I - G. Assessment and Management of the Risk of Soybean Rust

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Soybean rust occurs in both the Eastern and Western Hemispheres and is a major disease of tropical and subtropical areas (4,23,26). Two species of fungi cause soybean rust: *Phakopsora pachyrhizi* which originated in Asia and P. *meibomiae* which originated in South America (18). Bromfield *et al*. (4) and Melching *et a!*. (14) showed that isolates from Asia were more virulent and more aggressive than isolates from South America, producing lesions with more uredia and extensive necrosis. Because of its greater aggressiveness, the rust from Asia appears to be the more important threat.

The Asian soybean rust was found in Hawaii in 1994 (9). We must not ignore it because the U.S. produces more soybeans than any other country in the world. The disease causes considerable yield loss in many Asian countries with losses as high as 40% in Japan (4) and up to 80% in Taiwan (30). The history of U.S. soybean production documents many cases of grave economic impacts from introduced plant diseases, such as soybean cyst nematode introduced from Asia.

The risk of soybean rust to U.S. agriculture began in the early 1970’s. This topic has been well studied. Most of the studies were conducted at the USDA Foreign Disease and Weed Science Research Unit (FDWSRU). Research on risk assessment of soybean rust can be considered in two phases. In the first phase, efforts were made to understand epidemiology and crop loss of the disease based on data from research in the containment facility and in fields locations in Asia. Efforts in the second phase attempted to quantify, through modeling, potential effects of the disease on soybean yield and economic returns in the U.S., using computer modeling techniques to integrate information. I will discuss four topics: (i) epidemiological literature fundamental to information for risk analysis; (ii) modeling soybean rust; (iii) potential impact on U.S. agriculture; and (iv) potential management strategies

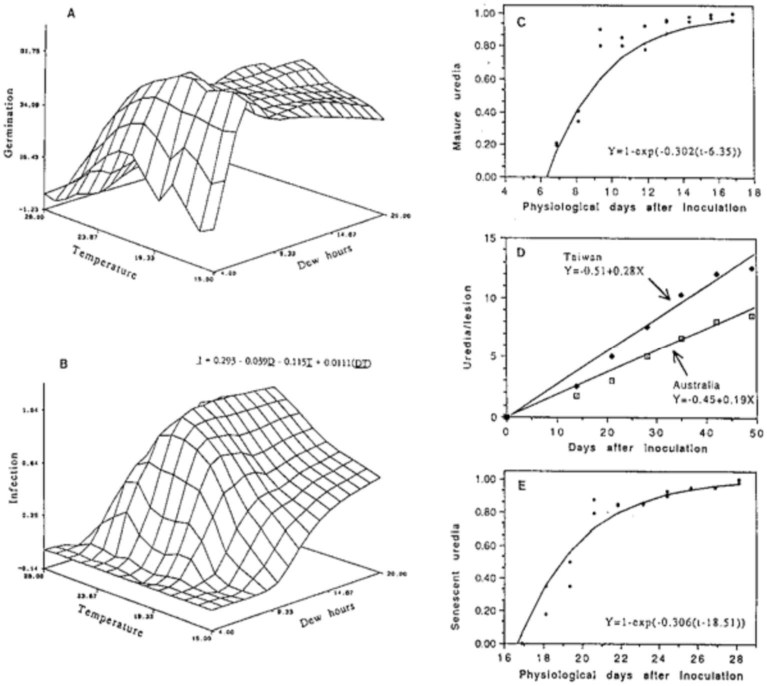

Figure 1. Relationships between disease components and environment obtained after analysis of published data from different studies. Effect of temperature on germination (A, data from Marchetti *et a!.* (12)), effect of dew period and temperature on infection (B, data from Marchetti *et a!.* (12)), physiological day of mature of uredinia (C, data from Yeh *et a!.* (34)), lesion expansion over time (D, data from Melching *et a!.* (14)), and physiological days of senescence of uredinia (E, data from Yeh *et a!.* (34)).

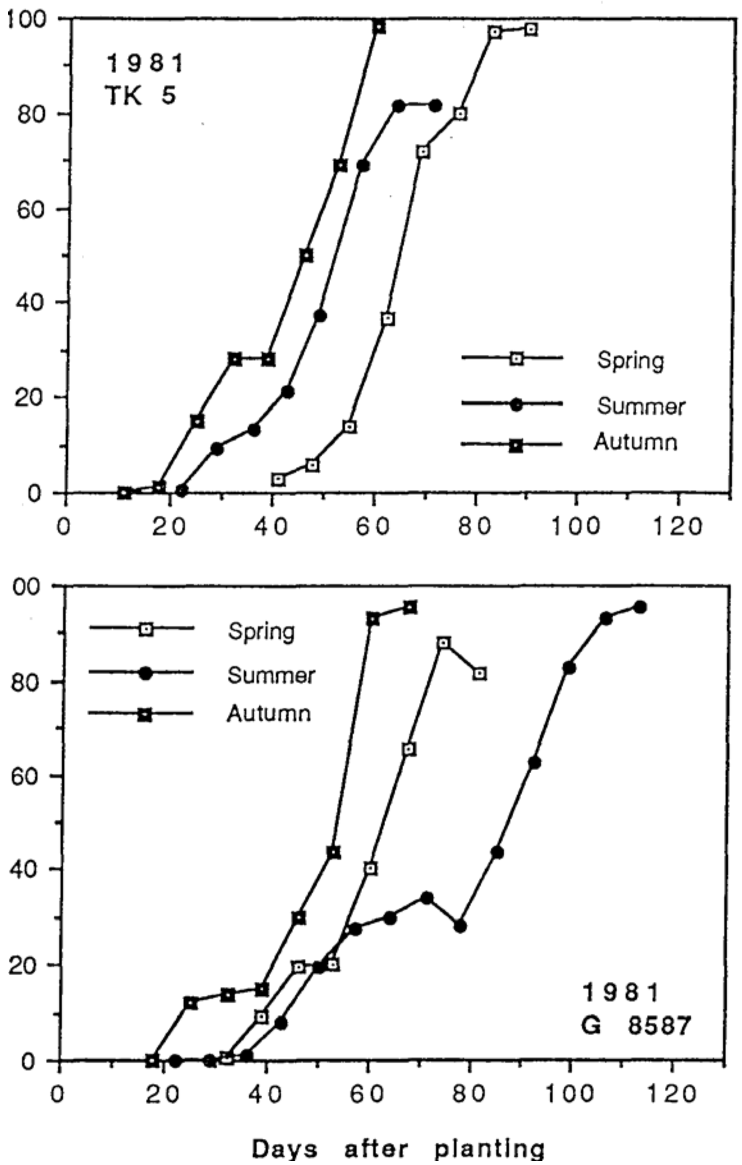

Figure 2. Soybean rust progress curves recorded from epidemics in Taiwan (from Yang *et a!.* (33)). Disease progress of soybean rust in three cropping seasons, spring, summer, and autumn in cultivar G 8587.

EPIDEMIOLOGY AND YIELD LOSS

Quantify the disease. Epidemiological studies on soybean rust generally are in two phases, the quantification of disease components, and analysis of epidemics in the field. In the past, because soybean rust did not occur in the U.S., this exotic pathogen could be studied only in containment facilities in the U.S. The FDWSRU has a facility which represents the highest level of containment for plant pathogen research (15). In this facility, plant pathogens of any type from any geographical area can be studied at any time. Research in the containment facility focused on determining the importance of each component in the disease cycle and quantifying its response to host and environmental variation. The components, spore germination, infection, latent period, lesion expansion, sporulation, and senescence of uredinia have been thoroughly studied by different researchers (12, 34). The effects of dew period and temperature on infection has a well quantified two-dimensional relationship from which an infection model was developed (31) for simulation purposes (Figure 1). By examining the relationship between infection and dew-temperature, Marchetti *et al.* (13) concluded that environmental conditions in the U.S. were suitable for soybean rust. Effects of alternative hosts (22) and resistance (5) as well as spread of pathogen (4) have been quantified.

To study soybean rust epidemic in the field, a cooperative agreement between FDWSRU and the Asian Vegetable Research and Development Center (AVRDC) was established in 1979. Southern Taiwan was ideal for field studies based on two major considerations. Soybeans are grown nearly year round there which provides a great environmental variation in rust epidemics, and the climate in Taiwan is similar to that in some southern states of the continental U.S. Many epidemiological experiments were conducted and results have been documented by Tschanz (26) and Yang *et a!.* (32). Among these, an extensive sequential planting experiment greatly contributed to our understanding of rust disease epidemiology. In this experiment, two soybean cultivars, differing in photoperiod sensitivity, were planted weekly from December 1979 to October 1981. Rust severity and defoliation were assessed at weekly intervals for each planting. The weekly planting created a series of environmental windows, each of them having a unique weather and host growth condition resulting in various types of epidemics (Figures 2

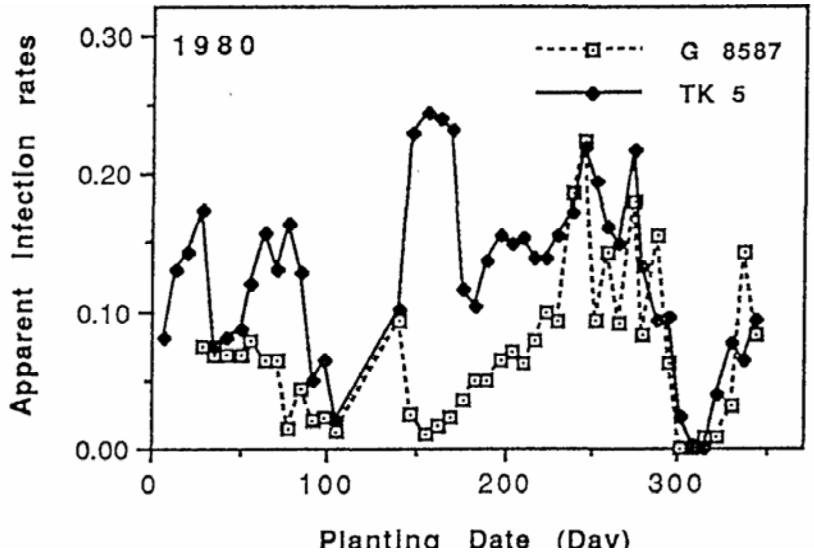

Figure 3. Epidemic rate of soybean rust (*Phakopsora pachyrhizi*) from 73 sequentially planted soybean population. The apparent infection rates of rust epidemics were on soybeans for cultivars TK-5 and G-8587, each point represents a disease curve on soybean planted at different dates.

and 3). The seasonal differences for epidemics may produce effects similar to geographic differences in terms of weather effects. Also, these experiments provided information on the effect of plant growth on disease development.

Yield loss. Crop loss assessment was done as another major study, which provided information for modeling the impact of disease on yield. These experiments were conducted with six cultivars differing in rust reactions. Effects of disease on: (i) indirect yield components, (ii) direct yield components, (iii) plant yield, and (iv) plot yield were measured (30). Although many plant growth processes such as shoot growth, abortion of pods, and seed growth were affected, the closest relationship between disease and the crop response was green leaf area duration and plot yield. A significant relationship between yield and relative area under the disease progress curve (RAUDPC) was developed with six cultivars (Figure 4). Hartman et al. (8) also developed a similar relationship between yield and soybean rust severity. This indicated the best starting point for linking a disease model with a soybean growth model. If a plant growth model is chosen, it should simulate plant growth at the process level in order to reflect disease effects correctly. Studies also showed differences among cultivars in yield losses, perhaps due to differences in their tolerance (26).

DISEASE MODELING

Rust model. The basic model used for risk assessment was the simulation model. This model was developed using the data collected from FDWSRU and AVRDC. The model was a simple disease model but included the most important factors influencing disease epidemics. It was defined to determinatively simulate daily development of soybean rust on two susceptible soybean cultivars, TK-5 and G-8587. The model consists of a main program, an input and an initiation program, and a graphic and statistic output program. The main program has five subroutines with 10 state variables, four rate variables, five driving variables, and some constants (Figure 5). Plant growth regression models (32) were used to calculate the growth of leaf area of a soybean population. The regression models were developed based on extensive data from sequential planting experiments (26) with R2=0.89 and 0.92 for two different cultivars. An equation of relative infection rate in the simulation model was developed after reanalyzing the data published by Marchetti *et al.* (Figure 1). The relationship between physiological days after inoculation (t) and percentage of uredinium maturity (R3) or uredinium senescence (R4) was exponential (Figure 1) (P=0.0001). Models of infection rate, latent period, and senescence were developed and relationship between relative infection rate (R2) and dew period and temperature was significant (Figure 1), The model of latent period explains up to 98.7% of the variation with F-test P<0.0001. A parameter of B1=6.35 indicants that there were no uredinia mature until 6.35 physiological days after inoculation. Sixteen physiological days after inoculation, up to 95% of the lesions became infectious. The senescent rate model explained 99% of the variation (P=<0.0001).

The simulation model reflected the effects of environment on disease development as shown predicted trends following the observed which varied from season to season. Accuracy of the model was demonstrated by the regression between predicted and observed disease levels.

The prediction of onset stage also was shown by values of intercept which were close to zero with deviations less than 10% in most cases during the regular planting seasons. The progress of the epidemic in the regular planting seasons was well predicted. The slope values were up to 0.85 and

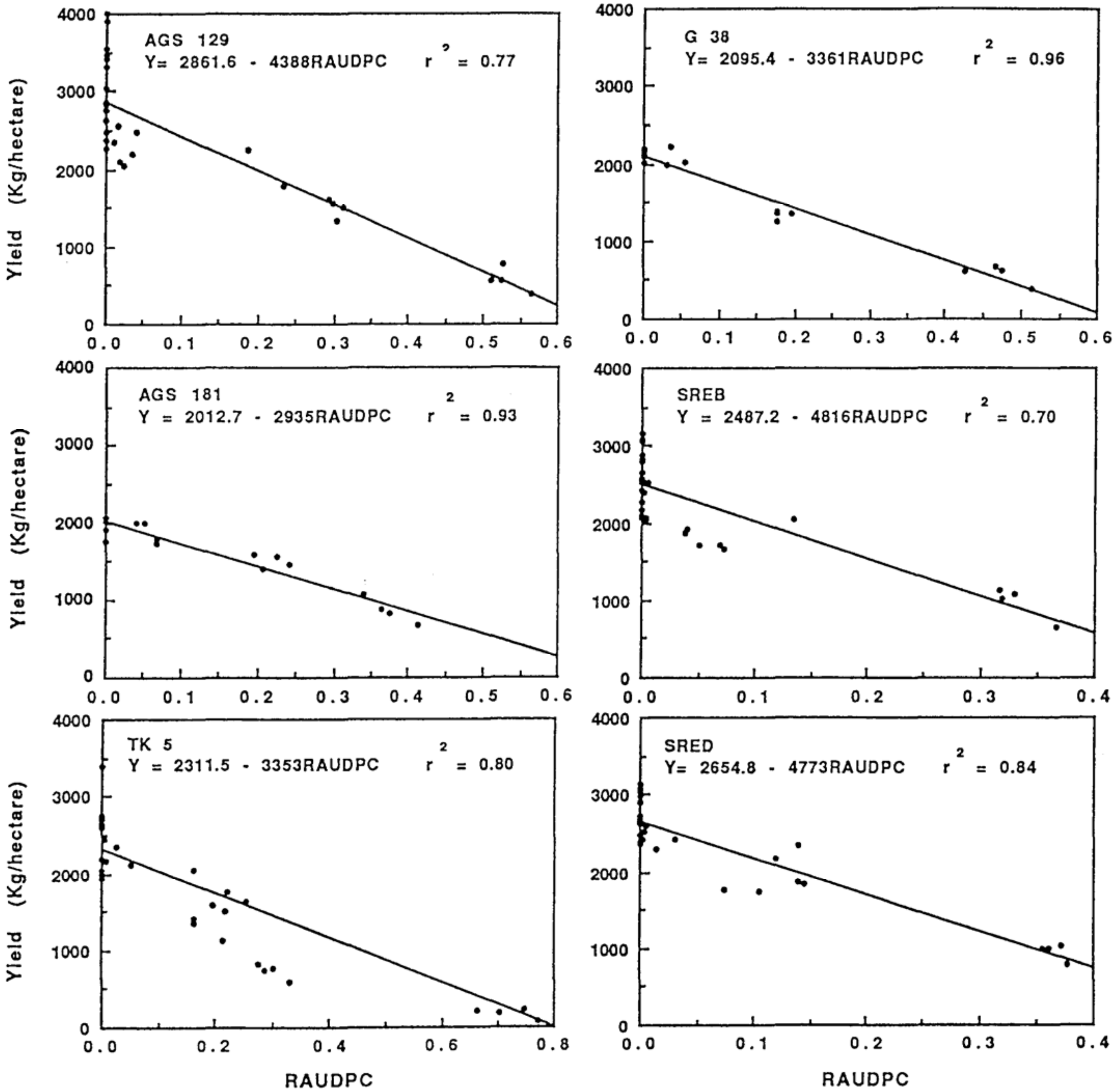

Figure 4. Quantitative relationship between soybean (*Glycine max*) yield and relative areas under the disease progress curves (RAUDPC). The greater the RAUDPC, the more severe the rust epidemic.

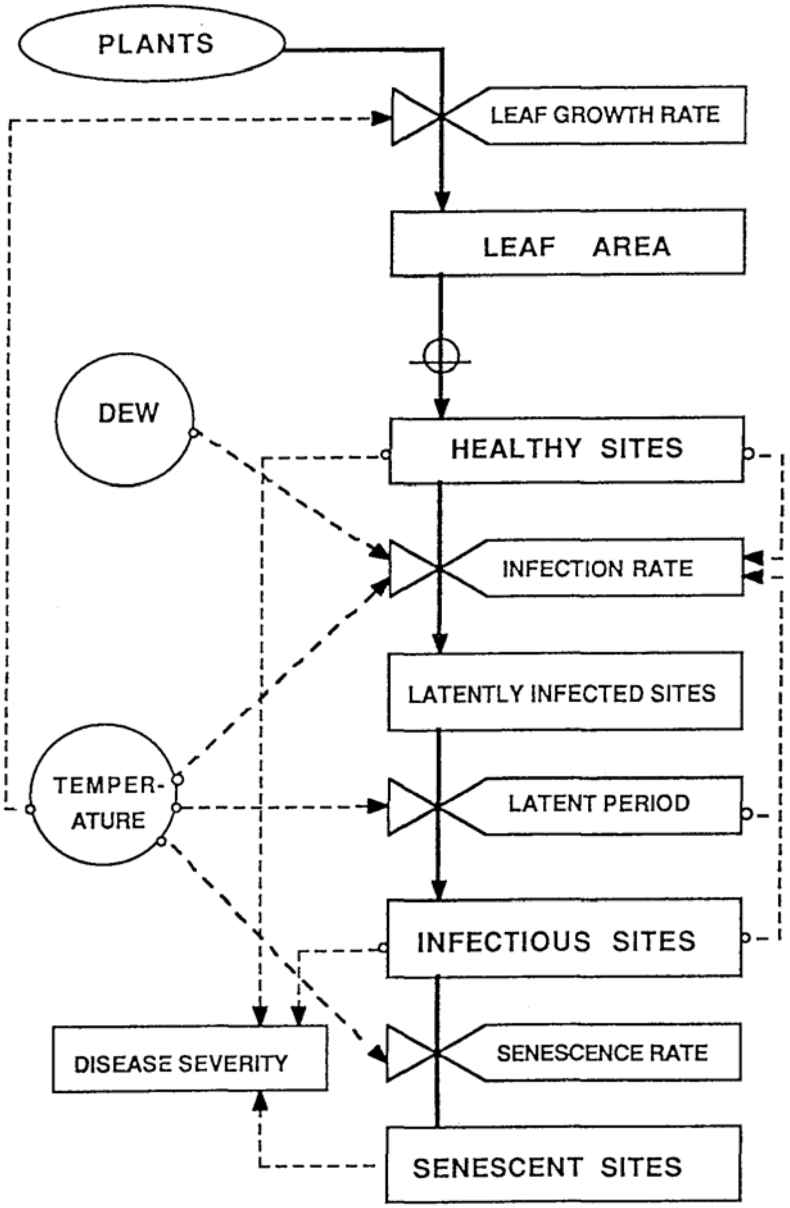

Figure 5. Flow chart of SOYRUST, a simulation model of soybean rust epdemics and the model was used in assessing impact of soybean rust on the U.S. mainland.

r^2 were greater than 0.9 in most cases (31). For the epidemics during the winter (day zero to 30 and day 300 to 365), the deviation between predicted and observed was high. For summer plantings simulation results were not as good as those of the regular seasons, shown by the low r^2 and B1. The deviation between expected and calculated coefficients was less in TK-5 than in G-8587 during these periods. In 1981, the deviation for presummer planting was less than what occurred in 1980. In general, the results for TK-5 were better than that of G-8587.

The simulation model was validated with data from Taiwan and it well predicted disease development during the regular season when validated with data that was not used in model development. The predicted lines fit the observed ones well although the epidemic period of three growing seasons varied from 65 days (autumn 1980) to 95 days (spring 1979) in TK-5 and 80-112 days in G8586 (Figure 6). However, the simulation model often underestimated the disease development when disease severity was up to 90% (31). For G-8587, results of the summer planting had greater deviation between calculated and expected coefficients than those of TK-5.

Soybean model. Integration of a disease model with a soybean growth simulation model was another method used to improve the ability to detect geographic differences. A soybean growth model, SOYGRO, was used for this purpose (28). It was further improved for application by the International Benchmark Station Network for Agritechnology Transfer (IBSNAT) at the University of Hawaii. The model represents the highest level of crop simulation today. The model simulates soybean plant growth at hourly intervals using soil, weather, and cultivar variables as inputs and provides daily output. It can be used for research purposes such as analysis of the sensitivity of soybean growth and yield to planting density, variety, soil type, and weather. It has been extensively validated over many years and locations. The computer model is friendly and has been used by scientists in many institutes for different research purposes.

SOYRUST can be integrated as a subroutine of SOYGRO 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 (33), only leaf area in the growth

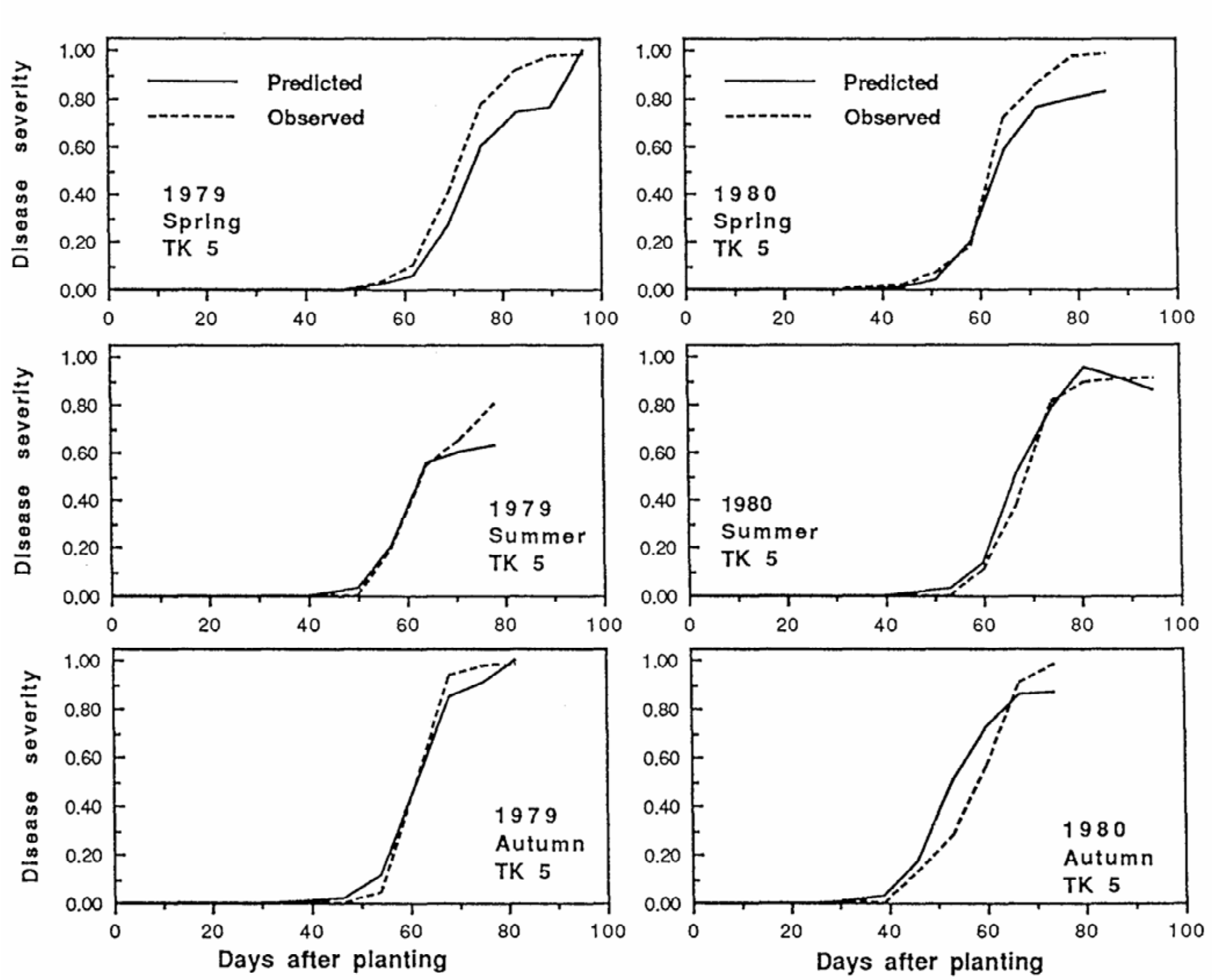

Figure 6. Validation for soybean rust simulation model, SOYRIJST. The data were from cultivar for resistance studies and were not used in model development (from Yang *et al.* 1992)(30).

model was considered affected directly. SOYRUST takes the variable of AREALF (leaf area cm of SOYGRO as an input. It calculates the disease every day and passes diseased leaf area (DISLA) as an output back to SOYGRO. In SOYGRO, DISLA has been built in as a variable determining plant photosynthesis for growth, plant growth under the disease effects can be calculated. At the end of the simulation, the model outputs disease progress during the season and predicted yields with and without the disease. Anyone familiar with FORTRAN language can use this simulation model.

In the past, total of three types of rust development models varying from empirical to mechanistic were developed and compared with data mentioned above, The first empirical model, used “days after inoculation” as the predictor and explained only 28% of disease variation among 73 epidemics of the sequential planting experiments. The second model used “degree days of pathogen and plant” as predictors and determined up to 75% of the total variation in the data (29). A disease simulation model (31), SOYRUST, which predicts the disease on a mechanistic basis further improved the disease prediction (r^2=0.84). SOYRUST consists of four rate variables driven by dew period and temperature and six state variables. It predicts disease development in daily increments.

IMPACT ASSESSMENT

Concepts. Pest risk analysis consists of risk assessment - a scientific estimation of the likelihood and magnitude of establishment of a given pest risk. The assessment is concerned with estimation of the potential or actual consequences after introduction of an exotic pathogen. Risk is an act or event which holds the adverse/negative consequence. The U.S. National Academy of Sciences (17) has defined risk assessment as the use of scientific methods, models, and data to develop information about specific risks. In plant quarantine, risk assessment has been variously defined as a "process of determining and evaluating the potential risks, their magnitude and the probability of their occurrence", with respect to exotic pests (24). Two steps may be discerned in risk assessment. The first is called risk determination, which is to identify and characterize the source of risk. The second step is called risk estimation, which is a scientific estimation of the likelihood and magnitude of adverse effect of an introduced organism in an ecosystem.

Approaches. A systems approach was used because risk assessment is the process of tying together pieces of information in a rational way. Synthetic modeling usually is used in risk assessment because it projects the way the soybean rust epidemics would proceed in the continental U.S. under a wide range of weather conditions. These projections are based on the frame of interactions of the host-pathogen- environment. Because of the nature of risk analysis of exotic pathogens, information is collected over a large range of time and space with different conditions. By using a synthetic approach, the information is organized into a rational system. Geographic approach was used because risk analysis of an exotic foreign pathogen impacts decision making at the national level, the U.S. is a country with wide geographic diversity of soil, climate, crop cultivars, and alternative hosts. Therefore, the severity of an epidemic will be different from one region to another. The geographic distribution of a disease will have different effects on the geographic economy (11). The geographic approach provides opportunity for predicting, surveying, and monitoring the movement of pests. It is a powerful programmatic tool for planners and may assist the economists in evaluation of the economic impact. Weltzien (27), who first developed the concept of geophytopathology reasons that if geographic distributions of pathogens and hosts are known with sufficient information on their ecological requirements available, the disease occurrence in previously uncontaminated area could be predicted.

Impact. Yang *et al.* (29) selected different geographic regions of the continental U.S. to assess potential yield losses by soybean rust in the scenario of introduction. Weather data and soil type at each location were used as the input to run the integrated model. The simulation showed that a considerable yield losses would occur in some areas of the continental U.S., particularly in the Mississippi delta area and the southeastern coastal region where moisture is high, high temperatures may retard disease development, whereas cooler temperatures may favor disease development. Predicted yields with and without disease were compared with measured yields at Gainsville, Florida from 1976 to 1988. Yields predicted in the absent of disease fit the measured yields (Table 1). Predicted yield losses by rust varied with years, ranging from 5-48%. In Taiwan, actual losses up to 80% have been recorded (26). However, care must be taken to interpret the assessment because two assumptions were used as: (i) the commercial cultivars grown at the location are susceptible to rust; and (ii) initial infection at every location occurs at the initiation of soybean flowering. The first assumption may be valid but the second one may not.

Table 1. Soybean (Glycine max) yields (kg/ha) measured and predicted with SOYGRO under disease and nondiseased condition at the University of Florida, Gainsville in different years.

Year	Measured yield	Predicted no disease	Yield with disease	Yield loss (%)
1976	3439	3421	1971	45
1978	3041	3088	2904	6
1979	2891	3004	2937	5
1980	3323	332	2794	17
1981	3045	3376	3035	12
1982	---[a]	2910	2452	16
1983	---	2421	1282	48
1984	3732	3235	2689	17
1985	2016	3369	2755	19
1986	---	3366	2173	36
1987	---	2910	2063	29

[a] Data not available

Royer and Yang (21) made a second assessment using Geographic Information Systems (GIS). GIS is emerging as a powerful tool for handling spatial data. GISs are computer software that use specific mathematical algorithms to enable the input, management, analysis and display of geographic data (3). In a GIS, each type of data over a geographic area may be considered a layer over that area. An impact map of a region can then be composed from the spatially interrelated maps of individual layers. Royer and Yang (21) used GIS to generate a potential epidemic map of soybean rust in Pennsylvania and Maryland with higher resolution than the first assessment. The results indicated that the epidemics could occur during the summer in these two states.

The overall conclusion for the 15 years of study is: the Asian rust races pose a greater threat to the continental U.S. than the South American races do. If the Asian races were introduced into the continental U.S., one should 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 the southeastern coastal areas. Because of the suitable climate and the presence of alternative hosts (22), the area most likely for the pathogen to overwinter is the Mississippi delta. Based on 1984 prices, it will result an estimate annual loss of $7.2 billion to the U.S. economy.

Uncertainty. All assessments are based on incomplete data (7). Alexander (1) suggested the 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 occur in current risk assessments related to estimation of rust epidemics, plant growth, and reliability of the geographic database. A key question is whether the pathogen can overwinter in the continental U.S. after entry and form a rust reservoir and rust dissemination path. For example, although the conditions for soybean rust development are met as far north as Minnesota, the pathogen may not exist there. Furthermore, the risk should be expressed as a frequency distribution of probability of yield losses by stochatically simulating the disease development under various weather patterns if access to a large database with rich historic weather data is available.

RISK MANAGEMENT

The risk of rust in Hawaii should be manageable because of limited acreage affected by the disease and the risk source is small. The management strategies can be divided into management of source areas in Hawaii and management of introduced areas in the mainland. To manage the risk, we should first determine the likelihood of transit associated with tourists, soy bean increase, and local soybean production.

Management in Hawaii. Soybean rust was found in soybean fields on the islands of Kauai, Oahu, and Hawaii with disease incidences from 10-100%. No disease was reported from Maui where the most tourists visit. There are weed hosts in Hawaii (9) and the disease is considered widespread in the Hawaiian islands.

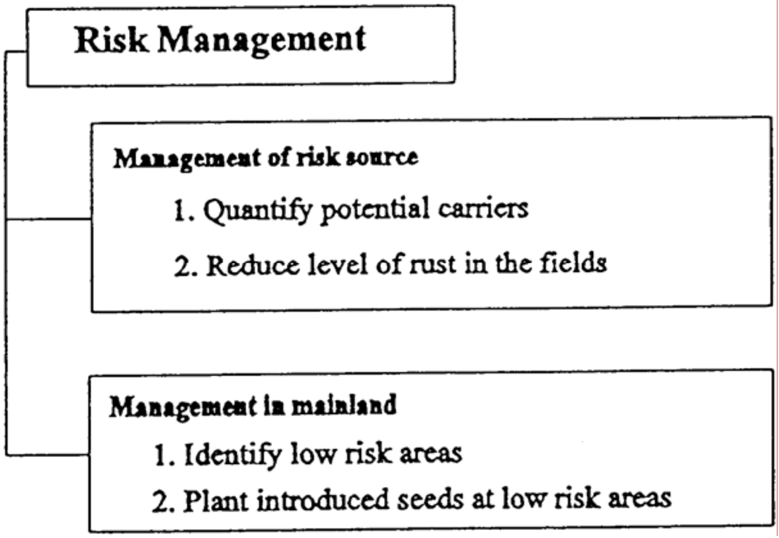

Figure 7. Potential approaches to manage/reduce the risk of soybean rust to the continental U.S. soybean production.

Disease was observed on the Big Island (Hawaii) in 1994 but not in 1995 (A. W. Tschanz, W. Schuh, personal communication)

Theoretically, there are three means for the transit of spores produced or infested soybean plants from Hawaii to the continental U.S. One is with seed-associated materials. Another is with tourist-associated activities such as spores trapped in their clothing and then carried to the continental U.S. A third possibility is wind blown spores blown to the continental U.S., which is unlikely because the small acreage of soybeans in Hawaii producing a limited quantity of spores that would reach the continental U.S. These components are discussed below. Although the soybean rust pathogens are not seedborne (34), the fungus can be carried with debris and other seed-associated materials. Besides legal seed movement by soybean breeders, illegal movement of soybean materials by local residents is another potential source of introduction. This has been suggested as the source of the latest introduction of the disease from Asia to Hawaii. The likelihood of transit depends on the degree of fungal contamination. The more severe a field is infested, the greater the chance of contamination, and of transit. The probability of introduction by illegal movement also would decrease if the level of disease in the islands is reduced.

Tourists are the second type of potential carrier of soybean rust. Millions of tourists visit Hawaii each year. The pathogen is airborne and spores can be caught in the airs around infested fields (26). These spores may be trapped in the clothes of tourists and carried to the continental U.S. Although the areas where the disease was found generally receive fewer tourists, the spores may easily be carried over the mountains from Waimanalo or Kahuluu into the heavily-touristed areas on south Oahu to Waikiki where trade winds prevail (from the N/NE) (S. C. Nelson, personal communication). The spores were carried between islands by wind currents.

Surveys should be conducted in different soybean growing seasons to assess the source volume of the risk (amount of rust) on islands where the disease has been found (Figure 7). Soybean acreage and disease severity should be determined and the information could be used to estimate the probability of spread of wind-blown spores to other islands and the continental U.S. Data on alternative hosts and their distribution could also be determined. Other potential carriers, such as activities of local soybean growers or gifts made of host soybean plants need to be monitored.

We also need to study the annual occurrence of the disease in Hawaiian soybean fields to develop effective disease control measures. To examine the seasonal variation of disease development, experiments need to be conducted in Hawaii where the disease has been reported. We also need to develop chemical and cultural control measures in Hawaii to reduce the sources of spores. In the plots mentioned above, benomyl and other chemicals which are effective to control rust could be used to manage the disease.

Risk management in the continental U.S. Yang *et al.* (29) showed that considerable yield losses would occur in some areas of the U.S., particular in the Mississippi delta area and southeastern coastal region where moisture is high. However, this assessment cannot be used directly to make risk management decision because no low risk areas were identified in that study for safe introduction of seeds from Hawaii. A quantitative regional assessment requires that analysis of vast amounts of spatial data, in addition to the development of a risk map of soybean rust for the continental U.S. soybean production regions be done by linking the disease model with a geographic information system. The map is useful for seed companies to identify low risk spots where contaminated seeds from Hawaii can be safely grown.

A new technique, neural network (NN), can be used for this purpose. The NN is an artificial intelligence technique that can identify relationships in patterns of information. Like the human brain, they can be taught to memorize patterns of information, and to classify new patterns according to memorized patterns. Using this technology, it is possible to capture the biological relationships of soybean rust in other countries and transfer this information to U.S. environmental and crop conditions at a fraction of the cost of developing a biologically-based model, Preliminary work at Iowa State University (ISU) (Batchelor, Yang and Tschanz, unpublished) has shown that the NN can predict soybean rust much more accurately than traditional models (Figure 8).

Once the NN model for soybean rust is developed, it can be used to predict potential disease severity at any site in the soybean belt for which the required input data (daily values of maximum and minimum temperature and rainfall) are available. However, there are two problems with this approach (25). Since there are many sites with weather stations in the soybean belt, it would be a formidable task to run the NN model individually for each site and each year over many years (e.g., 50 sites and 10 years would require 500 model runs). Also, there are vast rural areas not adequately covered with weather information because most official weather stations are situated at major airports only. By linking the NN model with GIS, a model output with a high resolution could be developed. Based on these maps, one will be able to distinguish between high-risk and low-risk areas.

DISCUSSION

Studies in the last two decades shows that soybean rust poses a great threat to the continental U.S. soybean production. One should 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 the southeastern coastal areas. Because of suitable climate and the presence of alternative hosts (29), the area most likely for the pathogen to overwinter is the Mississippi delta. The estimated loss to the U.S. economy in 1984 was $7.1 billion (11).

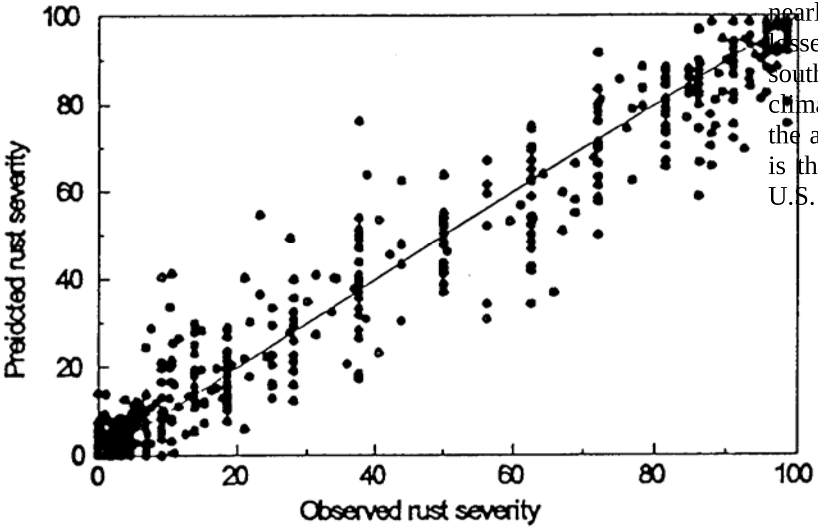

Figure 8. Comparison of neural network model predictions with observed soy bean rust values. The line indicates perfect prediction (Batchelor, Yang and Tschanz, unpublished).

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