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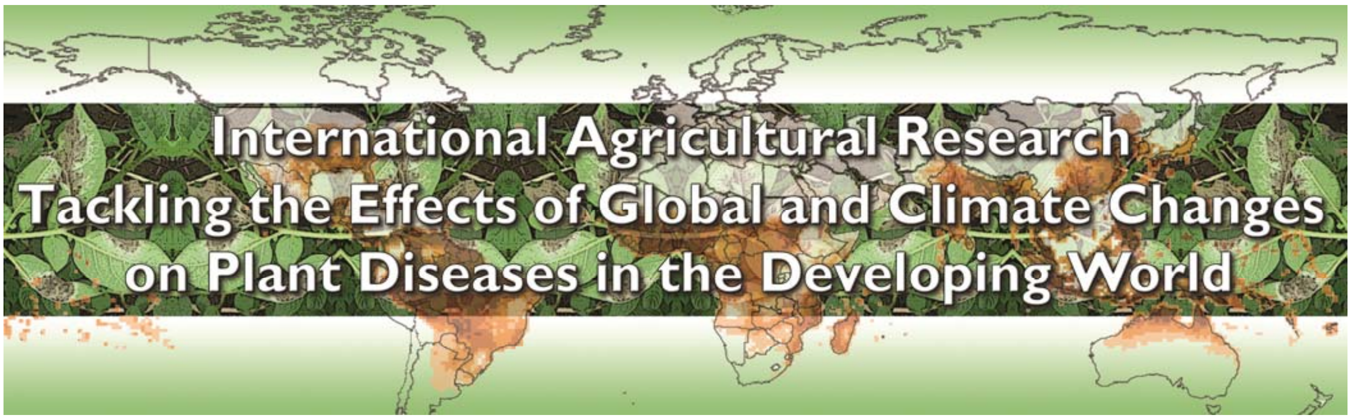

International Agricultural Research Tackling the Effects of Global and Climate Changes on Plant Diseases in the Developing World

Problem Identification

Climate change (48) has a number of observed, anticipated, or possible consequences on crop health worldwide, as a series of reviews have discussed (3,10,17,20,21,35,60), especially recently (18,29,30,36,38,54,65,68,88,100,118,129). Global change, on the other hand, incorporates a number of drivers of change (72,83,141), including global population increase, natural resource evolution, and supply–demand shifts in markets, from local to global. Global and climate changes interact (Fig. 1) in their effects on global ecosystems (72).

Identifying and quantifying the impacts of global and climate changes (123) on plant diseases is complex (20,118). A number of nonlinear relationships, such as the injury (epidemic)–damage (crop loss; 153) relationship, are superimposed on the interplay among the three summits of the disease triangle (host, pathogen, environment; 139). These relationships depend on (i) production situations (*sensu* Rabbinge and De Wit [103]—the ecological, social, and economic context where agriculture takes place), (ii) pathosystems, and (iii) the occurrence of other injuries to plants. Work on a range of pathosystems involving rice, peanut, wheat, and coffee has shown the direct linkage (Fig. 1A) and feedback between production situations and crop health (110). Global and climate changes influence the effects of system components on crop health (Fig. 1B). For instance, shifts in production situations (107) may accelerate, leading to a new crop health status; or the range of management options may decline because of changes in production situations; or again, adaptations to changes may generate new disease threats (because of, e.g., the introduction of novel crops). The combined effects of global and climate changes on diseases, therefore, vary from one pathosystem to another within the tetrahedron framework (humans, pathogens, crops, environment; 156) where human beings, from individual farmers to consumers to entire societies, interact with hosts, pathogens, and the environment. Figure 1 proposes a very simplified (16: Fig. 26.7, p. 770) view of a complex, networked (92) system, with an emphasis on man-made agricultural systems. Figure 1 attempts to distinguish the effects of global change from those of climate change, which we refer to as "indirect" and "direct", respectively, bearing in mind that both climate and global changes refer to sets of drivers that are not independent.

This article highlights international phytopathological research addressing the effects of global and climate changes on plant diseases in a range of crops and pathosystems. We first propose a typology of pathosystems that may help assess the importance of diseases in relation with the structure of Figure 1, and may help prioritize options for management. Challenges to address plant diseases under global and climate changes in the developing world are then briefly addressed. Third, a series of current research approaches are briefly presented. Fourth, outcomes of these methods on a range pathosystems are highlighted. Fifth, we propose an outlook of approaches and priorities to address the management of crop health in a changing developing world.

The following framework and the set of examples in this article indicate how progress is taking place, with several entry points of developing strategies that incorporate a number of different options, and how the harnessing of new methodologies will help better identify priorities, target research products, and enhance technology diffusion.

A Broad Typology of Plant Diseases and of Approaches to Manage Them

Drawing from the medical literature (64), we propose to consider plant diseases in three broad categories—chronic, acute, and emerging (Fig. 2)—using these terms in a way similar to public health medicine. We define the terms as:

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(i) chronic, a disease that occurs on a systematic basis over large areas, causing regular attrition in system performances, including reductions in crop yield;

(ii) acute, a disease that occurs irregularly, both temporally and spatially, and which, when occurring, may cause massive disruptions in system performances; and

(iii) emerging, a disease whose range is expanding to new areas.

Such a categorization is by no means intended to be prescriptive, i.e., a disease may belong to more than one of these categories, sometimes because of the very changes we witness today. Figure 2, for instance, shows that diseases can overlap among categories.

This categorization connects with the assessment framework for complexities developed by Garrett et al. (36), and may help problem identification and the development of solutions. One may propose that:

(i) the level of *biological interactions* is similarly variable across the three groups of diseases;

(ii) chronic diseases are less responsive to *climate variables across their range*;

(iii) diseases within each of the three groups are similarly variable in their *responsiveness to climate change*;

(iv) chronic diseases are often less variable in their *spatial variation*, whereas acute and emerging diseases show increasing levels of variability;

(v) chronic diseases are often associated with strong *feedback with crop and disease management*;

(vi) there is an increasing *discrepancy between epidemic and management networks* from chronic to acute, and to emerging diseases;

(vii) the three types of diseases may have similarly variable effects on *ecosystem services*; and

(viii) the three types of diseases may have equally variable *consequences on climate change*.

Again, the above eight assumptions should not be seen as prescriptive, chiefly because one disease may belong to more than one of the three groups (chronic, acute, or emerging). A series of pathosystems is considered in turn in this article to gauge these hypotheses and to show that generalizations can be dangerous. Yet the linkage between Figures 1 and 2 may provide useful insights for comparison.

Chronic diseases call for lasting solutions. While this applies to any disease, chronic diseases have to be managed every season. Chronic diseases further pose the challenge of often being persistent constraints in production situations where other yield-reducing and yield-limiting factors often occur. In this context, "lasting solutions" refer to control options that account for both a multiple-constraint environment and a limited range of control choices. Solutions for chronic diseases do not need to provide complete disease control, but rather lead to (i) limited crop losses, (ii) production of stable results that farmers can trust, thus enhancing technology adoption, and (iii) prevention of the occurrence of quality losses, including toxin accumulation, a recurrent public health issue (68) that hampers income generation for poor farmers. By contrast, acute diseases require much higher levels of control. These levels often should not be maintained for extensive periods, however. This is because (i) pathogens may adapt to the selection pressure created by these management options, which (ii) in turn may lead to negative externalities or hidden costs, such as pesticide mis- or over-use (138) or the use of less-preferred varieties by farmers under normal conditions. Emerging diseases represent the greatest difficulty. By definition, they lead to risk uncertainty over time and

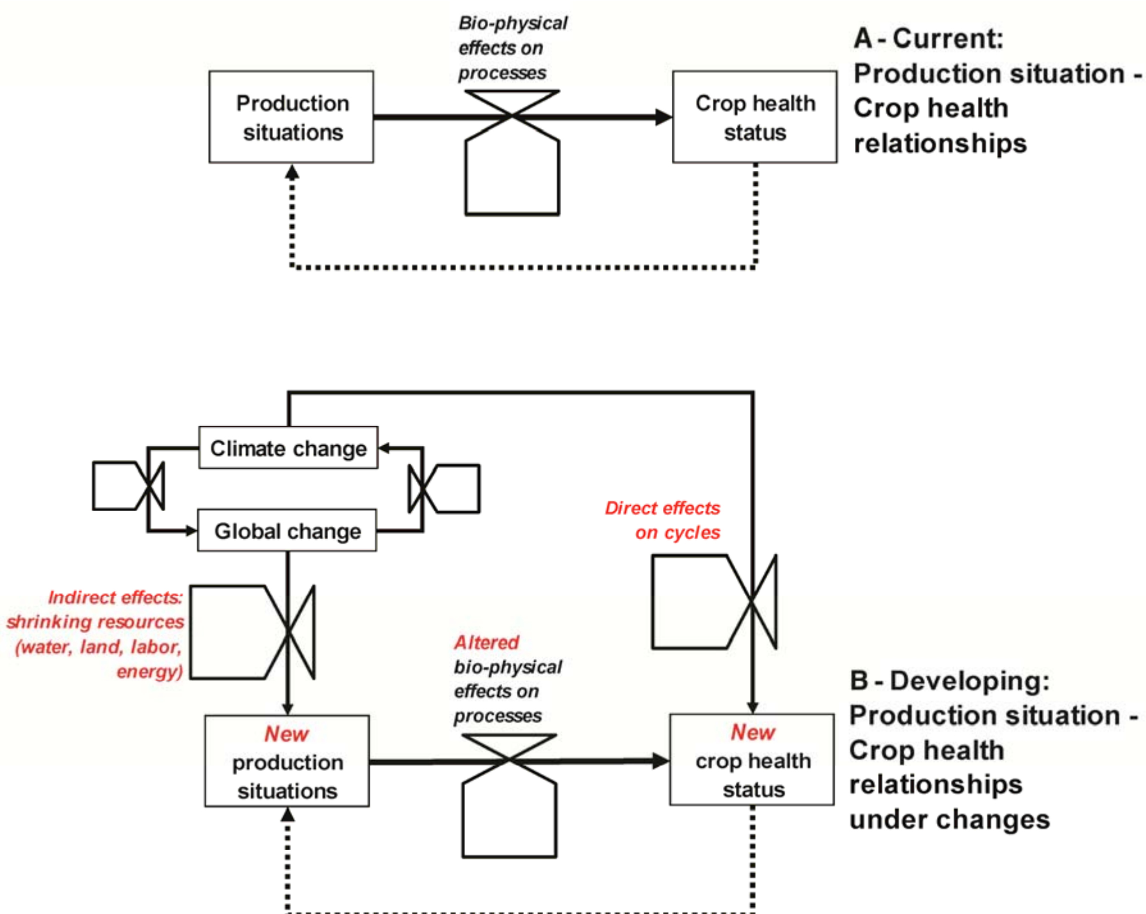

Fig. 1. A simplified representation of the effects of global and climate change on plant diseases. **A** Shows relationships between production situations and crop health (110), as demonstrated in a number of (multiple) pathosystems of rice in tropical Asia, peanut in West Africa, wheat in Western Europe, and coffee in Central America. **B** Illustrates in a simplified manner how the Production situation - Crop health association is affected, directly or indirectly, by the interacting global change and climate change (derived from 16).

space; and this very uncertainty, and the fear it generates, often lead to considering such problems as priorities.

An overview of international agricultural research suggests that the bulk of the efforts have been devoted to acute diseases (including bacterial blight and blast in rice, dry root rot in chickpea, and late blight in potato) and, in a more erratic manner, to emerging diseases such as stem rust of wheat, wheat blast, and Phytophthora blight of pigeonpea. By and large, it would seem that chronic diseases, such as brown spot in rice, wheat spot blotch, and maize ear-rot, have not received the level of attention they deserve (Fig. 2). One element to explain the emphasis given to acute diseases is that the key control option targeted by international research programs has often been to breed for complete resistance with major genes: this is because breeding for such types of resistance on huge numbers of entries was possible. Recently, paradigm shifts have taken place. For instance, CIP has implemented research toward durable

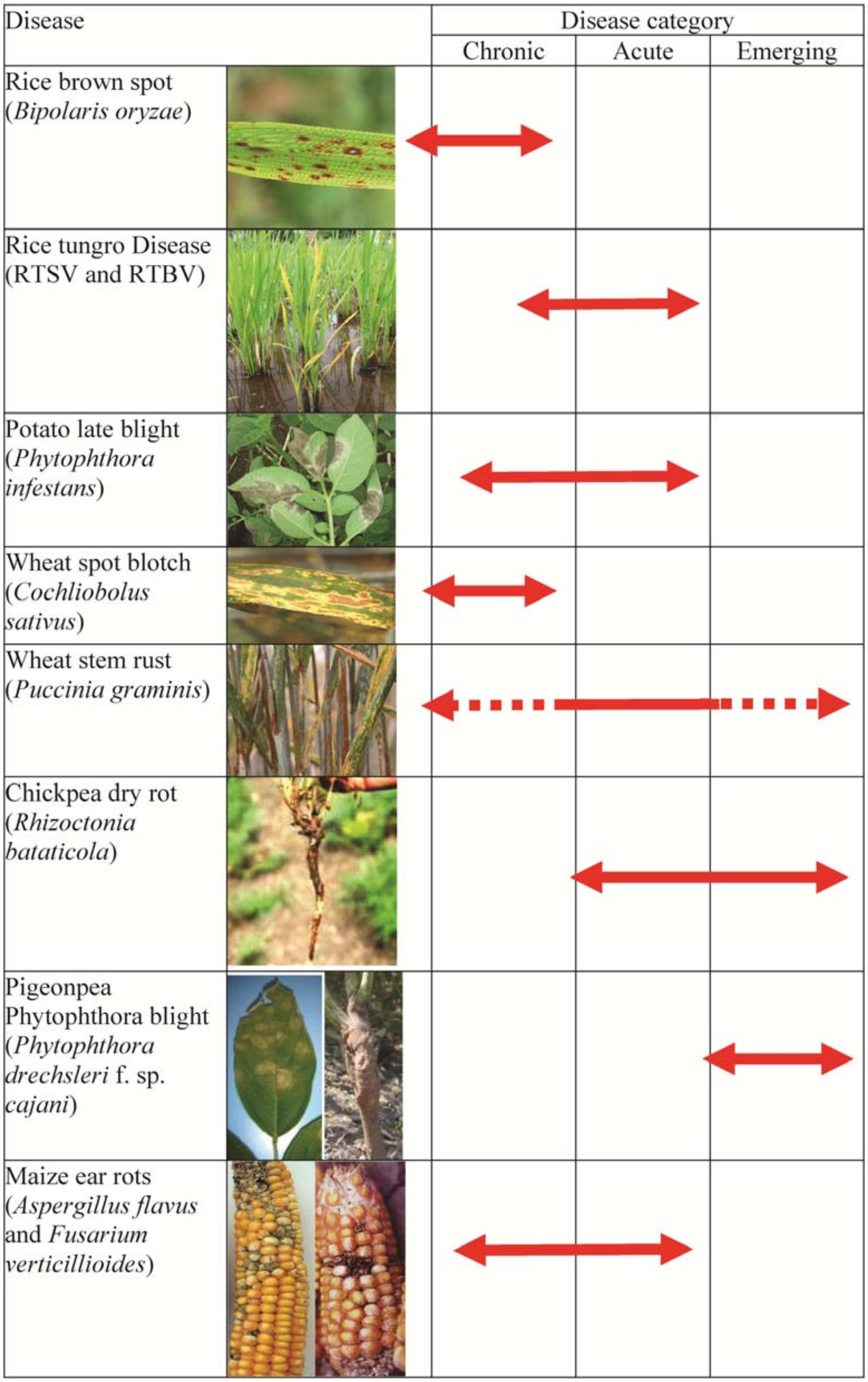

Fig. 2. Schematic categorization of some important diseases in the developing world on various key crops.

resistance to late blight based on partial resistance and careful genotype by environment (G × E) analysis (151). CIMMYT employs a similar multiple, minor genes–based adult-plant resistance approach for wheat rusts (119).

Challenges

Key challenges we wish to underscore are:

(i) Crop losses (yield and quality) caused by diseases amount to a double penalty: the "untaken harvest" (80), and the waste of resources invested in crops (inputs, labor, land, seeds, water, and non-renewable energy). The latter component of the penalty is not borne by farmers only, but also by communities, societies, and entire economies. Obviously, the less-developed world is more vulnerable to these two components.

(ii) The lag between research onset and product deployment by farmers is commonly 30 to 40 years (2,6,89,90). This stresses the need for forward-looking approaches enabling prioritization and problem-definition (58) frameworks to guide research.

(iii) Because of nonlinear relationships (39,51,52) and interactions (and thus emerging properties of pathosystems; 24,137) among the four elements of the disease tetrahedron, combined effects of climate and global changes on disease may have unexpected consequences. One analogy here is useful: climate change alone predicts global water demands that are quite different from those associated with climate change *and* human population growth combined (142).

So far, most plant pathologists addressing climate change effects on plant disease have focused on the direct effects of climate variability on single diseases (e.g., disease cycles, Fig. 1B). However, indirect effects triggered by climate and global changes, via shifts in cropping practices and their socio-economic contexts (Fig. 1B), are important, much more rapid (i.e., have relaxation times much smaller) than climate change–induced variation, and may become increasingly so in their effects on plant diseases.

Approaches

Simulation modeling. Simulation models are powerful tools to answer questions of the "what if…?" type (155) by assessing a system's responses to variation in its parameters or its driving functions (23). Thus, simulation modeling is an effective approach for addressing the impact of global and climate changes on crop diseases. Because they are process-based, simulation models can improve our quantitative understanding of the dynamics of epidemics or yield loss buildup. They are also useful for the formulation of strategies, management decisions, research priorities, and the analysis of future scenarios. Simulation models often mobilize detailed biological understanding and quantification of the processes involved, including the effects of weather (102). They are therefore suitable for studies of climate change effects on plant diseases.

Many weather-driven epidemiological models have been developed and used to predict plant disease epidemics under variable climatic conditions (26,108). In many cases, daily or hourly weather data (25) are used as model inputs to match the time step of the processes simulated (e.g., infection). Such high-resolution weather data are not, however, generated for climate change scenarios by current climatic models. Two approaches have so far been implemented to address this issue: (i) interpolation of weather data (150), and (ii) generation of high-resolution weather data from low-resolution weather data using stochastic weather generators (43,66). A third promising approach involves the development of metamodels (125,126).

Agrophysiological models simulating the physiological effects of disease injuries on crop and yield have also been developed for many crops (110,133), and this quantitative knowledge can be used to model yield losses under climate and global changes. Since a crop in general is exposed to several diseases, which often interact in their yield-reducing effects, multiple disease models can be used to predict the relative importance of diseases during a crop cycle, as well as the efficiencies of different crop health management strategies under future scenarios. Such validated models exist for two key crops on a global scale, wheat and rice (98,146–148).

Addressing both plant disease epidemics and their impact on crop losses can be achieved by coupling dynamic simulation models of epidemics with crop models (59,102). Such an approach has been advocated to analyze the effects of climate and global changes (133). The implementation of such models, however, requires (i) the availability of generic, simple models that can be modified for diverse production situations for use at a global scale, and (ii) coordination and standardization of collection of input data. Generic modeling platforms from collaborative international research, such as IBSNAT (8) and CROPSYST (127), can be considered as starting points. However, model simplification and testing (93) will be required to address large-scale future scenarios. In order to incorporate the human element of the disease tetrahedron (156), such as farmers' attitudes to risk in decision making (152), simulation modeling should preferably go beyond climate effects on crops and diseases. Modeling the disease effects of varying production situation components (109) in response to global change elements such as fallow period duration, fertilizer input, crop rotation, or water stress has not been addressed adequately, and should be emphasized in future research.

The relevance of simulation modeling has been questioned for not translating results into direct, field-based applications (11,143). The purpose of the approach we refer to here is strategic rather than tactical (153), and has shown progress in Europe and at CIP (40). New progress is underway where simulation models can become effective tools for technology targeting.

Ecological niche modeling. We need to anticipate invasion risks from both exotic and indigenous pests (61,129). Ecological niche models, or species distribution models, are powerful tools to predict future disease epidemics, and provide support for developing strategies against new threats.

Ecological niche models are defined here as correlative models that predict a species' potential geographical range based on two types of georeferenced data, biological data describing the species' known distribution (presence and absence) and environmental data that describe the landscape conditions where the species is found (33,94,140). A broad range of algorithms are used in these models. Because of their reliance on environmental data, e.g., climatic or weather data, these models are well suited to studies of the effects of climate change on plant disease, and exotic pest introductions.

The ability of ecological niche models to use limited data such as species presence and generic environmental data makes them complementary to simulation models. In many cases correlative approaches can provide a reasonable indication of high-risk areas for prioritization.

One may distinguish different classes of ecological niche models. Climate envelope models, which involve climate matching, have been used to create predictive maps of critical pests' risk. CLIMEX and NAPPFAST, for instance, have been used by plant pathologists for predicting plant disease occurrences. CLIMEX (130) exemplifies well these tools, and has been used by plant pathologists to predict the likelihood of pathogen establishment under current climatic conditions (95,99) or, more rarely, under climate change scenarios (97). NAPPFAST (North Carolina State University – United States Department of Agriculture [USDA] Animal and Plant Health Inspection Service [APHIS] Plant Pest Forecasting; 69) is a more recent model that was developed for rapid risk assessments, and has been used for first guesstimates of establishment risk for exotic pests (69).

Other model algorithms exist that have not been as widely used by plant pathologists, but could prove to be useful. The OpenModeller (77) software package employs several "plug-ins" or model algorithms used for ecological niche modeling in one package. This is useful for comparing the predictions of several different models or combining them into an ensemble model of species' ranges, which results in more robust forecasts (5).

The ecological niche model approaches discussed here currently can only utilize presence/absence and environmental information to predict disease risk at a specific geographic point, usually a grid cell in a geographic information systems (GIS) raster file. This makes ecological niche models useful for identifying current high-risk locations or interactions in future scenario analysis. Future challenges exist in analyzing the distribution of plant diseases. This departs from many ecological distribution model applications, because it involves (i) an interaction between at least one host and a pathogen species, (ii) pathogen reproduction, evolution, and dispersal, at extremely variable rates, and (iii) human intervention as a defining factor of agricultural systems. Thus, information about the spatial structure of host availability and the risk of disease buildup in neighboring areas are important features to assess risk at any given location (36,70,71). These effects should be incorporated into ecological risk models in a GIS to achieve a more complete picture of risk.

Geographic information systems and mapping disease risks. Uses of GIS in plant pathology implement early concepts developed by Weltzien (144,145). GIS brings about the possibility of overlaying, geographically, a wide range of very different information, whether pertaining to pathogens, hosts, and environments, as well as to socio-economic and infrastructural systems, such as road networks (and thus access to markets and inputs), or irrigation systems. The information can also be organized over time. The ability of the GIS to integrate such diverse data has resulted in its widespread application in agricultural sciences. GIS is commonly used to evaluate and model the spatial distribution of plant disease or to analyze relationships between environmental factors and plant disease intensity. Such information, when mapped together, creates a powerful tool for monitoring and management. Inclusion of geo-referenced socio-economic data can add important targeting and impact assessment information. The body of techniques associated with GIS has been instrumental in understanding, managing, and predicting public and animal health (42,96). The International Agricultural Research Centers were early users of GIS, with initial activities dating back to the early 1980s (15). GIS technology is increasingly applied to cover many different aspects of plant disease research and management. General approaches are highlighted using selected examples.

International disease networks, global germplasm collections, and extensive multi-decadal international trials all constitute rich data resources that can support geo-spatial analysis of plant disease. GIS can exploit these resources in diverse ways, from the perspective of disease resistance discovery, of disease monitoring, as well as for risk mapping and epidemiological purposes. Global gene banks can also be mined to maximize the likelihood of finding desirable traits involving the spatial predictions of areas where selection pressures may occur (e.g., disease-prone environments). For instance, Bhullar et al. (7) describe the utility of the approach for identifying new sources of resistance to powdery mildew in wheat.

Monitoring and forecasting of trans-boundary diseases relies on coordinated international surveillance networks. GIS provides a platform for data management of disease surveys, integrated analysis of dispersal, and risk assessment. Hodson and DePauw (44) describe the application of GIS for monitoring and risk assessment of new virulent races of wheat stem rust, whereby standardized global disease survey data are integrated with wind models, crop varietal distribution, crop phenology, and climatic data.

Climate-based probability mapping for plant disease or disease vectors using GIS has also received considerable attention. Customized software tools such as Floramap (53) have been used to determine climate probability models for important disease vectors such as whitefly (74). Coupling of disease forecasting models to climate databases within a GIS enables predictions that combine the spatial perspectives of GIS with the stronger representation of temporal processes of forecast models. Hijmans et al. (43) outline this GIS-linked model approach for potato late blight. Use of such climate-based, GIS-linked models facilitates exploratory analysis of likely distributional shifts under differing climate scenarios (125,126).

Use of GIS to determine spatially explicit disease management outcomes is another approach. Using GIS, Phytophthora blight (PB) caused by *P. drechsleri* f. sp. *cajani* was monitored in the major pigeonpea growing regions of the Deccan Plateau of India. GIS indicated that PB occurs on improved as well as local cultivars of pigeonpea, irrespective of soil types and cropping systems (84). Based on this information and historical weather and disease data over four decades, simulation of different disease management option outcomes, including host plant resistance, has been initiated.

Technology targeting. The importance of technology targeting for efficiently implementing disease management tools as global change and climate change unfold is highlighted with three contrasting examples.

Chickpea and pigeonpea are mainly grown in different cropping systems by resource poor farmers in harsh, climatically and economically volatile environments of Asia and Africa. Host plant resistance to diseases thus represents a primary research objective in such environments (84,85). In this context, research on the effects of climate and global changes on host–pathogen interactions is critical to develop durable resistances. Dry root rot of chickpea and Phytophthora blight of pigeonpea are two key examples. Epidemiological knowledge, combined with biophysical and socio-economical understanding, are then required to deploy resistances and achieve sustainable disease management.

Potato viruses represent another example of the potential use of modeling for technology targeting. Farmers throughout the highland tropics have traditionally produced seed at higher altitudes where vector populations are lower (135). As accelerated climate change in higher mountain ranges allows insect vectors to reach higher elevations, the virus-free (or virus-low) areas disappear. This has the double cost of pushing farmers up into ever-more fragile environments and, eventually, denying farmers seed production options. A logical solution to this problem is the introduction of potato cultivars with high levels of virus resistance. However, as noted, the lead-time needed for variety development to have impact, particularly in a vegetatively propagated crop, highlights the need for accurate identification of high-risk zones, as well as of low-risk zones, where potato seed production is feasible.

The toolkit for rice leaf blast management is another example, with three groups of tools: knowledge, physical, and communication tools (132). Rice varieties, whose resistances represent the pillar of the management of several major diseases (82), are part of the first group. The over-arching link between these groups of tools is a systems-based knowledge of blast epidemiology that incorporates elements as diverse as decision aides, cultural knowledge, and fungicide and fertilizer use. Technology targeting in this case is again strongly dependent, not only on biophysical (epidemiological, population genetics) information, but also on socio-economic understanding: the toolkit does not have only to be inherently effective; it also has to be adopted by farmers.

Ground truth. Ground truth, i.e., the actual measurements of disease in the field, their proper recording and processing, requires sufficient resources, including skilled manpower (49,56,131, 134,156). Much of this information, over space, i.e., over production situations as they evolve, as well as over time (50), used to be gathered by extension systems and national organizations, which cannot be replaced by international research.

Persistence pays (2,89): strong benefits can be derived from sustained support to the agricultural research and development sector. Yet the agricultural extension systems in many developing countries are weakening. This decline cannot be disconnected from global change: this is partly a reflection of policies, of different ways farmers are seen in their roles toward societies, and perhaps of a different way farmers see their roles themselves. Policy makers in particular often take crop health assessment, monitoring, and management for granted, despite the methodology, skills, and training required to generate the reliable information needed to make recommendations. Thus, extension systems are frequently transferred to local, e.g., provincial, authorities, often leading to reduced coordination and efficacy, which unfortunately coincides with increased demands for information and knowledge associated with adapting to climate and global changes. The process of diversifying production systems away from reliance on climate-sensitive or market-vulnerable crops or practices is very knowledge intensive, and formal extension services by themselves will not be able to meet the substantial knowledge and information demands. Overall, the financial resources allocated to the agricultural system have been shrinking (2,89), often under the assumptions that (i) the private sector would replace public services, and (ii) farmers would gain more autonomy, in part because of increased wealth, in part because of increased knowledge.

Extension systems are progressively declining in the developed world, too. However, while farming in, e.g., Western Europe, is an occupation chosen by few, farming is often the only option for the millions of resource-poor farmers in the developing world. Being a farmer in Western Europe implies considerable levels of training and leads to access to multiple sources of information, while farmers in the developing world still depend on their own knowledge and, in general, limited access to information. In a world of transition, insufficient information and inadequate training puts farmers in a weak position among the many stakeholders of agriculture.

This decline in ground truth intelligence results in extreme difficulties in several areas. One is difficulty in ensuring that proper measures are being undertaken when emerging disease problems occur, such as the yellowing syndrome of rice in the Mekong Delta (I. R. Choi, IRRI, *personal communication*). A second is difficulty in generating sufficient evidence to show that, in some instances, a crop health problem does not necessarily have the importance it is supposed to have according to some of the stakeholders of plant protection—including scientists. Lack of information leads to uncertainty; uncertainty leads to fear; fear leads to overreaction (154). A third is the use of blanket recommendations for pesticides, leading to pesticide misuse and abuse, as well as the erosion of decades of farmers' knowledge in managing crop health.

The following section highlights how ground truth is critical for advances in managing diseases under global and climate changes in the developing world. Ground truth represents the very fabric on which our research is based, against which we can test models, assess strategies, and measure *ex-ante* and *ex-post* impacts. Ground truth appraisal using a systems approach (e.g., for rice, 109,110,112) also enables progress in prioritizing the importance of diseases, their relationships with production environments, and technology targeting for disease management as global changes take place.

The following examples show how the problems faced, and the solutions envisioned, may differ. This is of course due to the wide differences among the considered pathosystems, but also, and perhaps more importantly, to the social and economic backgrounds where agriculture takes place in the world's ecoregions. Depending on the latter group of reasons, rather than the former, the impact of global and climate changes on the importance of diseases, and on the relevance of solutions, vary.

Selected Examples of Outcomes

Rice. Rice diseases may be chronic (such as brown spot; Fig. 2), acute (such as rice blast or rice tungro disease), or emerging (such as the rice yellowing syndrome, which develops in the Mekong Delta [I. R. Choi, *personal communication*]). Climate change effects on rice diseases and pests have been carefully studied for a few pathosystems (133). Much of this work has focused on specific diseases, aiming in particular at analyzing the effects of climate change components on specific disease cycle phases in given pathosystems (55) and modeling the effects of climate change on risk probability (epidemics) or risk magnitude (yield losses) using generic crop growth models such as ORYZA or CERES-Rice. One early effort is exemplified by the development of BLASTSIM, a simulation model for leaf blast epidemics (12). This paved the way toward two directions. First, epidemics of leaf blast under climate variability were addressed by combining BLASTSIM to a climate data generator in a GIS. Thus, blast epidemics were simulated at 53 locations in Asia representing a range of agroecologies (66). Second, BLASTSIM was coupled to CERES-Rice and weather generators in a GIS to assess yield losses associated with rice blast (67). Efforts in modeling yield losses also led to a CERES-Rice based model enabling addressing the effects of blast, weeds, and defoliators in isolation or in combination (98).

Further research concerned the characterization of injury profiles (diseases, animal pests, and weeds) and production situations (cropping systems, crop rotation, and management) in the tropical and subtropical lowlands of Asia (112), which roughly account for 90% of Asia's and 80% of the world's rice output. This risk probability analysis was complemented by an experimental risk magnitude study where yield losses caused by injury profiles in a range of production situations corresponding to attainable yields varying from 1 to 10 t ha^{-1} were analyzed (111). This enabled the development of RICEPEST, a simple, generic, production situation–specific yield loss model (147). RICEPEST represents a tool to set research priorities in plant protection for rice. Beyond considering only yield losses, this model further allows one to consider yield gains accrued from new plant protection technologies, alone or in combination. One important outcome from this research is that disease syndromes were shown to be strongly associated to production situations (112) and by drivers of agricultural change (water stress, labor shortage, reflected by a shift from transplanting to direct-seeding crop establishment; 108). Thus, risk factors for syndromes of injuries attached to production situations as wholes, or their components, can be derived (109). Importantly, variation in these components of production situations depends on global change, climate change, or both.

New steps are underway. One is the recent development of EPIRICE (S. Savary, I. B. Pangga, J. Aunario, L. Willocquet, and A. Nelson, Crop Prot., in press), a generic epidemiological model for fungal, viral, and bacterial diseases that accounts for different levels of hierarchy in a crop canopy (leaves, sheaths, entire plants) depending on the nature of the disease. EPIRICE has been parameterized for five major (Asian) rice diseases (brown spot, leaf blast, bacterial blight, sheath blight, and tungro), and has been linked to a GIS to simulate potential epidemics (Fig. 3). Another step will be to link RICEPEST to a GIS in order to develop global simulated risk magnitude maps. Critical to the success of these new steps will be the acquisition of geo-referenced ground truth data. These different simulation modeling, statistical modeling, and GIS approaches can be combined to develop scenario analyses, where the best control tools can be determined, based on biophysical and socio-economic contexts. The biophysical and socio-economic contexts, in turn, will define domains where strategies may be deployed.

Wheat. Two wheat-based pathosystems illustrate very different paths of relationships of Figure 1, and extreme examples of the categories of Figure 2, with one chronic disease and a group of diseases that belong to the acute–emerging groups.

Spot blotch, caused by the hemibiotroph *Cochliobolus sativus*, is the main chronic disease affecting resource-poor farmers in marginal lands, in warmer wheat growing regions where relative humidity and night-time temperature are high (9,115). Such conditions prevail in parts of Brazil, as well as in the vital rice-wheat system of the eastern Gangetic plains, where the disease is recurrently severe. Spot blotch intensity depends on crop physiology, and thus on environmental factors, including soil fertility (low N and K in particular), water supply, and heat (104,113,114). In South Asia, the optimum wheat growing period ranges from the second half of November to March–April. Any delay in wheat sowing (after rice) increases the risk of crop exposure to heat stress (i.e., warmer night-time temperatures) at critical growth stages. This stress, if associated with the physiological switch from vegetative to reproductive, increases the susceptibility to spot blotch in late sown crops (115). Thus, while the areas for optimum wheat cultivation in South Asia are expected to decline in the future (45) as a result of changing climate, yield losses to spot blotch are expected to increase (115). Improved crop management provides spot blotch control. Thus, breeding for resistance combined with good crop husbandry are the main components of an efficient integrated management of the disease (27). Wheat spot blotch shares many similarities with rice brown spot (*Cochliobolus miyabeanus*): brown spot depends heavily on crop physiological predisposition and mainly occurs in poor soils (lacking K and/or N) when drought occurs (82). As in spot blotch of wheat, good crop husbandry and improved water supply contribute to disease control. Parallel epidemiological analysis and syntenic modeling of the two diseases could enable the definition of joint parameters for breeding for resistance and disease management. Changes in cropping practices, including reduced tillage (wheat) or direct seeding (rice) to avoid heat stress, adaptation to declining agricultural labor, and optimization of resources (water, energy) will affect these diseases on the two crops. Strategies to address these shifts in disease importance do not differ and call for similar management options.

The spread of obligate wheat rust (*Puccinia* spp.) pathogens depends on large numbers of propagules being dispersed over large distances onto suitable hosts. Globalization increases the risk of accidental introductions, while increased severity at a given location increases the probability of windborne movement and the emergence of new virulences. Yellow rust, for instance, has been shown to adapt to warmer environments (73). Further, the movement of the *Yr*9-virulent race of *P. striiformis* from the East African highlands from 1985 to the Indian subcontinent (Nepal, 1997) exemplifies the spread of the disease associated with the "western disturbance" weather system (78). Earlier, virulence for the *Yr*2 gene had been first recorded in Turkey and traced to Pakistan

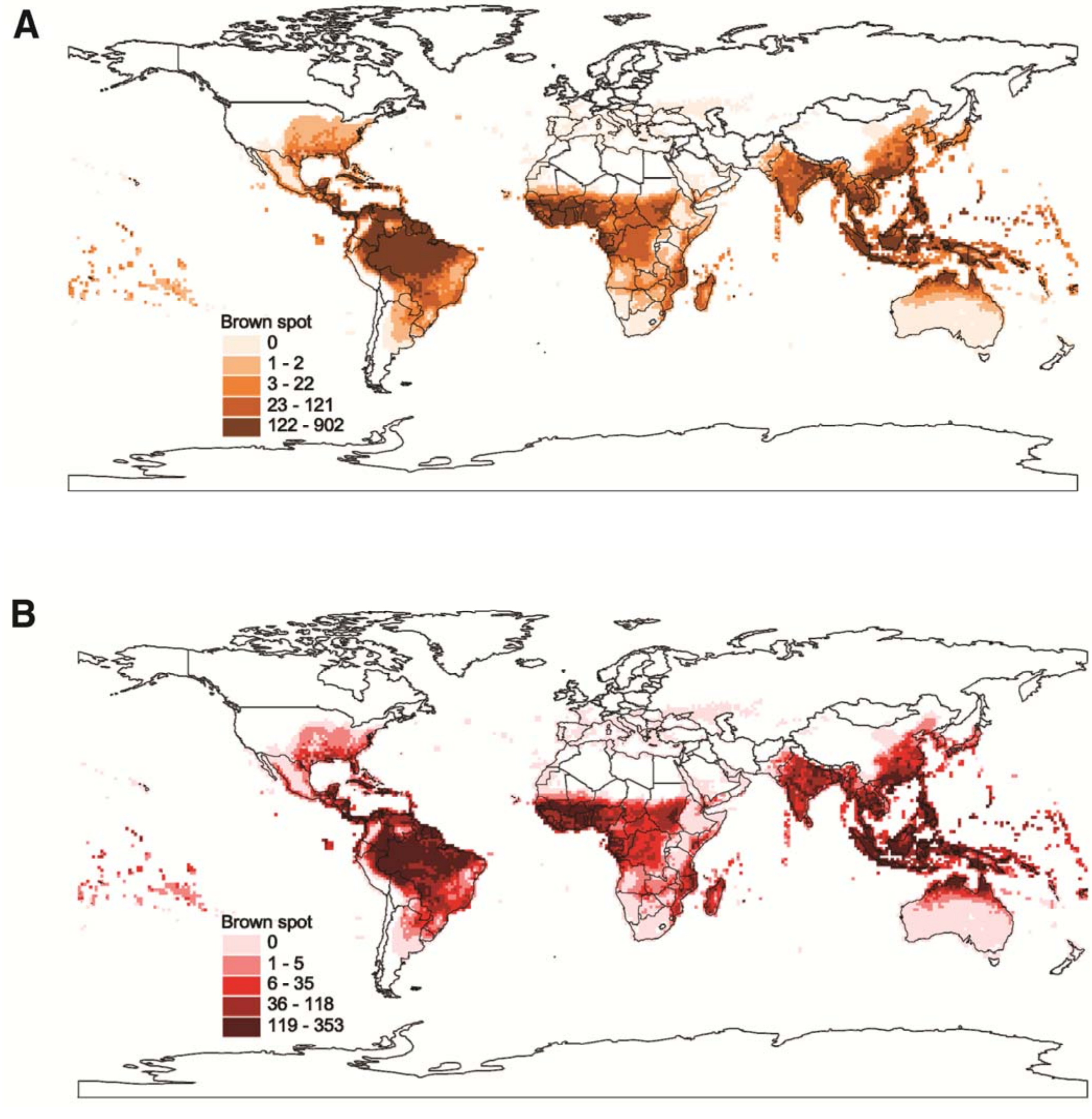

Fig. 3. Simulated global maps of potential rice brown spot epidemics. **A,** Mean areas under potential disease progress curve (AUPCs) of disease severity on leaves in %.days simulated using EPIRICE using global daily climate data and crop establishment dates over cropping seasons averaged over 12 climatic years (1997–2008). **B,** Standard deviation of AUPCs of potential brown spot epidemics.

(121). These examples suggest that Asia's entire wheat area, except perhaps China, consists of a single epidemiological zone, which is of even greater concern when considering that genetically uniform "megacultivars" cover most of the area grown to wheat (28). The emergence of a *Sr*31-virulent strain of stem rust (*P. graminis* f. sp. *tritici*), typified by race TTKSK (Ug99), triggered international concern, since commercial cultivars are strongly susceptible (119,120). Anticipating the spread of new virulent pathotypes and preparing the replacement of existing varieties for resistant ones in vulnerable wheat-growing regions such as West and South Asia is a priority. GIS tools are increasingly used to integrate factors determining likely spread (44). The combination of improved crop distribution and biophysical data at high spatial resolutions also enables exploring scenarios for disease risk (45). Increased availability of near real-time daily weather data should further improve predictions, as well as enable region-scale modeling of dynamic processes such as disease progression or crop water status (45). A dedicated web portal (Rust SPORE) and associated tools, e.g., RustMapper (19), provides up-to-date information on the current status and potential spread of Ug99 and its derivatives. Continued investment in disease and environmental monitoring, development and deployment of durable resistant varieties, and effective seed multiplication and delivery systems, will be required to address both current and future challenges posed by wheat rusts.

Potato. Potato late blight typifies the acute disease group, yet with areas where it must be considered a chronic disease (Fig. 2). The total losses to potato late blight caused by *Phytophthora infestans* alone were recently estimated at nearly $US 13 billion (10 billion Euros) in developing countries (41). The management of late blight is particularly difficult in the tropical (and subtropical) highlands because in these areas potatoes are produced year-round and disease is generally present at all times (32). Therefore, farmers must protect plants from emergence to harvest. Traditionally, farmers have used a number of approaches to control late blight, including planting mixtures of genotypes (136) and planting more susceptible cultivars at higher altitudes. The latter practice is efficient because higher altitudes correspond to lower disease risk, since disease severity is reduced by low temperatures (57), as in the case of the high-altitude production areas in Peru that were virtually blight free until recently. Because of rising temperatures, however, some high-altitude communities have recently seen late blight for the first time, with devastating results (W. Perez, *personal communication*).

The primary adaptation components include a more frequent use of resistant cultivars and increased disease management know-how among farmers. The International Potato Center (CIP) and its partners in developing countries have identified a number of potato genotypes that provide levels of resistance to *P. infestans* that greatly reduce the need for fungicide application. The challenges that remain include the identification of particular genotypes that fit local conditions and needs (particular markets or subsistence needs) and then multiplication and diffusion of these selected materials. The latter is hindered by the low multiplication rate of potato and by the absence of structured seed systems in developing countries (135). Farmers need to understand basic epidemiological concepts to enhance host resistance and fungicide efficiencies. Capacity building is therefore critical for successful management strategies (4,81).

CIP has been working on risk assessment related to the effects of climate change on late blight for nearly a decade. The initial approach has been to use technology based on simple decision rules run within a GIS to display potential late blight risk (43). This work has evolved more slowly than initially hoped, especially because of the mismatch between available climate data and model requirements. The initial plot-level forecasts for risk require hourly temperature and humidity data, while data available from global climate models are spatially and temporally much coarser (126). Work is underway to downscale climate change data to finer resolutions. A more recent approach is to calibrate disease risk models for coarser resolution input weather data using metamodels (125).

The potential is strong for climate change modeling of late blight risk for several reasons. First, late blight is highly weather driven (31). Second, in addition to the nascent spatial modeling indicated above, there is extensive experience on plot and plant level simulation modeling and a good understanding of disease epidemiology. Finally, spatially specific aerobiological models have been developed and validated (122).

Maize. Maize, the staple food for millions in Africa, Latin America, and Asia, is mainly produced under rainfed conditions, making it vulnerable to climate variability and rainfall patterns (46,47,79,124). We especially focus here on one major group of chronic (Fig. 2) maize diseases, which lead to mycotoxin contamination, because this group of diseases is expected to strongly respond to climate change (68,91), and because of the public health problems they entail (34,105).

Maize ear rots are caused by a range of fungi, among which *Fusarium graminearum*, *F. verticillioides*, *Aspergillus flavus*, and *A. parasiticus* are the most important (14). Under suitable conditions, *A. flavus* and *A. parasiticus* produce aflatoxin, *F. verticillioides* produces fumonisin, and *F. graminearum* produces deoxynivalenol (DON) and zearalenone (ZEA) that render maize unsafe for human and animal consumption (14). Production of toxins may take place prior to harvest, but in many cases, it increases after harvest under favorable postharvest conditions.

Maize ear rot fungi are widely distributed in the tropics, but can occur anywhere in food systems. Increases in temperature might result in a shift in the distribution range of mycotoxin-causing fungi and the types of mycotoxins they produce, because of the specific ecological requirements of each mycotoxin-producing fungus (13,101). Increased temperatures and occurrences of droughts may for instance lead to geographical displacement of *F. graminearum* by *F. verticillioides*, translating into a shift from deoxynivalenol and zearalenone to fumonisin.

Environmental conditions adverse to the plant (such as drought, high temperatures [106], soil nutrient deficiency, or animal injuries [62]) have been shown to favor infection by *A. flavus* and *F. verticillioides*, and mycotoxin accumulation (22). The *A. flavus* population increases during hot dry weather, resulting in increased aflatoxin contamination. The case of acute aflatoxicosis in Kenya in 2004 is well documented (63,128). Insects may also (i) act as vectors (larvae spreading spores from kernel to kernel), (ii) provide ingress into kernels, and (iii) predispose the plant to infection (76). Insect injury depends, in turn, on both crop management and climatic conditions.

Therefore, the mycotoxin problem requires considering a series of interacting components: (i) pathogens, (ii) epidemics, including spread by vectors, (iii) toxin production, (iv) crop status, and (v) storage environment, all of which are influenced directly or indirectly by global change or climate change. The need for strengthened research to reduce infection by toxin-producing fungi and the accumulation of toxins during storage should involve a systematic monitoring of mycotoxins-producing fungi, particularly in high-risk environments, linked to geo-referenced mycotoxin and climatic data, in order to better predict health risks from mycotoxin contamination.

A general lack of information among farmers, extension specialists, and policy makers in most developing countries on the causes of mycotoxin contamination is slowing progress toward minimizing the burden of mycotoxins. Capacity building of stakeholders in languages they can understand is needed for successful management of mycotoxins.

Legumes. The many diseases of legumes in the developing world may be illustrated by dry rot of chickpea as an acute–emerging disease and by Phytophthora blight of pigeonpea as an emerging disease (Fig. 2). Models addressing legume diseases in the tropics have not so far emphasized the effects of climate and global change. However, weather-dependent models to predict the development of legume diseases such as Ascochyta blight and Botrytis gray mold in chickpea have been developed to provide sounder bases for fungicide use (86).

Increased heat and drought stress and monsoon shifts in South Asia tend to push legume production toward more marginal lands, where management options are fewer. Climate change alters the spectrum of diseases in terms of pathogen distribution and virulence and appears associated with the emergence of new pathotypes. For example, with increased temperature and more frequent moisture stress, Rhizoctonia blight is becoming more intense in typically tropical-humid areas, while viruses and rusts dominate in warm but dry zones. Data collected in India from 2000 to 2010 show higher incidence of dry root rot (*Rhizoctonia bataticola*) in chickpea varieties that are resistant to Fusarium wilt in years when temperatures exceed 33°C (84,116). This is consistent with greenhouse experiments where different soil moisture levels and temperatures were manipulated, showing that *R. bataticola* infected chickpea plants and caused dry root rot faster at 35°C with soil moisture levels less than or equal to 60% (116). By contrast, cooler temperatures and wetter conditions are associated with increased incidence of stem rot on soybean (*Sclerotinia sclerotiorum*), blights in chickpea, lentil, pigeonpea, and pea, and anthracnose (*Colletotrichum* spp.) in lentil and chickpea (85,87,149). Recently, studies indicated that the epidemic of Phytophthora blight of pigeonpea (*Phytophthora drechsleri* f. sp. *cajani*) in India over the last decade can be attributed to high intermittent rainfall (>300 mm) within a week during the crop season (85,117).

It is critical that there be progress toward pro-poor, environmentally neutral, host plant resistances, as well as toward drought tolerance in chickpea (ICRISAT), beans (CIAT), and cowpea (IITA) (1,37), combined with systems-adapted integrated disease management technologies.

Outlook and Conclusions

Despite, or because of, the close interaction between climate change and global change (Fig. 1), far too little research has addressed the effects of the latter on crop health. Global change may affect crop health in quite different ways depending on the type of disease considered (Fig. 2). This is because global change entails different networked relationships (75,92) in influencing disease increase (or suppression) and impact, depending on whether a disease is chronic, acute, or emerging. The network theory and its approaches (75,92) offer a fresh, novel, and probably useful way to consider such relationships. This is even more important when one considers that chronic, acute, and emerging diseases will predominantly call for strategic long-term, strategic short-term, or tactical (110,153) decisions, respectively. Thus, different elements are likely to play different roles in a hierarchical network of stakeholders, including farmers, advisors, farmers' communities, retailers, consumers, policy-makers, and research planners.

In addition to the network theory, this article touched upon only a sample of methods to analyze and interpret data, including simulation modeling, ecological niche modeling, and GIS. These methods may lead to applications, if they are shared by a suitable range of disciplines, whose linkage will determine the level of relevance of plant protection in the years to come. These methods offer, to varying degrees, opportunities for interdisciplinary work and impact, as this article illustrates.

Never have there been so many new methods available for plant pathologists to analyze data. However, the availability of ground truth data on crop health will soon become a serious issue: the collection of systems-based, holistic data remains the keystone toward progress to understand and manage constantly evolving pathosystems. Effective disease management depends on these combinations of resources, methods, and disciplines. We believe that such combinations exist, with massive benefits toward food security in a biosphere shared by seven billion humans.

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