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Framework development in plant disease risk assessment and its application

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Abstract

This article reviews recent developments in plant disease risk assessment. The role of risk assessment as an application area in macrophytopathology and its contribution to the development of macroscale disease study are discussed. This article also discusses the concepts and components of risk assessment for different end points and the assessment framework of different potential ranges of a new pathogen: establishment range, suitability range, damage range, and dispersal range. Different end points generate risk information suitable for decision makers at different levels. New insights gained from selected major diseases, especially from risk assessment due to the recent global movement of soybean rust, are presented. The role of pathologists in presenting risk information has extended beyond the professional research domain and has become critical in influencing decision-making, evident by soybean rust in both South and North America. The bias components of risk communication are defined, and different levels of receivers for risk information are identified based on their interpretation capability of risk information, bias potential, and utilization of risk information. Lack of predictability of dispersal potential contributes to uncertainty of risk assessment for airborne diseases. Potential research areas in disease risk assessment are discussed.

Introduction

Risk assessment is part of botanical epidemiology. Some principles of disease risk assessment can be found in disease epidemic forecasting in the early development stage of epidemiology. In the 1970s, threat analysis was used in regulatory plant pathology to determine quarantine subjects. Now, different terms such as threat analysis, risk analysis, or risk assessment are used for studies to determine the epidemic potential of exotic, new, and emerging diseases. Over the last ten years, advances in computer computation have made quantitative analysis with large sets of climatic data possible, along with risk assessment of exotic diseases (Yang et al., 1991). The most systematic study is on soybean rust, *Phykoposora pachyrhizi.* Since the introduction of Asian soybean rust into the New World, tremendous resources and effort have gone toward assessing the risk of soybean rust. This article reviews recent developments in risk assessment of exotic and emerging new diseases with special reference to soybean rust.

Definition of risk assessment

In a narrow sense, risk assessment involves determining the potential epidemiological and economic impact of emerging or new diseases (domestic or foreign). The information is critical to decision makers at higher levels, for example, in deciding policies to deal with risk mitigation and risk preparation at regional or national levels. In a sense, risk assessment is the application of epidemiology to regulatory plant pathology or to disease management. A study of risk assessment is a macroscale, long-term disease prediction that encompasses assessment of establishment potential, entry potential (when the range of a disease expands beyond a political border), and epidemic potential (epidemic frequency and epidemic severity or extent of the disease), and the potential losses in a region or country once an epidemic occurs. Risk assessment is an epidemiological study to predict future occurrence of a disease by using non-experimental approaches, often involving computer modelling. The modelling

Table 1. Comparison of purpose and scales of risk information among different users of risk information for Sclerotinia stem rot of soybean, caused by *Sclerotinia sclerotiorum*, in the North Central region of the United States (from Yang, 2004)

User	Purpose	Temporal scale	Spatial scale
Farmers	Chemical control	In-season	Fields/farm
	Variety selection	Coming season	Fields/farm
	Tillage	Coming season	Fields/farm
Extension		In-season	Fields/area
Agronomists	Advice	Coming season	Fields/area
Seed/chemical	Marketing strategies	Next year	Regional
Companies	Breeding decisions	Next few years	Regional
	Product development	Years/decade(s)	Regional
Government	Funding decision	Years	Regional

results are not repeatable with extrapolation from limited field studies or published data.

In a broad sense, risk prediction or risk assessment has been extended to predicting the seasonal occurrence of endemic diseases, especially in horticultural and high-value crops (Luo et al., 2001). Research in this area involves predicting the upcoming season's disease occurrence in a defined production area. Use of the term 'disease risk' for disease forecasting reflects advances in disease risk communication at the farm-level. Yang (Yang, 2003) recently outlined a conceptual example of risk prediction according to a temporal and spatial scale that uses risk information (Table 1). In this article, I exclude the seasonal prediction of the outbreak risk of an endemic disease in a region for disease management practices.

Need for risk assessment

The rapid development of risk assessment reflects the adaptation of plant pathology to new global agriculture trends, the consequence of which leads to an increased risk of new diseases. The first trend is frequent seed and plant material movement by international companies. For example, some soybean and corn seeds planted in the US Midwest are now produced in South America. The movement of large amounts of germplasm is thus unavoidable and could facilitate the movement of plant pathogens and consequently the introduction of new diseases. Assessments are made for regulatory decision-making, and several studies are underway in this area. The second trend is climate change (IPCC, 2001). Climate change has been shown to be a driving force in the long-term dynamics of plant diseases (Yang and Scherm, 1997); new diseases and re-emerged diseases have been attributed to climate change (Rosenzweig et al., 2001). Such changes can result in the emergence of new threats from minor diseases or to range expansion of a disease to production regions where the disease previously was not a concern. Expansion of the damage range of soybean bean pod mottle virus into the US North Central Region and sudden death syndrome (SDS) into the northern United States are recent examples. The increase of SDS prevalence in US north central region has been associated with increased planting of soybean in early spring, a production measure associated with warmer springs. The third trend is the change in farming practices, exemplified by the expansion of no-tillage systems.

As an applied research area, disease risk assessment has recently gained importance in the political arena of biosecurity (Madden and Van den Bosch, 2002;Madden and Wheelis, 2003). Because biosecurity-related risk assessment is new and is highly relevant to political issues, risk assessment in this area will likely embed bias potential, and contributions of research from this area to risk assessment are needed.

Risk assessment and macrophytopathology

Macrophytopathology is the study of disease occurrence patterns and disease management at the macroscale (Zeng, 2003). A narrower definition is the study of statistical patterns of disease distribution, disease range, and epidemic frequencies on large spatial and temporal scales. Ecologically, macrophytopathology addresses the questions when, where, and why a new disease emerges and becomes a major production threat. Such a study can be used to predict the damage potential of a disease (Yang, 2003). A theoretical framework of macrophytopathology has not yet been developed. The concept of risk assessment predates macrophytopathology. Risk assessment is the application of epidemiological methodology to predict the long-term risk of new or emerging diseases. With such information, disease risk can be mitigated by managing the movement and distribution of a new disease on a macroscale (Magarey, personal communication). Regulatory measures are effective approaches for risk mitigation. Strategically, a sound assessment helps make decisions in developing resistance programmes, such as screening for resistance germplasm. Development of resistant varieties is an expensive, long-term investment and would not be initiated until the entry of the disease.

It has been suggested that macrophytopathology is basically the same as geophytopathology as initially proposed by Weltzien (Weltzien, 1972). Conceptually, macrophytopathology is different from geophytopathology in two respects. In his review, Weltzien used the idea of geophytopathology in which 'documentation, analysis, and prognosis of plant epidemics seem to be an appropriate theme for maps as basic contributions.' For geophytopathology, the study began in advanced stages of epidemiology and uses quantitative epidemiological approaches to study disease occurrence patterns on a large scale. At the time geophytopathology was proposed, botanical epidemiology as a discipline or field was in its cinfancy. In macrophytopathology, new information technology is integrated with sophisticated modelling techniques to handle vast climatological data. It also includes disease management on a macroscale. The core area of macroscale study, risk assessment, is the application of theories and methods of epidemiology. In the context of macrophytopathology, risk assessment is equivalent to disease forecasting in the conventional scale of plant disease study. Weltzien (1972) did foresee the potential of geophytopathology for disease management, but it has yet to be demonstrated in macrophytopathology.

Disease range concepts and risk assessment

The concept of disease range was proposed by Yang and Feng (Yang and Feng, 2001) to describe the two-dimensional distribution of the occurrence of a disease over a geographic area. When an exotic disease is introduced into a new geographic region or a new disease emerges, assessment of the potential range of the disease is to determine the geopathosystem range, which is directly associated with impact assessment. Epidemiologically, a disease range is related to the following four other ranges important to the ultimate impact of a disease.

1) *Establishment range*, or year-round survival range, in which a pathogen can sustain itself from one growing season to the next by completing disease cycles. For a soil-borne disease, the establishment range is the same as the disease range. For an airborne disease, the establishment range is smaller than the disease range, and the establishment region serves as the source area of inoculum for other regions during a season. For example, with wheat rust in the United States, the establishment range is the overwintering range of wheat rust fungi in southern Texas and Louisiana.
2) *Suitability range* defines a geographic area where the conditions are suitable for disease to occur, which is important for airborne disease risk assessment. A range suitable for a disease to occur does not necessarily mean the disease will occur in all areas defined by the range because of the uncertainty of inoculum availability. The airborne inoculum may never reach certain areas defined in the region. Assessment based on this range represents the maximum risk.
3) *Dispersal range* defines the geographic area into which airborne diseases can spread seasonally from overwintering areas defined by the establishment range. Dispersal range of a disease does not mean range of inoculum spread, which is far larger than seasonal disease dispersal range. Recent studies show that air currents can, within a season, carry the spores of soybean rust from Brazil to almost anywhere in the Western Hemisphere.
4) *Damage range* is a region where the disease can cause significant economic yield loss in a frequency that warrants implementation of production measures. Sometimes, it can be referred to as the endemic region of a disease. Geographically, the physical sizes of

these ranges for an airborne disease have the following order: establishment range < damage range < dispersal range < suitability range. For soil-borne diseases, the establishment range should be equal to the suitability range and no smaller or larger than the damage range (establishment range = suitability range > damage range).

Components in risk assessment

The fundamental parameters of potential risk of a new or exotic disease to crop production in a geographical region are disease range, frequency of potential epidemics, and intensity of epidemics in terms of economic losses. Epidemiologically, risk assessment for a new disease consists of the following exercises, each of which can be independent. Negative results of each assessment indicate the non-threatening status of a new disease. These components are establishment potential, suitability of the environment to disease occurrence, dispersal potential, and yield-loss potential. In risk assessment, almost all assessment starts with a suitability assessment, and the order of assessment procedures is determined by the availability of techniques and data at the time when the assessment is made. Because effects of temperature and dew are known key factors in determining the infectivity of a plant pathogen, these factors are investigated first in epidemiological studies and therefore are available for the environment suitability assessment of risk assessment. For soybean rust, there are three critical components of uncertainty: 1) suitability of climatic conditions for rust epidemics in soybean production areas, 2) likelihood of establishment of the fungus in North America, and 3) the seasonal dispersal potential of the pathogen from overwintering regions to major soybean production regions.

Establishment assessment

This assessment addresses the question: once an exotic pathogen is introduced, can it survive from season to season in a country or geographic region, and if so, where? If the disease cannot be established in the region or in an area of reachable distance during the growing season, the pathogen should not be considered a threat. For this assessment, the key aspects are to determine the availability of alternate hosts of the pathogen and its overwintering potential in a non-host growing season. Quantification of the source strength early in spring may be important to mid-term season disease forecasting for airborne diseases.

Suitability assessment

This assessment determines the suitability of the climate in the studied geographic region or country. Suitability assessment is almost always the first assessment to address in risk analysis. If the climate is unsuitable for the occurrence of the disease, no further assessment is needed. The normal approach for this assessment is to use a disease model together with climatic data to assess the epidemic potential in the region. Sometimes, the epidemic potential is further fed into a yield-loss model to determine the maximum yield loss potential of a disease. When long-term climatic data are available, determination of potential epidemic frequencies and severity, a higher level of assessment, are useful to policy makers. If severe epidemics of a disease have a frequency one-in-eight or ten years, the disease may not be a major production concern. However, suitability assessment is almost always made with an assumption that initial inoculum is available early in a growing season. Therefore, the estimated risk would be greater than the real loss if the disease is airborne because initial inoculum of an airborne disease is not always available. Risk estimated from such an assessment represents maximum risk.

Dispersal potential assessment

This assessment applies to a disease caused by an airborne pathogen that establishes regionally in a country but poses a threat to the rest of the production area. The damage level of the disease depends on the yearly reintroduction potential of inoculum. It is not a concern for soilborne diseases, however, once the establishment assessment is completed. For soybean rust, the pathogen overwinters in southern Florida and Texas, which is far from the major US soybean production region. For risk assessment, this is the last component to study because epidemiology does not

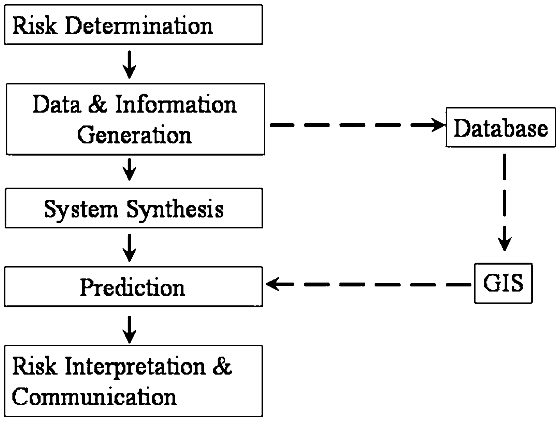

Figure 1. Flow chart showing the process of a risk assessment study. To have a completed risk study, the last step of risk interpretation and communication by the modellers is essential.

provide methodology for such an assessment. For soybean rust, this uncertainty has been a factor in decision-making in Argentina where the disease can overwinter only in the northern production regions. Figure 1

Conceptually, risk assessment for exotic, new, or emerging diseases could be generalized according to the types of assessment (Figure 2). The outcome of each assessment and its usefulness depend on the type of assessment. Information from the establishment assessment is significant for quarantine purposes. The risk from the suitability assessment is the maximum risk useful for policy decision-making in which accountability is a concern. The maximum risk could be far from the real losses because of a lack of inoculum in a season or missing a dispersal component in the study. For epidemiologists, the challenging part is to determine the most likely losses, which is information useful for industry, whose concern is on the impact of a new disease on its profitability. The arrow in Figure. 2 indicates the most likely losses assessed with comprehensive epidemiological information. Depending on the availability of information/data and skills provided to an assessment, the assessed risk may be higher or lower than the most likely risk. Over time, the assessed value from a risk assessment should approach the most likely risk.

Examples of assessment for a soilborne disease

Risk assessment of soybean sudden death syndrome (SDS) caused by *Fusarium solani* f. sp. *glycines* is an example of an emerging disease. This soilborne disease was first reported in Arkansas in the early 1970s and caused endemic production

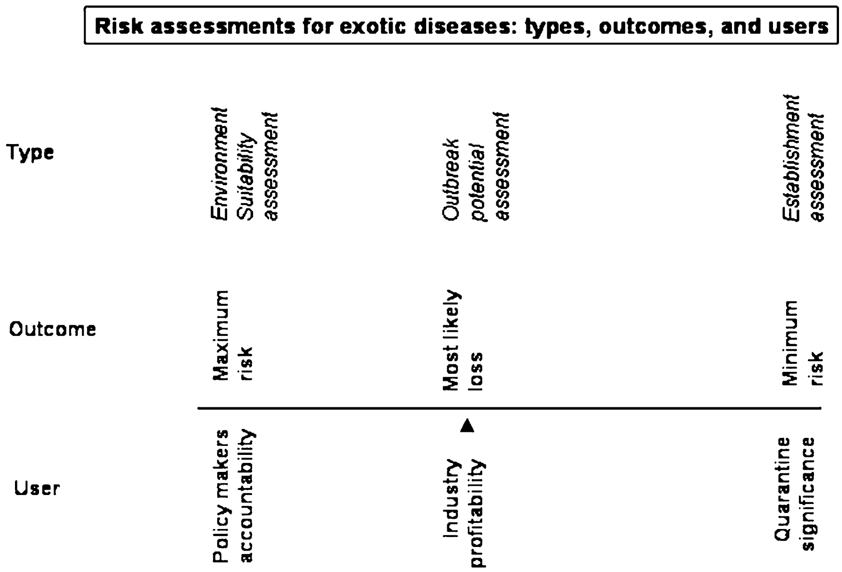

Figure 2. Conceptual framework of risk assessment for exotic, new, or emerging diseases, showing the types of assessment, outcome of each type, and users of each outcome. The arrow indicates the most likely losses assessed with comprehensive epidemiological information.

problems in the southern states (Roy et al., 1997). It was initially domestic and no establishment assessment was needed. Because it is soilborne, the dispersal assessment was also not applicable. The need for a potential impact assessment was not realized until 1993 when the disease was found in Iowa, a leading soybean production state. The soybean industry needed to know the level of the threat from this disease to the North Central Region, which produces 78% of US soybean, so that the funding agencies could prioritize investment of research funds. A risk assessment for SDS was conducted using Climex, computer software developed by CSIRO (Sutherst and Maywald, 1991), with disease parameters generated from experiments conducted under controlled conditions (Scherm and Yang, 1999). The assessment predicted that the disease would cause more losses in the north central region than in the southern United States where the disease originated. The assessment has proved correct. By 2002, SDS had spread into Canada and Minnesota and was ranked the number one damaging fungal disease in the north central US soybean production. When data were presented in 1995 at a regional soybean conference, SDS immediately gained the attention of the soybean industry. Breeding for resistance to SDS had started before the disease became a production problem in the US North Central Region. Now, many seed companies have resistant varieties available to growers. Without this risk assessment, which promoted resistance breeding and management research, current disease prevalence levels and the frequency of epidemics would probably be higher.

Example of assessment for an airborne disease

Suitability assessment

Risk assessment of soybean rust, caused by the fungus *Phakopsora pachyrhizi*, to US soybean production is the best example for an airborne disease. The assessment started in the early 1980s and was one of the earliest risk assessment programmes. Risk assessment of this disease has contributed to the development of general concepts and quantitative methodology. For suitability analysis, research efforts were divided into two phases: 1) understanding infection components based on research in a containment facility at Fort Detrick in Federick, MD, and in fields in Asia, which provided baseline information for disease modelling; and 2) development of computer modelling to quantitatively assess the potential effects of rust on soybean yield in the United States.

Research under controlled conditions focused on determining the importance of each epidemic component or subcomponent in the soybean rust disease cycle and on quantifying its response to host and environmental variation. The components—spore germination, infection, latent period, lesion expansion, sporulation, and senescence of uredia—were studied by several researchers at Ft. Detrick and elsewhere (Keogh, 1974; Marchetti et al., 1976; Bromfield et al., 1980; Meching et al., 1989); Patil et al., 1997; Hundekar and Hiremath, 2001). The effects of dew duration and temperature on infection have been quantified as a two-dimensional relationship from which an infection model was developed to estimate infection (Marchetti et al., 1976). These studies provided critical background information for building epidemiological models for risk assessment. The field experiments were conducted at the Asian Vegetable Research and Development Centre in southern Taiwan. Soybean can grow year-round in this area, and disease occurs most of the year, except during the winter. These data allowed analysis of the seasonal variation in rust epidemics.

From the data compiled from field and greenhouse studies, a computer simulation model, SOYRUST was developed. This simple disease model includes most weather variables that influence disease epidemics. The model was validated with data from Taiwan, and predictions matched observations. SOYRUST was integrated, as a subroutine, into the soybean growth model SOYGRO (Wilkerson et al., 1985), developed at the University of Florida to simulate disease progress during the production season and to predict yield. With the assumption that spores are available early in the growing season, the simulation results showed that considerable yield loss could occur in some areas of the United States. In recent years, USDA–APHIS generated a US risk map by using continuous moisture measurements and dew days data. The general consensus is that the environmental conditions in the US soybean production regions are suitable for the occurrence of this disease (Bromfield, 1984).

Establishment assessment

Predicting the year-round survival of the soybean rust fungus is important for determining availability of spores in the spring and for determining potential dissemination into major soybean production regions during a growing season from an overwintering area. Models were used to predict where climatological conditions are suitable for the year-round persistence of *P. pachyrhizi* worldwide. Long-term meteorological averages were used to assess stress by using the CLIMEX software developed by Sutherst and Maywald(1985). Integration of stresses was used to predict the likelihood of survival of *P. pachyrhizi* within a location (Pivonia and Yang, 2004). The assessment shows that areas presumed suitable for year-round survival of *P. pachyrhizi* in the Western Hemisphere extend from southern Brazil to southern Texas and Florida. In the United States, the fungus is likely to overwinter in areas where climatic conditions in winter are similar to those in southern China. During mild winters, the coastal region of the Gulf of Mexico is also in the *P. pachyrhizi* year-round survival zone (Figure. 3). The reported occurrence of soybean rust in kudzu plants near Tampa, Florida, in February of 2005 validated the assessment.

Dispersal assessment

Several means existed for long distance spread of airborne diseases, such as the tobacco blue model to assess spore movement from the Caribbean to the southeastern US. For soybean rust, there are several means for northward movement. Climatological models have been integrated with epidemiological models for prediction of soybean rust

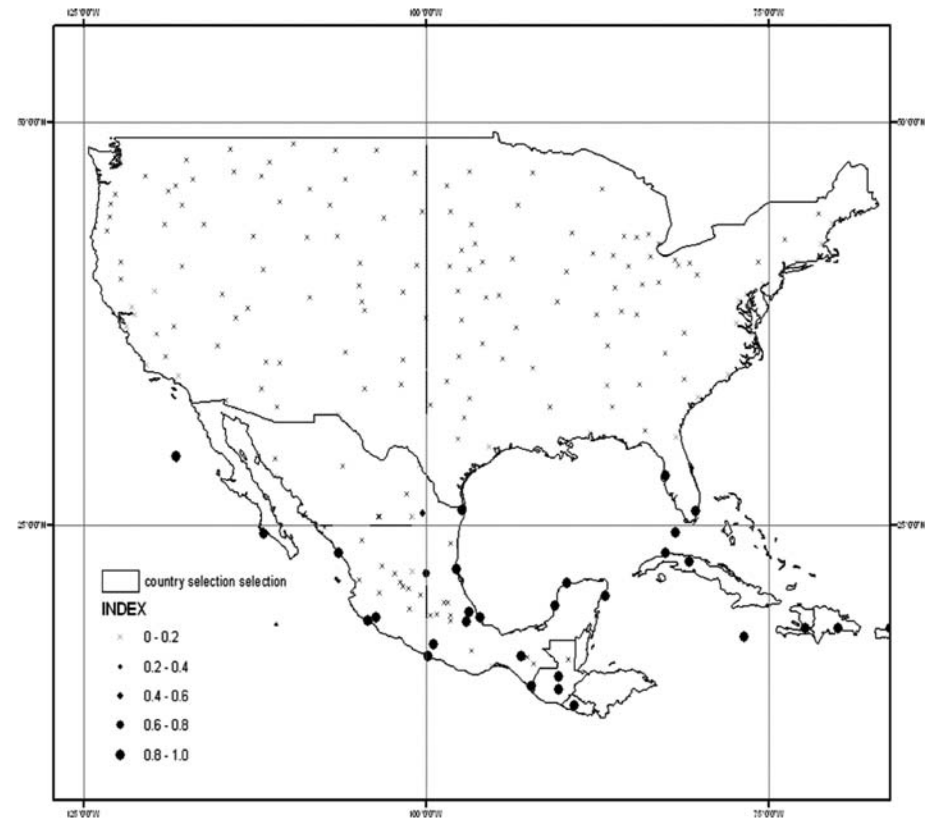

Figure 3. Illustration of the potential range of soybean rust, *P. pachyrhizi*, in North America with a focus on the United States (Yang, 2003). The establishment range is indicated by the probability of overwintering, which is the US coastal area. The suitability range is estimated to extend to from Gulf Coast to northern border of the US in east of Rocky Mountain. The dispersal range and the damage range are yet to determined.

movement. Such integration could be a potential research area to generate new directions for epidemiological research. The MM 5 model is a global circulation model for air particle movement and high split model for rust prediction. The model has been used to correctly predict the 2004 season rust spore movement to Argentina and Colombia. In August 2004, it also predicted the spore movement from Colombia to the southern US before the disease was found in Louisiana.

Risk communication

To plant pathologists, risk communication is relatively new in the framework of risk study compared with plant disease risk analysis. Elements of risk communication consist of receivers of risk information, interpretation of the uncertainty, and delivery of the information with an approach or method according to information receivers and the capability to digest risk information of receiver aspects. To the risk communicators who are often plant pathologists, it is crucial to understand the epidemiological principals used in the assessments. Most models are built with certain assumptions that are critical to risk interpretation. Without stating the underlining assumption while discussing the risk, the risk level can be overestimated, which often occurs when risk information is disseminated by non-pathologists. For soybean rust, when citations are made for the study of USDA economic assessment or yield loss (Yang et al., 1991), the writers often reported figures of potential losses from a risk assessment without providing the assumptions addressed by authors in their studies.

Receivers of risk information

After the risk assessment is made, the information is disseminated to the public. There are several levels of receivers: policy makers, scientists in chemical or seed companies for product development, managers of funding agencies, producers for day-to-day farm operation, and crop advisers in private and public domains. Based on the decision levels, the risk information is generated differently in terms of temporal and spatial scales (Table 1) (Yang, 2003). For decision-making, the temporal scale ranges from decades to weeks, and the spatial scale ranges from the entire country to individual farms. The capability of digesting risk information varies, and the purpose of taking risk information differs. Therefore, interpretations of the risk on the receiver sides are different. Receivers of risk information can be grouped by three levels based on their knowledge and interpretation of disease risk.

Level 1. This level consists of pathologists or groups of professionals who have in-depth knowledge of plant pathology. Detailed outcomes on risk assumption can be explained and the uncertainty of the information is fully understood by receivers. This level includes industry experts in chemical and seed companies whose annual profitability relies on decision with a measured risk. The setting for risk information delivery includes professional meetings through presentations by authorities on specific topics, and this level has no bias in interpretation of disease risk.

Level 2. This includes decision makers at the policy-making level at the public domain, such as government officials or society leaders who have limited understanding of assumptions or who overlook the assumptions made for assessment for political liability and address the maximum risk. Bias interpretations of the risk assessment are not uncommon. To make a better argument for making policies, the maximum risk is used most frequently for accountability reasons. The example is the frequent use of soybean rust economic assessment of US $ 7.2 billion (Kuchler et al., 1984) in decision-making, although a later much smaller figure (~US $ 1–2 billion) has been made in a new risk assessment.

For high-level policy makers, decision-making is based on political rational and accountability, which has a tendency towards self-protection and therefore naturally embeds bias of select use of risk information. For soybean rust, decisions at higher levels were likely made using the worse-case scenario. Economic calculation is less essential compared with the producers or profit-driven businesses. Finally, risk communication varies from culture to culture. Some cultures are more sensitive to disease risk than others. For soybean rust, the response of industry to soybean rust in the United States has been much greater than in South American countries.

Level 3. This includes laypersons or producers who have a limited knowledge of plant pathology. Some highly competitive producers, however, have good plant pathology knowledge and should be considered in level 1. For level 3, communication is made through indirect approaches. Information is delivered mostly through media, agricultural magazines, or radio, where normally the maximum risk of a disease is presented without further explanation. Risk is often selectively stated by media to achieve sensational effects. In the dissemination of soybean rust information, only maximum yield losses of assessments (loss of 80%) were used, without providing the dispersal assumptions used in the assessment. Unfortunately, producers are handlers of risk in production, and risk information indirectly delivered to them decreases the effectiveness and quality of risk management. Overreactions to soybean rust were common among the US soybean producers in the first two years.

It is important to disseminate risk information differentiated by simplicity or complexity to different receivers to avoid confusion or panic and to maintain the credibility of the research community. One example was the early release of spore dispersal assessment. In 2003 winter, a USDA trajectory analysis for the Western Hemisphere was prematurely released. The results showed that air parcels carrying fungal spores from lower elevations in Brazil soybean production regions could reach the United States. Unfortunately, this statement was interpreted by receivers as indicating the possibility of soybean rust occurrence in the coming season in the United States, which caused unnecessary panic in some US growers who consequently purchased fungicides for the predicted arrival of spores during the next season.

Future research for risk assessment

Our knowledge in epidemiology has enabled us to assess environmental suitability, establishment potential, and survival potential after the introduction of a plant disease. By adding yield loss models, yield loss potential can be determined. The outcome of risk assessment from the above-mentioned components represents the worst-case scenario. For soilborne diseases, the establishment range of a disease is equivalent to the distribution range or the range suitable to disease occurrence, with the damage range being smaller than the pathogen distribution range. Assessment with the worst-case scenario may not approach the realistic maximum damage of a soilborne disease. However, for airborne diseases, the establishment range of a disease would be no larger than damage range and smaller than the suitability range, depending on the dispersal potential of the disease. To have a more realistic assessment, the long-distance continental dispersal potential of the airborne disease needs to be predicted.

Dispersal potential is a key uncertainty in predicting the risk of an exotic airborne disease, which is important in determining the entry risk and damage risk after establishment. For the example of soybean rust, uncertainty of the disease risk depends on our understanding of dispersal potential of the disease. Before entry of this disease, dispersal information was critical to determine when the disease would arrive in the United States. Such information is critical for chemical companies to determine when to stockpile fungicide for disease control. For commodity groups, entry time is used to embargo the importation of soybean from occurrence countries, a temporary strategy to raise the local market price.

Once a disease establishes in the new country, its damage potential to the production region depends on the seasonal dispersal of airborne spores from overwintering regions into major production regions. Models for the dispersal potential are still in their infancy, and the prediction needs to determine the source area and its relationship to inoculum density in the receiving region, after long-distance dispersal. Such a relationship should exist in a pathosystem as demonstrated by Zeng (1988) in wheat stripe rust.

Latent period after entry. There are two critical times after the entry of an exotic plant pathogen into a new geographic region: time of first detection and time of first outbreak. For risk mitigation, when the pathogen can be detected after entry and when the first outbreak would occur are key questions. Practically no introduced diseases have produced severe, region-wide epidemics in the first season of detection in the United States. Similarly, soybean rust in South America did not cause economically significant losses in the 2000–2001 growing season after it was first found in southern Brazil and Paraguay. It caused losses >$125 million in the second year of detection (Yorinori et al., 2003). However, predicting when an introduced pathogen would become prevalent after subsequent entry and reach outbreak levels is critical to disease prevention or risk management. The available response period depends on detection efficiency—and the earlier the better.

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