig. 6), particularly in the Mississippi delta area and southeastern coastal regions where moisture levels are high. In the United States, soybean is grown during the summer. High summer temperatures may retard disease development, whereas cool summer temperatures in the temperate region may favor disease development. Predicted yields with or without disease were compared with measured yields at Gainesville, Florida, during 1976 and 1978–1987. Predicted losses to rust ranged from 5 to 48% (Table 1). In Tai-

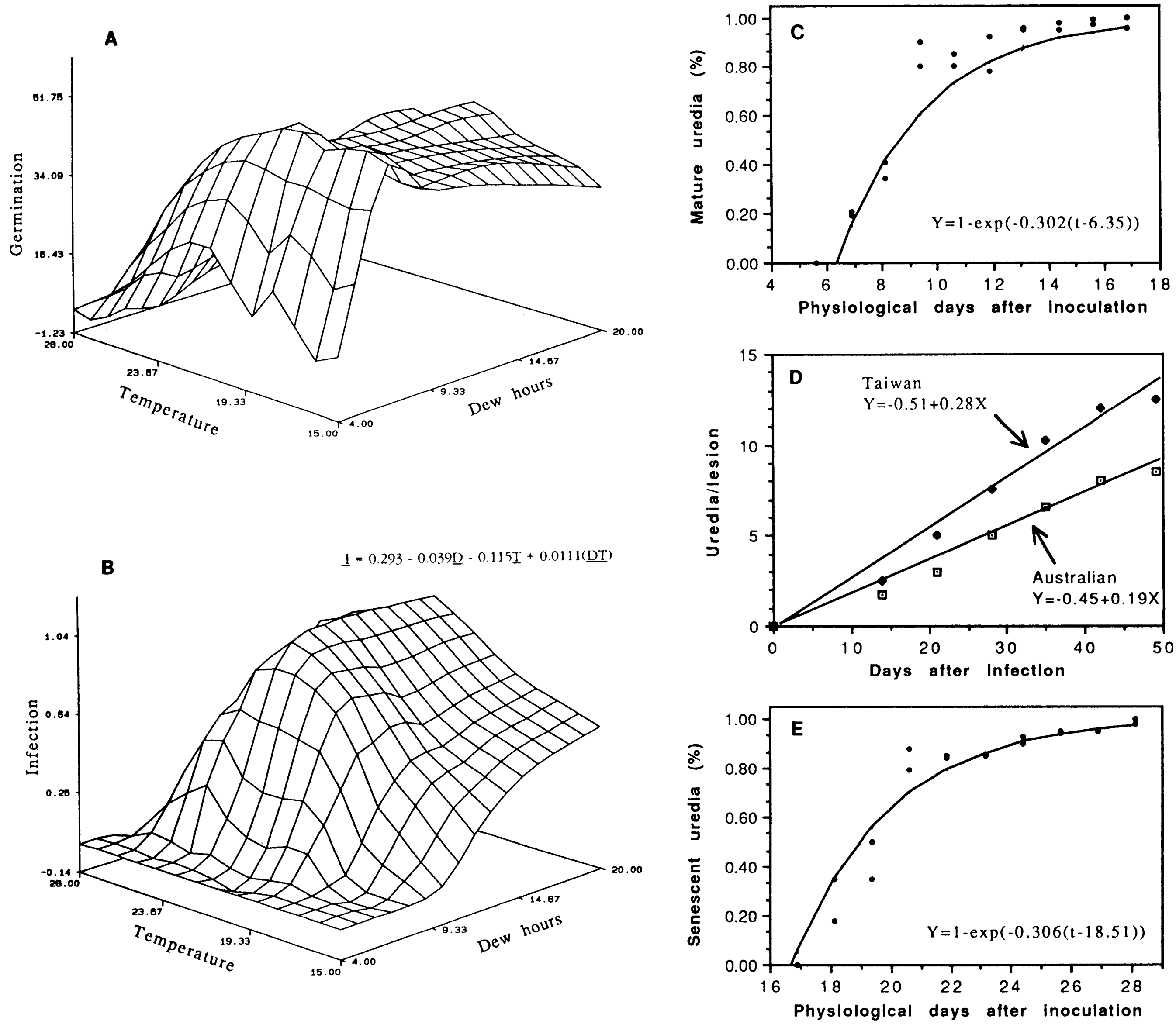

Fig. 3. Relationship of environment to soybean rust based on reanalysis of data from containment facility (Yang et al [27]): Increase in (A) germination and (B) infection with increase in dew period at optimum temperature of 20-24 C (Marchetti et al [12]). (C) Physiological days to maturation of uredia (Yeh et al [30]). (D) Lesion expansion over time for isolates from Taiwan and Australia (Melching et al [14]). (E) Physiological days to senescence of uredia (Yeh et al [30]).

wan, actual losses up to 80% have been recorded (28).

Reducing Uncertainties

All biological assessments are based on incomplete data, since we never have all the information necessary to answer all questions or foresee every difficulty (8). This project shows that threat analysis is a dynamic process that moves from qualitative (10) to quantitative (Fig. 6), from less certain to more certain. A similar situation exists regarding assessment of the ecological consequences of releasing genetically engineered organisms. Alexander (1) suggested a need to improve the overall prediction capability by reducing the uncertainties of individual events. Uncertainty of each event will be minimized by continued testing and research.

Uncertainties in our risk assessments relate to estimation of rust epidemics, plant growth, and representation of the geographic database. A key question is whether the pathogen can overwinter in the United States after entry and form an inoculum reservoir and dissemination path for annual infection. For example, although the conditions for soybean rust development are met as far north as Minnesota (Fig. 6), the pathogen may not exist there. Because of suitable climate and alternate hosts (20), the area where the pathogen is most likely to overwinter is the Mississippi delta. Furthermore, the risk should be expressed as

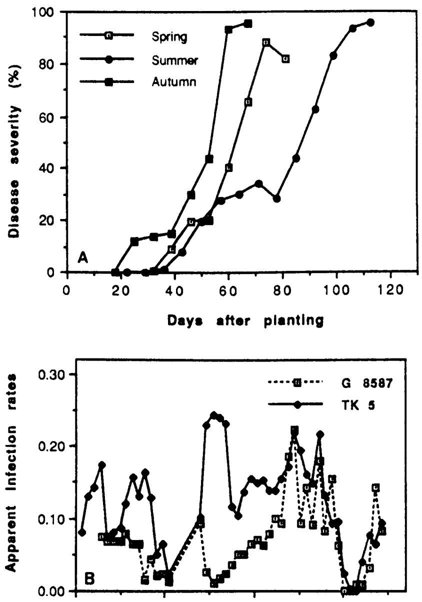

Fig. 4. Soybean rust occurs in Taiwan year-round but varies in severity: (A) Disease severity in cultivar G 8587 during three cropping seasons and (B) apparent infection rates (*r*) in cultivars TK 5 and G 8587 according to planting date, with each point representing an *r* value of the disease curve.

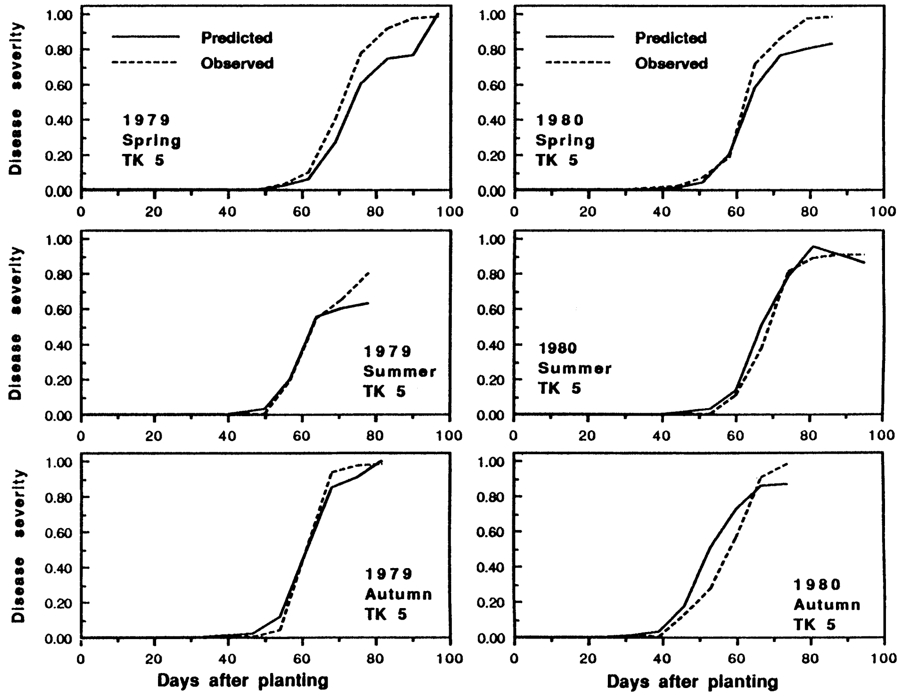

Fig. 5. Validation of soybean rust simulation model SOYRUST, using data obtained from cultivars planted for resistance studies.

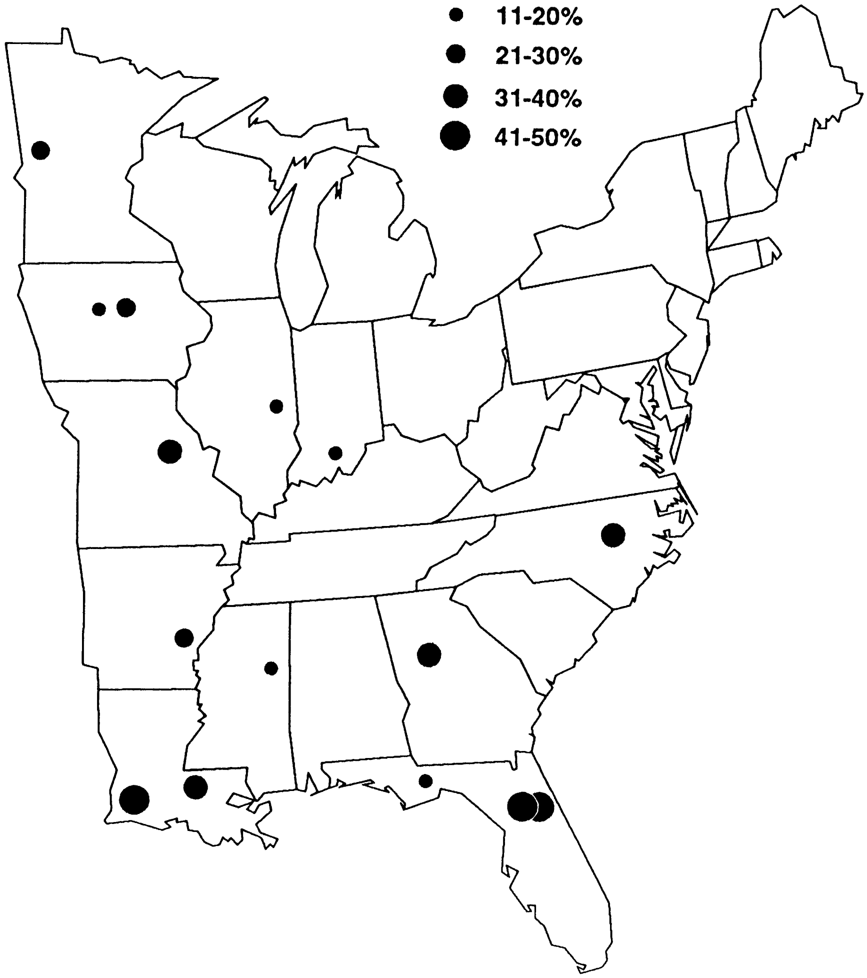

Fig. 6. Percentages of potential yield losses at 15 locations in the United States, with loss = 100 × (potential yield − diseased yield)/potential yield.

frequency distribution of probability of yield losses by stochastic simulation of disease development under various weather patterns if a large database is accessible.

Protocol

We propose the following protocol to assess the risk and impact of an exotic pest:

1. Gather biological information about the pathogen from previous research, containment facility research, and local field studies to form a pathogen database.
2. Analyze available information and use the synthetic approach to model pathogen-environment and disease-loss relationships.
3. Develop an integrated model of the effect of environment on host and pathogen development.
4. Develop a geographic database that includes the key variables for disease development and host growth.
5. Overlay the disease prediction map on a host distribution map to provide a potential impact map.

Information and Database

Gillett (8) points out that microcosm studies may present statistical difficulties regarding extrapolation to the field. We feel that although we can generate specific and reliable data in a containment facility, we cannot simulate field studies with all the variables entailed. Computer simulation greatly enhances our imagination by allowing us to synthesize the pieces of information into a holistic system, but we gain a more confident view of disease population dynamics from field data. Finally, to extrapolate population dynamics from limited field experiments to nationwide projection, we must use computer modeling combined with microcosm studies.

The database is the kernel of risk analysis of exotic pathogens and requires at least two types of data: the biological parameters of the pathogen and the geographic information. Currently, this type of database is being developed at several institutions, including IBSNAT at the University of Hawaii. At FDWSRU, a world plant pathogen database has been developed that serves as a tool for risk analysis of exotic pathogens (19).

Our Conclusions

The soybean rust project: 1) demonstrates that the potential impact of an exotic pathogen can be quantitatively assessed and 2) illustrates the methodology employed in this type of assessment. We determined that the Asian rust races pose a greater threat to the United States than do the South American races. If the Asian races were introduced into the United States, we anticipate that significant (>10%) yield losses could occur in nearly all soybean growing areas, with the greatest losses (up to 50%) in the Mississippi delta and southeastern coastal areas.

Table 1. Measured yields (kg/ha) of soybeans compared with yields predicted by SOYGRO of soybeans with and without soybean rust, caused by *Phakopsora pachyrhizi*, at the University of Florida, Gainesville

Year	Measured yield	Predicted yields: Without disease (Y_h)	Predicted yields: With disease (Y_d)	Yield loss[a] (%)
1976	3,439	3,421	1,971	45
1978	3,041	3,088	2,904	6
1979	2,891	3,004	2,937	5
1980	3,323	3,332	2,794	17
1981	3,045	3,376	3,035	12
1982	NA[b]	2,910	2,452	16
1983	NA	2,421	1,283	48
1984	3,732	3,235	2,689	17
1985	2,016	3,369	2,755	19
1986	NA	3,366	2,173	36
1987	NA	2,910	2,063	29

[a] Loss $= 100 \times (Y_h - Y_d)/Y_h$.
[b] Data not available.

Acknowledgments

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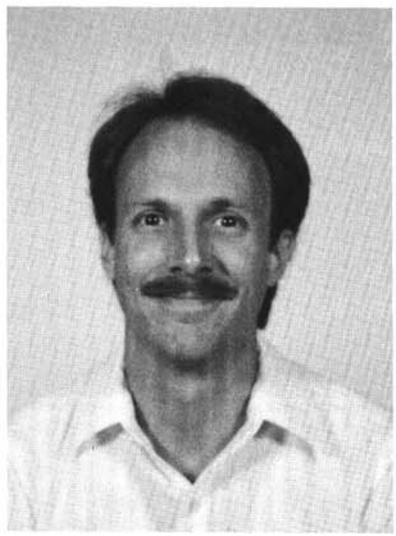

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