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Edited by W. M. Scheld, M. L. Grayson, and J. M. Hughes
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Chapter 18

Emerging Infectious Plant Diseases

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Healthy plants are essential to the survival of humans and animals on earth. Solar energy, absorbed by chloroplast pigments, is converted by photosynthesis into chemical bond energy of "energy currency" molecules such as glucose. Moving along the food chain, the once-solar energy is passed from plants to other living beings, fueling their activity and reproduction. Other living beings are inextricably dependent upon this process, whether they are herbivores, carnivores, parasites, scavengers, or decomposers. Furthermore, plants also serve as major global sources of fiber and structural materials. Biotic stresses reduce the health, yield, and nutritional value of plants and plant-based products. QU2

The purpose of this chapter is to provide insights into the types of biotic threats to plants, the nature of the U.S. plant health infrastructure, the resources available to address and mitigate losses due to emerging plant diseases, and whether they arise as a result of the arrival of exotic pathogens, the mutation of endemic pathogens, or the intentional dissemination of pathogens by perpetrators wishing to cause harm.

OVERVIEW OF PLANT PATHOGENS

Pathogens of plants, like those of animal and human hosts, belong to a number of different taxa including fungi, oomycetes, bacteria, viruses, nematodes, protozoa, and even parasitic plants. Although the most extensively studied pathogens are those causing disease

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on staple crops (i.e., wheat, corn, soybeans, rice, and potatoes), pathogens attack virtually all plants, including those cultivated for ornamental purposes and those in natural ecosystems such as forests and rangelands.

Types of Plant Pathogens

Fungi

Of all plant pathogens, fungi are responsible for the greatest damage to plants in both agricultural and natural ecosystems. Fungal plant pathogens often have complex life/disease cycles involving multiple (as many as five) phases, each of which occurs on a different plant host and is characterized by different reproductive strategies. The fungal spores or propagules produced at each phase each have unique propensities and mechanisms of dissemination and host infection. Most fungi exist as threadlike hyphae made up of cells surrounded by chitin-rich cell walls. These organisms produce enzymes and use physical pressure to create entry points through which the hyphae may invade plant interiors, where they colonize and usurp plant nutrients. Fungal genomes are diploid at most life cycle phases, although some stages and propagules are haploid. Fruiting bodies include the familiar mushroom-like organs in the Basidiomycetes, cup-shaped structures in the Ascomycetes, and simple multitipped stalks in the Fungi Imperfecti.

Oomycetes

A specific microbial group known as the Oomycetes, formerly classified as fungi, are now known to be more closely related to algae than to true fungi, having cell walls that lack chitin. *Phytophthora infestans*, the causal agent of the infamous disease late blight disease of potato in the devastating famines of 19th-century Ireland, is an oomycete that is credited with one of the largest human migrations in recorded history.

Bacteria

Many bacterial pathogens of plants, including members of the genera *Pseudomonas* and *Xanthomonas*, have epiphytic phases in their life cycles in which they form colonies on plant surfaces. Only when conditions become favorable do they enter the plant interior, often through stomata or lenticels, and initiate disease. Other bacterial pathogens, such as the wall-less spiroplasmas and phytoplasmas, and the agents of Pierce's disease of grapevines, are introduced directly into host tissues via plant-feeding insect vectors. Unlike fungi, which enter plants through direct penetration, bacteria require a natural opening, wound, or insect feeding site to enter plant tissues. Also unlike fungi, bacteria are prokaryotic, their cells lacking internal, membrane-bound organelles and haploid genomes. Bacteria can, and often do, exchange genetic material, making them remarkably adaptive to changing environments.

Viruses

Like human or zoonotic viruses, plant viruses are noncellular and consist of protein-coated nucleic acid, but the genomes of most plant viruses are composed of RNA rather than DNA. Viruses cannot live or replicate outside a susceptible host. Many plant viruses are insect transmitted, and the epidemiology of these pathogens is dependent upon the range and behavior of the specific insects that disseminate them.

Nematodes

Nematodes are microscopic worms that live in soil. Some of them cause disease in plants either by puncturing the plant cuticles with their stylets to feed or by physically invading the

plant's interior spaces, where they stimulate plant cell division, resulting in cysts or galls. In either case, they vie with plant cells for nutrients and fluids.

Protozoa

Although only a few protozoa are recognized as being pathogenic to plants, some, such as *Phytomonas* spp., cause serious impacts. Members of this genus inhabit the xylem vessels of palms, causing a wilting disease. The impacts of this disease are severe for tropical countries in which coconut palms are a significant economic industry both for fruit production and for tourism.

Parasitic Plants

Interestingly, plants can be attacked by certain other plants. Both mistletoe and dodder are flowering plants that survive by sending water- and nutrient-absorbing, flexible haustoria into the phloem of host angiosperms.

The Disease Triangle

The "disease triangle" that characterizes all plant diseases (Fig. 1) consists of (i) a susceptible plant, (ii) a virulent pathogen, and (iii) a conducive environment (1). Without all three components, disease will not occur.

Plant diseases can be categorized into several types based on symptoms: leafspots, wilts, cankers, declines, abnormal growth (witches' brooms, asymmetrical flowers, and adventitious roots, etc.), reduced yield, dieback, chlorosis, necrosis, and soft rot, etc. They may occur in the field or in storage (pre- and postharvest).

Hosts and Commodities

The majority of, if not all, known higher and lower plants have pathogens that attack one or more plant organs at various developmental stages. Many thousands of plant diseases have been described in the literature.

The best-characterized pathogens are those of field crops. Diseases of cereal grains, particularly wheat, are described in historical texts dating to late antiquity. Because human

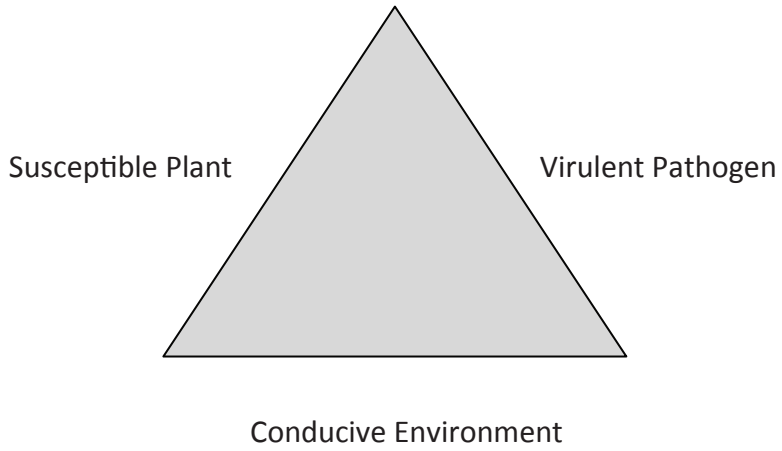

Figure 1. The plant disease triangle.

existence has depended upon the annual success of staple field crops since the invention of agriculture, failures due to disease spurred description and scientific inquiry to mitigate losses. Wheat stem rust (caused by *Puccinia graminis* f. sp. *tritici*) (13) and potato late blight (*Phytophthora infestans*) (28) provide two examples of the power and impact of crop diseases on society. Globally, diseases of cereal grains (wheat, rice, and maize), tubers (potato, cassava, yam, and taro), and vegetable crops (dry beans, peas, lentils and other legumes as well as cabbage and other brassicas) have affected human populations, and many continue to take their toll on production, particularly in underdeveloped countries lacking infrastructure to detect and mitigate diseases.

Diseases of fresh vegetable and fruit crops, depended upon to supplement staple diets with essential vitamins such as vitamin C to prevent scurvy, also have played a significant role throughout history. Many diseases impact crops in the field, but pathogens and toxin-producing organisms also affect grain (seeds) tubers or partially processed plant components in storage. For example, fusarium head scab of wheat (*Fusarium graminearum*) can decrease yield and quality from infection in the field and also produces mycotoxins amplified in storage (33). Other "molds," such as *Aspergillus*, can spoil grain in suboptimal, humid storage conditions and produce mycotoxins as well.

Huge markets exist for international trade of live ornamental plants. Flowers and other ornamentals include a wide variety of plant species that host a multitude of diseases. The movement of commercial ornamental propagation activities to tropical offshore facilities has generated new pathways for movement of exotic plant diseases into the United States. For example, *Ralstonia solanacearum* race 3 biovar 2, a serious pathogen of potato and tomato designated a "select agent," was introduced into the United States in 2003 on propagated geranium plants (15) from Central America and again in 2004 from West Africa, causing growers to destroy their inventories. Because plant pathologists and regulatory authorities were concerned that the pathogen would threaten U.S. potato (60) and tomato production if it escaped from nursery facilities, geranium growers who had received infested shipments were directed to destroy their inventories.

Plant breeders apply classical genetic and molecular approaches to develop new varieties and cultivars resistant to the most prominent and damaging diseases. The 1999 reemergence of a novel wheat stem rust *Puccinia graminis* f. sp. *tritici* strain Ug99 in Uganda, which overcame established resistance genes after centuries of breeding for disease resistance, provides a humbling example of the capacity of pathogens to mutate in response to selective pressure, acquiring new virulence traits and overcoming resistance genes (31, 32, 57).

U.S. and Worldwide Plant Pathology Research Infrastructure

With the exception of basic studies on model organisms and pathosystems, most research on plant pathogens is conducted in response to stakeholder problems and needs of a specific crop or commodity and is concentrated in regions where the economic and social value of the crop is sufficient to justify and sustain funding from federal, state, and/or private sources. At the federal level, United States Department of Agriculture (USDA) agencies (the Agricultural Research Service [ARS] and the U.S. Forest Service) conduct in-house research and support basic and applied plant pathology research through formal (National Institute for Food and Agriculture [NIFA], formerly the Cooperative State Research, Education, and Extension Service [CSREES]) and informal (Animal and Plant Health Inspection Service [APHIS])

extramural grants programs. Basic research on plant-microbe interactions is also funded by the National Science Foundation and other funding sources. Individual states fund plant pathology research at land grant universities (LGUs) in various academic departments (plant pathology, microbiology, horticulture, and agronomy, etc.). In addition, Cooperative Extension Service (CES) personnel conduct applied field research and provide advice directly to producers and serve as first responders to pathogen outbreaks.

Research at state Department of Agriculture (SDA) laboratories often addresses diseases and pathogens specific to the state's climate and commodities. Several large commodity groups, representing the agricultural production sector, collect "checkoff" funds from growers to support research on pathogens attacking that commodity, and seed companies monitor and conduct research on plant pathogens emerging in the United States as well as in countries where offshore nurseries are used to generate seed for subsequent planting in the United States.

Research abroad is funded by various sources, depending on the degree of development of the country and its agricultural research support infrastructure. Western Europe, China, Japan, Australia, South Africa, and India have long traditions of state-supported plant pathology research and have contributed significantly to global knowledge of plant pathogens that have emerged and spread from their origins to other parts of the world over the past century. The international germplasm centers (the Consultative Group on International Agricultural Research, the International Institute for Tropical Agriculture, the International Crops Research Institute for the Semi-Arid Tropics, and the International Rice Research Institute) were established in the 1950s with funding from the Rockefeller Foundation, World Bank, Food and Agriculture Organization of the United Nations, International Fund for Agricultural Development, and United Nations Development Programme to breed and develop staple crop cultivars best suited to the climate and pathogens indigenous to specific regions, delivering the "Green Revolution" (a term first coined by Nobel laureate and plant pathologist Norman Borlaug) to developing countries. Although their research support has waned considerably over the past two decades, these germplasm centers still make major contributions to global disease reporting, development of disease-resistant cultivars, and the conduct of basic and applied studies of pathogens emerging from developing countries.

PATHWAYS AND GLOBAL SPREAD OF PLANT PATHOGENS

Overview

Plant pathogens can be disseminated by many different mechanisms and pathways. Short-distance movement (plant to plant, soil surface to plant surface, and soil reservoir to root surface, etc.) is involved in local disease development and area affected, while long-distance spread (field to field, transregion, cross-country, or international) has much broader implications not only on crop production but also on political and economic issues. Most pathogen dissemination, of course, is natural. Microbes have evolved over centuries to assure their own survival—which necessarily involves encountering new susceptible host plants. Natural means of spread include weather, biological features such as aerodynamic spore morphology, the involvement of biological vectors, moving water, and even being borne on seeds or pollen, which are adapted for their own dissemination. These mechanisms, and their implications for disease epidemiology, are discussed in more detail below.

Epidemiology of Spread

The type of pathogen, i.e., fungus, bacterium, virus, nematode, etc., greatly affects dispersal and the subsequent patterns of disease in a crop system. Some pathogens have multiple dispersal systems. For instance, in fire blight of rosaceous trees, caused by the bacterium *Erwinia amylovora*, the bacterial ooze emanating from branch infections can be dispersed by rain splash or by honeybees, causing floral infections. Fungal pathogens have especially diverse dispersal mechanisms, some moving aerially as dry spores, others being splash dispersed to nearby plants or incorporated into droplets that can be carried great distances. Other fungal spores hitch rides on insects, birds, bats, or other mammals. Fungal pathogens that have multiple spore types use different dispersal mechanisms at different points in their life cycle. Viruses can be moved mechanically by abrasions, grafting, vector insects, and even vector fungi. Methods of pathogen spread that are influenced by humans, in contrast, include import/export of commodities and ornamental plants, illicit smuggling of foods and plants, inadvertent contamination of travelers' clothing or belongings, economic sabotage, and bioterrorism. Commonalities exist among dispersal mechanisms. Any propagule incorporated into water droplets will be subject to the physical properties of particle dispersal, given the same meteorological conditions, and could result in similar initial crop disease patterns. However, two pathogens having different dispersal mechanisms (such as vectored versus nonvectored) are unlikely to have the same dispersal patterns. Such knowledge can be used for disease control and mitigation. However, the initial inoculum concentration at the source, the unique meteorological conditions causing transport to and deposition on the crop, the topography of the land being traversed, and the topography and susceptibility of the newly infected crop differ greatly from one pathosystem to another and even one epidemic to another. Each of these initial, transient, and terminal conditions affects the success of pathogen infection, disease establishment, and epidemic potential of the new infection.

The number of disease cycles per growing season also differs from one pathosystem to another, defining the epidemic's temporal progress. A monocyclic epidemic consists of a single pulse of inoculum and thus a single period of host infection, as demonstrated by a fungal disease in which spores are dispersed just once per year. More common are polycyclic epidemics (Fig. 2A), in which propagules are dispersed, causing new infections, several to many times over the crop's lifespan. For annual crops, an epidemic starts anew each year, while for perennial crops, such as orchard trees, disease can build up due to multiple infection cycles over a period of years, resulting in a polyetic (Fig. 2B), or multiple-year, epidemic. Dispersal can be restricted to short distances or contained within the crop, or it can involve long distance, regional, or even intercontinental movement.

The direction of disease spread is highly variable, but it is rare for a pathogen to be dispersed equally in all directions (50). Long distance dispersals result in new foci of infection that contribute to future disease expansion. Depending on the mechanism and characteristics of each dispersal event, disease patterns within the crop can range from highly aggregated to diffuse. When a pathogen has the potential to infect a vast region of susceptible host plants, disease surveys must be done quickly to better control or mitigate the emerging epidemics. Several factors help researchers and regulatory agencies to develop effective survey and sampling methods for early detection, especially for emerging and exotic diseases. These include knowledge of the pathogen, its dispersal characteristics, prevailing and recent

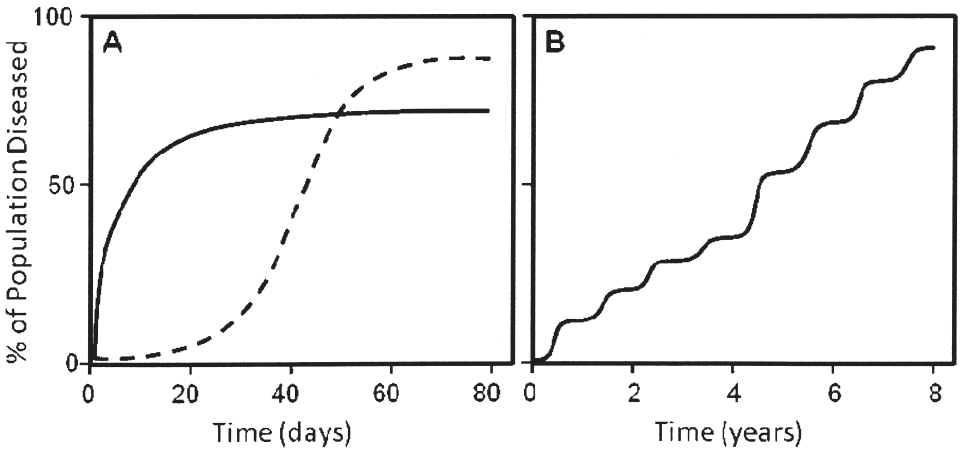

Figure 2. Hypothetical temporal increase of disease. (A) Monocyclic (solid line) and polycyclic (dashed line) increases; (B) polyetic increase, i.e., a multiyear epidemic.

meteorological activity, and potential points for inadvertent introduction by human activity. Early detection can greatly augment the possibility of eradication, disease mitigation, and/or disease control.

Types and Examples of Plant Disease Introduction

Natural Introduction: Asian Soybean Rust Example (*Phakopsora pachyrhizi* Sydow)

Asian soybean rust, caused by the fungus *Phakopsora pachyrhizi*, is a classical example of a naturally spreading, wind-borne pathogen capable of rapid clonal reproduction and dissemination where weather conditions are suitable and susceptible hosts are present (11). Although the urediniospore stage of the fungus, which is adapted to sail on wind currents, is sensitive to UV light, limiting the distance and altitude of dissemination, the pathogen can cycle from infection through spore formation in as little as 10 to 14 days, enhancing local spread on all susceptible hosts. *P. pachyrhizi* produces disease on a broad range of legume species, most notably soybean, the second most economically important field crop for animal and human food in the world after maize. The disease is historically termed a rust because of the rusted appearance of the lesions. High-yield losses can occur unless fungicides are applied in the early stages of infection, a costly economic input that significantly lowers the crop's value.

P. pachyrhizi was reported in South Africa in 2001 (47). Presumably, the fungus spread on wind currents to South America and was first reported in Paraguay (43) then moved quickly into Brazil and Argentina in 2002 (49, 62) and Bolivia in 2003 (61). Plant pathologists and other agricultural experts tracked the global spread of Asian soybean rust as it moved from West Africa into South America, then northward through Brazil into Colombia, as wind currents transported urediniospores of the fungus. The broad host range of the pathogen, which includes kudzu (*Pueraria lobata montana*, an invasive legume vine), in addition to the vast acreages of soybean in South America, contributed to rapid spread by

providing abundant hosts as the disease spread. *P. pachyrhizi* was introduced into the U.S. Gulf states in November 2004 (51). Epidemiologists hypothesized that fungal spores were transported across the Caribbean by Hurricane Ivan, which made landfall in Mississippi in September 2004.

The early discovery of *P. pachyrhizi* in research plots at Louisiana State University by a plant pathologist who had been recently trained by the National Plant Diagnostic Network (NPDN; see below) to identify the emerging disease provides a positive example of a successful program of surveillance and monitoring for an emerging pathogen. When *P. pachyrhizi* was first reported in Paraguay in 2001, raising concern that the pathogen would soon follow the historical pathway of wind-borne crop diseases through South and Latin America into the Southern tier states, USDA mounted a proactive surveillance and monitoring campaign, involving multiple agencies (ARS, APHIS, CSREES, and the Economic Research Service), LGUs, SDAs, soybean commodity groups, crop consultants, and extension agents. USDA developed a multiagency Soybean Rust Action Plan including short- and long-term strategies, development of emergency Section 18 fungicide registrations by the Environmental Protection Agency (EPA), and screening of U.S. soybean germplasm collections for resistance to rust for eventual integration of durable resistance into elite soybean lines.

The multiagency USDA response, led initially by APHIS, included a USDA-funded array of sentinel soybean plots placed strategically in soybean production states from the Gulf Coast to Canada, which were checked frequently by agricultural experts for disease symptoms. Suspect samples were forwarded to the APHIS laboratory in Beltsville, MD, where a visual identification based upon urediniospore morphology and a molecular diagnostic assay specific for *P. pachyrhizi*, developed by ARS scientists, were applied for confirmation of identity. A national database was established to receive data and Geographic Information System coordinates for positive identifications, and mapping tools that integrate weather and climate data were developed by APHIS and university and industry scientists in preparation for the eventual introduction of rust into the United States.

In addition to visual monitoring of sentinel soybean plots, state and county extension specialists and commercial diagnosticians deployed classical spore traps for fungal spore detection, using glass slides coated with Vaseline or double-stick tape inside free-rotating air chambers placed to face into the wind. Slides were examined by diagnostic technicians trained in identification of *P. pachyrhizi* urediniospores, and both PCR and commercial immunological assays were applied to confirm the identity. A second, innovative system for spore trapping involved collection, filtration, and application of rapid molecular diagnostic assays to rainwater samples, utilizing existing U.S. Geological Survey National Atmospheric Deposition Program rainwater collection sites (9).

Once rust was introduced in 2004, the logical determination was made by APHIS that regulatory actions to contain or eradicate the disease would be ineffective, and the surveillance and reporting network was turned over to CSREES (now NIFA). Diagnostic confirmations were entered into the national database, and weather data were integrated to provide a predictive assessment of the threat of soybean rust on a fine scale (30). The result was the Integrated Pest Management Pest Information Platform for Extension and Education (IPM PIPE) (http://sbr.ipmpipe.org/cgi-bin/sbr/public.cgi), a system of mapping and reporting via web-based tools that provides predictive assessments to extension agents, crop consultants, and producers (Fig. 3).

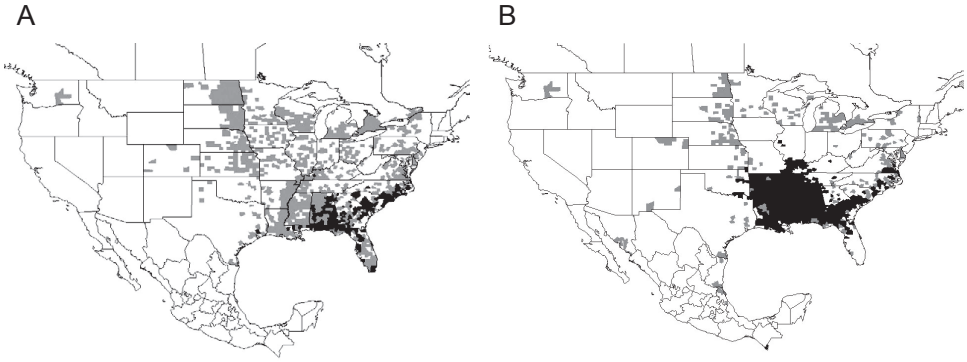

Figure 3. Extent of spread of Asian soybean rust in the United States as of December 2005 (1 year after discovery and 14 months after putative introduction by Hurricane Ivan in September 2004) (A) and November 2009 (B). Light-shaded areas indicate recently scouted (not cumulative for the year) surveillance plots; dark-shaded areas are positive for rust. Both images captured, with permission, from http://sbr.ipmPIPE.org, accessed 8 November 2009, courtesy of the IPM PIPE program.

Accidental Introduction: Citrus Canker Example

A common pathway by which exotic plant pathogens and insect pests reach and become established in new areas is accidental or unintentional human introduction (10). Since prehistoric times, humans have inadvertently moved pests and pathogens during travel. With escalating international travel, trade, and migration, such introductions are on the increase. Unless growers and regulatory agencies are aware of, and actively surveying for, potential introductions, plant diseases can go undetected until pathogen populations build up to noticeable levels, often when crop losses begin to occur. Some recent examples of accidental introductions are *Xanthomonas citri* pv. *citri*, a bacterium causing Asiatic citrus canker (24, 25); plum pox virus (PPV), causing plum pox or sharka disease of stone fruits (introduced from eastern to western Europe and, more recently, to Pennsylvania; New York; Michigan; Ontario, Canada; and Chile) (19); *Phytophthora ramorum*, an oomycete causing sudden oak death in many forest and landscape trees and shrubs (2); and "*Candidatus* Liberibacter asiaticus," an insect-transmitted bacterium causing citrus huanglongbing (originated in Southeast Asia and spread throughout Asia and recently the Western Hemisphere) (21, 22).

Although most countries have international phytosanitary measures, they are difficult to enforce, and the general populaces of most countries are unaware of prohibitions and regulations. With the advent of the Internet, plants, seed, and plant-propagating materials can be purchased and delivered from anywhere in the world, in disregard of regulations and often carrying unrecognized hitchhiking pests and pathogens. APHIS and the Department of Homeland Security (DHS) inspect at international ports of entry for prohibited plant material, but the number of travelers and sheer volume of incoming cargo makes it impossible to detect all introductions. Once in the country, pests and pathogens can be moved inadvertently by commercial trade networks.

As an example, the citrus canker bacterium, which first caused U.S. epidemics in the 1910s, was brought into the country on citrus plants imported from Japan. During the 1980s

and the 1990s, new introductions were attributed to homeowners who traveled internationally, returning with plants that they established in their dooryards (23). Pathogens resulting from these introductions were eradicated at great cost by destroying millions of citrus trees. An even more recent introduction was discovered in Miami in 1994. Eradication efforts were initiated swiftly, but mounting resistance by residential homeowners escalated to legal challenges, causing starts and stops to eradication over the next 10 years (24, 25). *X. citri* pv. *citri* is a splash-dispersed pathogen, and while legal battles ensued, tropical storms, hurricanes, and further unintentional human movement resulted in the disease's distribution across most of Florida's commercial citrus-producing areas (29). Hurricanes in 2004 to 2005 caused massive disease spread. In 2006, the disease was declared endemic, the 10-year, $1 billion eradication program was halted, and the Florida citrus industry has since attempted to control the disease by nonmandatory tree removal and numerous yearly bactericidal sprays.

The keys to dealing with exotic introductions of plant and animal diseases and pests are early detection by surveys and sampling, rapid regulatory response, and educational programs. These issues are discussed further in following sections.

Deliberate Introduction

Whether by weather events, accessory factors such as insect vectors, importation of commodities and ornamental plants that are (unbeknownst to those involved) infected, or illicit smuggling of contaminated foods or plant parts, the vast proportion of pathogens that enter our country do so without human awareness or intent. However, concerns about possible motives for intentional introduction of pathogens have resulted in an awareness of the need for capability to detect, mitigate, and respond appropriately to the deliberate use of plant pathogens to inflict harm on a person, company, industry, or nation (17, 18, 26, 37, 38, 54, 55, 58, 59). A variety of different motives, goals, and planned outcomes may characterize such actions; goals might include political gain, social disruption, military advantage, or a combination of these factors.

In general, three types of intentional use of pathogens can be distinguished; these were reviewed recently (55). Biowarfare, a state-sponsored and funded activity, includes economic or commercial sabotage for trade advantage, reduction of a nation's food resources for political gain, or destruction of illicit crops, such as drug sources. Because significant resources (financial, training, facilities, personnel, and access) are available to those conducting biowarfare, this activity has the potential of being well planned and relatively highly technical. Bioterrorism is generally the action of smaller groups or even single individuals who have ideological differences (political, social, and religious, etc.) with those in the targeted population. Resources available to bioterrorist groups range from ample to meager, depending upon the size of the movement, the existence of often unspoken links with governments, and the fortunes of the perpetrators themselves. Bioterrorism may target human or animal health, the environment, or a plant/crop of significance to cultural identity. Biocrime is often a smaller scale activity motivated by issues such as commercial competition, commodity price manipulation, recognition of a cause, revenge, or an attempt to create dependence on or a need for a particular product.

A plant pathogen, introduced deliberately into a new geographical area in which susceptible plants are available and weather conditions suitable for disease development, could quickly generate an emerging disease event. However, the actual risk is tempered by the

number of environmental, plant host, and technical factors that would need to be optimal, or at least supportive, for a pathogen to be able to survive, colonize, infect, and elicit disease in an important crop. A person, group, or nation wishing to cause harm to plant systems would likely choose an accessible, easy-to-grow, easy-to-disseminate, well-adapted, and highly virulent pathogen. However, their ability to obtain and successfully manipulate a pathogen system will depend upon their scientific knowledge, financial resources, technical facilities, ease of approach to the target site, and many other factors. Additionally, substantial knowledge of the level of genetic resistance of the target crop to a specific pathogen genotype may be required for success; such knowledge is often proprietary information, known only to seed companies who bred the product for planting in a specific region or climatic zone. Ultimately, the small likelihood that all of these factors can be met is likely to act as a deterrent to lower the risk that a deliberate attempt to seriously harm production of a crop or natural plant resource would be successful.

Interestingly, even the claim or suggestion that an intentional pathogen introduction has or is to be made can trigger a significant disruption of agricultural production and distribution as well as societal fear and reaction. Thus, hoax attacks on high-value crops or commodities could have a significantly higher probability of economic impact on the value of production and/or trade than a real attack on a field crop, particularly if media attention is captured in the former.

The U.S. Agricultural Bioterrorism Protection Act, passed by Congress in 2002 not long after the targeting of national sites and citizens by terrorists, set in place a series of roles and responsibilities for federal agencies, including the USDA APHIS, ARS, and CSREES (now NIFA), the newly formed DHS, and other entities, for minimizing the risk of intentional introductions and for mediating an event should it occur. These roles are described in other sections of this chapter.

Discrimination between a naturally occurring plant disease and one that was the result of an intentional pathogen introduction may be difficult, and in some cases impossible, despite the recent development of tools and guidelines that can assist in this activity (48). It is clear that a number of nations (including the United States) investigated the potential of plant pathogens as agents of warfare prior to the passage of the Biological Weapons Convention in 1975 and that animal pathogens have been employed intentionally in a number of cases (58), but it is not so clear whether plant pathogens have actually been deployed with the intent to harm (40).

RANKING THREATS AMONG EMERGING PATHOGENS

Pathogen Prioritization Factors and Criteria

Medical professionals must deal with pathogens of a single host, while veterinarians deal primarily with pathogens of fewer than 10 economically important hosts. Because there are tens of thousands of plant host species, prioritization of emerging plant pathogens from among the thousands known to exist is a daunting—but critical—task. A primary factor in priority ranking is the commodity affected, with threat levels generally based upon an economic threshold of damage to that plant species. Plant host commodity values are available from annual USDA reports (http://www.nass.usda.gov/Statistics_by_Subject/index.asp) and commodity trade groups, and models can be developed to predict the amount of disease

that a virulent emerging pathogen would cause, given a susceptible host and ideal climatic conditions. Using such tools, an arbitrary cutoff point can be determined for pathogens causing, at minimum, billions of dollars worth of damage.

To rank pathogens objectively, based on their relative threat to agricultural interests, information on pathogen biology is critical. The risk of establishment is dependent upon factors such as reproduction potential, longevity method of dissemination of infectious units, and environmental conditions optimal for host infection. Knowledge of the host range and distribution of susceptible plant germplasm also is required for informed decisions on the risk of pathogen establishment. A pathogen having a wide host range could infect weedy and/or native plants in addition to the primary commodity host, allowing reproduction outside the scope of surveys.

Decisions to include or exclude pathogens from priority lists must also consider the emergence of new genotypes (races or strains) of known pathogens in addition to new emerging species of pathogens. Emerging pathogens are, by definition, newly discovered, so critical information on their climatic and host ranges, pathways of introduction, and potential for establishment may be unknown or partially understood, making calculations on risk of introduction and establishment extremely imprecise. Some critical information may be available only in the literature of the country of origin, such as government reports or other publications not easily accessed by the international scientific community.

USDA APHIS Plant Pathogen Select Agent List

Although a list of select agents (pathogens of high threat) for humans had existed for many years, lists of comparable pathogens of concern for animals (livestock and wildlife) and plants (crops, nurseries, forests, rangelands, and other natural environments) were mandated in 2002 with the passage of the Public Health Security and Bioterrorism Preparedness and Response Act (Public Law 107-188; 12 June 2002). This law directs the USDA to enhance its ability to prevent, prepare for, and respond to acts of bioterrorism threatening the U.S. agricultural enterprise. By identifying specific pathogens deemed of greatest risk and designating them select agents, USDA APHIS officials established a rigorous registration, permitting, and reporting system for those receiving or using these particularly dangerous microbes. The USDA APHIS website information indicates that "implementing regulations detailing the requirements for possession, use, and transfer for select agents and toxins were published by USDA (9 CFR part 121 and 7 CFR part 331)."

Criteria for including a plant pathogen on the select agent list, as posted on the APHIS website, include the following:

- The effect of an agent or toxin on animal or plant health or products
- The virulence of an agent or degree of toxicity of the toxin and the methods by which the agents or toxins are transferred to animals or plants
- The availability and effectiveness of medicines and vaccines to treat and prevent any illness caused by an agent or toxin
- Other criteria that the Secretary considers appropriate to protect animal or plant health or animal or plant products

The plant Select Agent list is reviewed, and the agents reevaluated, on a periodic basis, but the current list includes the following plant pathogens:

- *Peronosclerospora philippinensis*
- (*Peronosclerospora sacchari*)
- *Phoma glycinicola* (*Pyrenochaeta glycines*)
- *Ralstonia solanacearum*, race 3, biovar 2
- *Rathayibacter toxicus*
- *Sclerophthora rayssiae* var. *zeae*
- *Synchytrium endobioticum*
- *Xanthomonas oryzae* pv. *oryzae* and *Xanthomonas oryzae* pv. *oryzicola*
- *Xylella fastidiosa* (citrus variegated chlorosis strain)

While the select agent lists for humans and animals include both endemic and exotic pathogens, plant pathogens that are established (unlikely to be eradicable) in the United States have thus far been excluded from select agent status. In addition, three plant pathogens (*Phakopsora pachyrhizi*, PPV, and "*Candidatus* Liberibacter asiaticus") that were included on the original list were delisted on subsequent versions of the list after they entered and became established in the United States.

In contrast to the extant, relatively simple online process of application for an APHIS permit to receive and use a nonlisted plant pathogen, the process for use of a select agent is significantly more detailed and the reporting significantly more stringent. The Application for Laboratory Registration for Possession, Use, and Transfer of Select Agents and Toxins includes the submission of a biosecurity plan, an emergency response plan, a containment plan, an inventory of listed pathogens, and a comprehensive listing of all personnel with access to individual agents. A site inspection by an APHIS official will confirm that physical facilities and containment procedures are adequate and that users are knowledgeable about restrictions and guidelines for use. Department of Justice background checks must be completed for investigators (including students, staff, and others) who would use or have access to the agents.

The rigorous registration, clearances, plan development, security measures, and reporting requirements for select agents are time-consuming and can be expensive. However, some plant pathologists have successfully completed the process and are working on critical research that will help prepare the United States to react quickly and successfully against the incursion of one or more of these select agents.

DETECTION, MONITORING, AND SURVEILLANCE OF PLANT PATHOGENS

Offshore Pest Risk Reduction: "Plants for Planting" Regulatory Changes

Plants for planting can be a primary pathway for the entry and establishment of new and emerging pathogens and other pests. Currently, most plants for planting are enterable if they are accompanied by a phytosanitary certificate from the exporting country and receive an

inspection at the port of entry. The USDA has recognized the vulnerability of this pathway and proposes a comprehensive review and revision of the plants for planting regulations, commonly referred to as Q-37 (http://www.aphis.usda.gov/import_export/plants/plant_imports/Q37_revision.shtml). This revision will occur in phases, starting with the creation of a new category of regulated plants, those plants whose importation is no longer authorized pending pest risk analysis (NAPPRA).

Plants for planting will be placed on NAPPRA if the scientific evidence indicates that the plant is either a quarantine pest or the host and pathway for introduction of a quarantine pest. The Agency would publish a Federal Register notice that would identify the new NAPPRA-listed plant, would cite the scientific evidence we considered, and give the public the opportunity to comment. This new category would allow us to take prompt action on evidence that the importation of the plant may pose a risk of introducing a quarantine pest.

Another aspect of the revision of Q-37 is to standardize existing offshore certification or systems approaches for mitigating pest risk and to expand their use to other plant imports with high pest risk. These measures would be similar to "industry clean stock" or "best management" programs and would be designed to detect and reduce the risk of emerging pathogens and other pests of concern at their origin, thus removing them from the import pathway (http://www.aphis.usda.gov/import_export/plants/plant_imports/downloads/q37_regulatory_sysapproach_protocol.pdf). Some of these protocols are already in use for the importation of *Pelargonium* spp., plants for planting from Israel, and artificially dwarfed plants, for example. U.S. regulators or third-party auditors would periodically inspect and certify approved programs in exporting countries. The new procedures would also allow for prompt action to modify existing programs or implement new programs in response to changing pest risk.

The goal of the revision is to substantially reduce the pest risk of imported plants for planting with the least possible impact on trade and within international standards and obligations.

Surveillance, Monitoring, and Detection within the United States

Over a billion U.S. acres are planted with food, fiber, feed, and fuel crops. In 2004, about 155 million acres were planted with corn and soybeans alone. Many other crops are grown over large acreages and/or are high-dollar, intensively grown specialty crops such as grapes, citrus, and vegetables. The sheer volume and extent of the U.S. agricultural enterprise creates the risk for natural and accidentally caused plant disease outbreaks and makes agriculture an easy target for those seeking to strike at the economy, the social stability, or the sense of security of the U.S. citizenry.

The challenges of maintaining surveillance over such vast areas and such diverse hosts create the potential of an extended lag time between the introduction of a pathogen or pest (intentional or natural) and its detection. This lag impacts the success of control strategies as well as the determination of the pathogen's source. Early disease diagnosis and pathogen detection are necessary to limit disease spread and impact, whether its initiation was natural or deliberate. The more time that passes between introduction and detection, the less distinct the pattern of outbreak becomes.

The USDA, along with the SDAs, the LGU system, the CES, commercial crop consultants, and agricultural industry and commodity associations comprise a robust domestic surveillance

system. APHIS systematically monitors for regulatory pest problems for domestic establishment by commissioning Cooperative Agriculture Pest Surveys, which provide resources to SDAs in all 50 states and three U.S. territories to search for and track more than 400 pests (4). Additional domestic surveillance is conducted by LGU CES and industry partners, coordinated via programs such as IPM PIPE (30).

The surveillance, monitoring, and detection systems mentioned above are highly dependent on human resources, including inspectors at points of entry, county extension agents monitoring sentinel plots, industry experts, university extension specialists conducting mobile surveillance, and farmers and their advisors walking into fields. Their efforts must be coordinated and guided by the best available risk information (14, 44).

Given that the largest constraints to monitoring agricultural resources in the United States are the tremendous area that must be covered and the limitations in human resources, ideal monitoring systems rely on technologies that anticipate threat and risk levels using epidemiological modeling and automated detection processes. Environmental monitoring has the potential to supplement active surveillance and narrow search parameters. Nucleic acid, proteomic, or spectral signatures of specific organisms (44) have been of limited success but, with appropriate engineering, could be highly effective (14).

Syndromic analysis of outbreak patterns using meteorologic and epidemiologic models can help discern both the pathway of introduction and the most likely directional spread. Such knowledge informs response-related surveys and sampling so that resources can be targeted to greatest effect. Intentional introduction of a plant pathogen will likely result in an unusual pattern of disease differentiable from that of a natural introduction (14, 44). Unusual aggressiveness, severity, or incidence also should trigger an investigation.

Monitoring at Ports of Entry and Official Border Crossings

U.S. Customs and Border Protection (CBP) is the unified border agency within DHS. CBP combines the inspectional workforces and broad border authorities of U.S. Customs, U.S. Immigration, and APHIS. CBP's more than 58,400 employees manage, control, and protect the Nation's borders at and between official ports of entry. Its primary mission is to prevent terrorists and terrorist weapons from entering the United States while also facilitating the flow of legitimate trade and travel (http://www.cbp.gov/xp/cgov/border_security).

CBP Officers and Agriculture Specialists clear carriers and passengers and control garbage and cargo at airports, maritime ports, and land ports to minimize the risk of introducing plant pests into the United States. In 2008, CBP employees inspected 397 million travelers and over 122 million cars, trucks, buses, trains, vessels, and aircraft at 327 ports of entry. They performed more than 25 million agricultural inspections and made 1.1 million plant material interceptions (3). Most of the latter were due to insect infestations; microbial pathogens are more difficult and more expensive to detect (3).

CBP Agriculture Specialists prevent pests from entering the United States by examining cargo and associated documentation; examining carriers; clearing passengers, crew, and their baggage; examining international mail; preventing the spread of pests; and preparing plant pest interceptions (5). Additionally, CBP performs Agricultural Quarantine Inspection Monitoring (AQIM) on passengers, vehicles, cargo, containers, rail cars, and other conveyances that enter ports (6). The AQIM Handbook supports the implementation of AQIM at

designated work locations, training employees on the basics of risk analysis and management and analyzing information so managers can make better risk-based decisions.

Monitoring and interception of plant pests involve the use of established strategies such as screening (selecting baggage for examination) and inspection (asking questions of passengers and performing thorough baggage inspections), detector dogs, and X-ray equipment as well as using information obtained from the Passenger Analysis Unit to evaluate risk. Plants and plant products not intended for growing as well as those intended for growing ("plants for planting") are also regulated by CBP via the *USDA Fresh Fruits and Vegetables Import Manual* (7) and the *USDA Nursery Stock Manual* (8). Most plants for planting are referred to the APHIS Plant Inspection Station, where they are examined and released if they are free of regulated pests. At the Plant Inspection Stations, APHIS Plant Protection and Quarantine (PPQ) officers examine imported plants and seeds to ensure that they are free from plant pests and pathogens that are not known to occur in the United States, that their import has been approved through the issuance of a permit, and that they otherwise comply with federal regulations. However, inspections for plant pests and disease symptoms are primarily visual, and advanced technologies for detection of cryptic phytopathogenic microorganisms are not yet deployed at the majority of the ports of entry in the United States, so entry of pathogens in asymptomatic plants or commodities remains a problem. When pests or diseases are detected, PPQ may require that the planting material be treated (e.g., fumigation), exported, or destroyed (e.g., incineration). However, CBP does inspect and process certain types of plants for planting, such as agriculture and vegetable seed, as well as precleared bulbs and dormant perennials. A complete listing of USDA manuals may be viewed at http://www.aphis.usda.gov/import_export/plants/manuals/online_manuals.shtml. CBP Agricultural Specialists also issue civil penalties to passengers carrying prohibited agricultural commodities without declaring them and issue violations to industries who fail to comply with quarantine laws, policies, and procedures.

APPLICATION OF DIAGNOSTIC TECHNOLOGIES

Diagnostic methods for plant pathogens can be grouped into those that are designed to detect pathogens, those that provide identification to a desired taxonomic level (e.g., genus, species, or strain), or those that both detect and identify. In general, low-technology rapid assays such as antibody-based lateral flow membrane strips provide rapid detection of the presence of a pathogen or group of related pathogens but often do not definitively identify the pathogen. Technologies relying on more complex chemistry and instrumentation, such as PCR, microarrays, or sequence-based assays, may provide definitive identification of a pathogen but lack portability and thus are more often deployed in clinical laboratories. A goal of researchers and diagnosticians is the development of portable, inexpensive diagnostic technologies that can rapidly detect and definitively identify an emerging pathogen.

Regardless of the technology, sampling and sample preparation represent the limiting step in execution of microbial diagnostics. While a wide variety of protocols and commercial reagents is available for extraction of nucleic acids and proteins from plant and environmental samples, the daunting scale of agricultural production areas and the statistical requirements for robust sampling represent significant impediments to the development and implementation of rapid diagnostics.

In the Field

Diagnostic assay deployment in the field is significantly limited due to requirements for portability, exposure of samples and assay reagents to temperature extremes and harsh conditions, and need for rapid sample collection and processing from complex environmental matrices. Field diagnoses are generally conducted by extension pathologists, crop consultants and producers skilled in visual disease detection, often using only a simple hand lens to magnify disease lesions and symptomatic tissues. Soybean rust was first identified in this manner by a field pathologist recently trained in visual identification of the disease (51).

Commercial assays for field diagnostics are currently dominated by lateral flow membrane strip technology, which provides rapid pathogen detection and preliminary identification to the genus (and occasionally species) level. Rapid sample processing kits now available consist of small plastic bags containing extraction buffer for leaf or stem tissue maceration and release of pathogen antigens into solution. Membrane strips are dipped into the extraction solution on-site, with a rapid visual reading indicating the presence or absence of the pathogen. Such assays are increasingly used by producers, extension agents, crop consultants, and those conducting surveillance for pathogens at sentinel plots and field sites.

In the Clinic

Diagnostic laboratories utilize detection technologies ranging from relatively low-tech, such as visual examination of diseased tissue for pathogen signs (e.g., lesions containing fungal spores), to sophisticated molecular and immunochemical assays targeting pathogen biochemistry. In some cases, as in the screening of foundation stocks of woody perennials (e.g., grapevines and fruit and nut trees), disease assays using indicator hosts may be required to confirm a suspected pathogen. The range of technologies and the expertise in any one laboratory vary considerably across the United States, although laboratories with formal diagnostic and/or regulatory authority generally have a full or wide range of capabilities. Plant diagnostic laboratories are affiliated with the USDA APHIS, U.S. Forest Service, SDAs, and LGUs. Some charge a modest fee to help cover expenses. Private laboratories also perform diagnoses on a contractual or fee-for-service basis, and others, affiliated with seed and agricultural companies, support research and development programs. Thus, in the United States, a comprehensive infrastructure supports diagnosis of extant and emerging plant diseases.

Financial support for this diagnostic infrastructure varies considerably. Shortfalls in state and university budgets continually threaten the long-term viability of some diagnostic clinics. Although this problem is not new, greater awareness of the importance of these clinics emerged following the events of 11 September 2001 with heightened concern about the vulnerability of agriculture to intentional and accidental introductions of high-consequence pests. Plant health experts have long recognized the importance of early detection and accurate diagnosis to inform rapid response and mitigation measures. Success of mitigation programs is also dependent upon effective communication among plant health professionals within government, university, public, and private sectors.

In 2002, with funding provided by NIFA (then CSREES), the nation's existing plant diagnostic laboratories were integrated into a cohesive network to help address needs in agricultural biosecurity (53; www.npdn.org). The NPDN, which includes a diagnostic clinic in every U.S. state and territory (Fig. 4), was established with the objectives of (i) establishing a

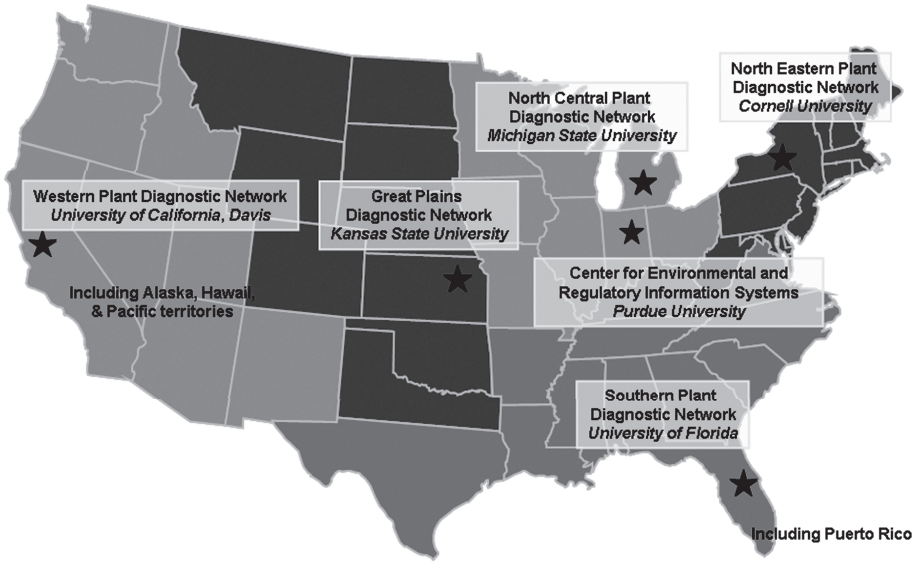

Figure 4. The NPDN. Shading shows the five regional divisions; stars indicate regional hub labs and the central database at the Center for Environmental Regulatory Information Systems at Purdue University.

communications system linking LGU, SDA, state and federal agencies, and national expert laboratories; (ii) providing support to improve diagnostic infrastructure in LGU and SDA laboratories; (iii) conducting advanced training programs for diagnosticians; (iv) developing a national registry of first detectors through face-to-face and online education and outreach; and (v) developing capabilities for capture and analysis of diagnostic records in regional and national databases for rapid identification of outbreaks. Unusual field events lead first detectors (growers, county extension educators, and crop consultants, etc.) to collect and submit samples to one of the network's >60 clinics. The principal initial focus of the NPDN was on plant pathogens because of their prominence on the USDA APHIS select agents list, but as the Network has matured, all agricultural pests (insects, weeds, and nematodes, etc.) and forest pest agents (3) fall within its area of responsibility. More detail of the structure and mission of the NPDN was reported by Stack et al. (53).

The impact of the NPDN on the nation's plant diagnostic clinics has been rapid and significant. Some clinics, poorly funded and at risk of closure, are now able to continue to provide services with the new funds. For others, federal funds helped leverage additional state monies to enhance laboratory capabilities. Many clinics have acquired real-time PCR instruments, network-enabled microscopes for distance diagnosis, secure information systems for archiving and transmitting diagnostic records into regional and national databases, critical reagents and supplies, and facility upgrades for secure processing of samples that require containment. Advanced programs and workshops for diagnosticians have helped to bring NPDN labs to similar levels of proficiency in the use of standardized protocols for high-consequence agents.

This coordination of the United States' diagnostic and reporting capabilities has been crucial in providing needed surge capacity and data for syndromic and forensic analysis that have been critically important during recent outbreaks of *Phakopsora pachyrhizi* (Asian soybean rust), PPV, *Phytophthora ramorum* (sudden oak death), and other diseases and pests. APHIS identifier laboratories provide standard operating procedures for validated assays, diagnostic training, proficiency testing, and lab-accrediting audits for management of high-consequence pathogens of regulatory importance. A program is under way to formally accredit NPDN laboratories to provide standardization and defined verification of best diagnostic practices. Only accredited laboratories can make determining and confirming diagnoses on regulated pathogens. Many NPDN labs provide triage, diagnosing common problems and eliminating negatives, but move unknowns or suspect samples to an accredited lab.

The NPDN and programs in other countries having similar mandates and operational objectives, such as Plant Health Australia (http://www.planthealthaustralia.com.au/go/phau), provide models for enhancing the capacity and capabilities of diagnostic clinics as part of a nation's response to plant pest emergencies.

In the Forensic Laboratory

The anthrax attacks of 2001 demonstrated the need for a capability in the United States to rapidly identify and characterize biological agents to enable data to be collected for attribution analysis so that the perpetrator(s) could be apprehended and potential future attacks thwarted. Prior to the anthrax attacks, the United States lacked a dedicated capability to conduct forensic analysis of biological agents or biological agent-contaminated evidence. Since 2001, the new scientific discipline of bioforensics or microbial forensics has emerged and is expanding.

Bioforensic analyses and assays that can identify and characterize an agent used in an actual or potential biocrime or bioterror act are similar or identical to those that would be used in a diagnostic context to identify the cause of a disease outbreak and to support epidemiological investigations to identify its source. Bioforensic analyses for a number of human and animal high-consequence biological agents have been developed; these utilize a range of identification and characterization technologies such as culture, phenotypic characterization, microscopic examination, and serological or antigen detection and molecular techniques such as real-time PCR assays and whole-genome sequencing. Bioforensic assays and techniques must be stringently assessed and validated for their use with environmental samples and, when possible, be published in peer-reviewed scientific literature and undergo the rigors of accreditation by a recognized international organization for testing and analysis labs such as International Standards Organization 17025 accreditation. Such assessments and validations will enable the bioforensic analyses to meet the Daubert Standard (a court-mandated requirement that evidence based on new or unusual scientific information must be proven reliable and valid before it can be admitted in a courtroom) for the submission of scientific evidence in a U.S. federal prosecution. The development of similar bioforensic analyses/assays for plant pathogens has lagged behind those for human and animal agents, but the need for this capability for the range of high-consequence plant agents is now well recognized and efforts are moving forward through the development of new assays by APHIS and ARS, the DHS National Bioforensic Analysis Center, and the National

Institute of Microbial Forensics and Food and Agricultural Biosecurity at Oklahoma State University.

RESPONSE TO AND RECOVERY FROM INTRODUCTIONS

The Short Term: Control and Mitigation

Recovery involves immediate, short-term, and long-term responses. Immediate responses include quarantine and eradication, performed largely (and mandated by statute) by APHIS. Short-term recovery strategies may include the identification of pesticides that will allow management of a new disease until other methods can be developed. Pesticide use is usually predicated on the relabeling of registered pesticides or the development of emergency exemptions for use on new sites, an activity often facilitated by close cooperation between USDA and the EPA. Other short-term strategies are the development or identification of resistant crop germplasm; vector management; biological and cultural controls; surveillance and prediction; and the education of growers, the agricultural community, and the general public.

APHIS' PPQ program safeguards U.S. agriculture and natural resources from the introduction, establishment, and spread of plant pests and noxious weeds. APHIS, as the lead federal agency for plant health emergencies, works through its PPQ program to cooperate with national and international plant protection organizations; federal, state, tribal, and local agencies; universities; industries; and private entities in developing and implementing a science-based framework to provide optimum protection against invasive pests and diseases. The framework consists of four key elements: prevention, preparedness, response, and recovery. For more information on APHIS' role in crop biosecurity, see http://www.aphis.usda.gov/plant_health/plant_pest_info/biosecurity/index.shtml.

PPQ has provided federal leadership to respond to plant pest emergencies since the inception of APHIS in 1972. PPQ responds quickly to new pests in a manner structured to take advantage of the resources at hand, in concert with state cooperators. Homeland Security Presidential Directive number 5 (HSPD-5) issued 28 February 2003, requires that all federal departments and agencies adopt the National Incident Management System in their domestic emergency management. The National Incident Management System provides a consistent nationwide approach to federal, state, and local governments to work effectively and efficiently together to prepare for, respond to, and recover from domestic incidents, regardless of cause, size, or complexity. When responding to plant health emergencies, PPQ uses the Incident Command System, which provides responding agencies and entities a unified strategy for working together in response to emergencies.

PPQ works with federal agencies, state, tribal, and local governments, and industry to prepare, build, and sustain operational capacity and capabilities, including early detection, timely diagnostics, and effective control strategies against plant health threats and pest introductions. PPQ's New Pest Advisory Group (NPAG) assesses exotic plant pests that are new or imminent threats to U.S. agriculture or the environment and recommends appropriate actions to the PPQ Deputy Administrator. The typical trigger for NPAG is a confirmed pest identification by APHIS or an APHIS-designated laboratory. NPAG coordinates information and solicits expertise from federal and state agencies, university systems, and international organizations. NPAG recommendations range from "no action necessary" to "eradicate the pest and quarantine the infected or infested area." The New Pest Response Guidelines, which

are updated as applicable information or new scientific tools become available, are posted on the PPQ website for timely access. Once a decision has been made to respond to a pest, the New Pest Response Guidelines provide basic information for developing a site-specific action plan and required environmental documentation. Particularly for pests new to the United States, PPQ may convene a Technical Working Group, an ad hoc group of scientific experts from federal and state agencies, universities, the private sector, and international organizations who provide PPQ with information about the particular pest or disease to inform a science-based response. Core Technical Working Group members are identified and consulted at the emergency's outset to address technical questions in support of the response. Rapid detection and delimiting surveys are typically conducted immediately, as they inform the development of an overall response strategy, including efforts to contain, control, and eradicate the pest. Sometimes the resources required for the response increase over time, especially when surveys detect the pest in new areas. Funds available for response activities are derived initially from discretionary funds at the PPQ regional and headquarters levels, though, if needed, other APHIS support can come from contingency funds or reprogramming funds. Should additional resources be needed, the Secretary may declare an agricultural emergency, in which APHIS can request access to Commodity Credit Corporation or other USDA funds. A declaration of extraordinary emergency by the Secretary provides PPQ with greater authority to conduct the response when a state's resources are inadequate, and finally, Congressional supplemental funding may be provided to address unanticipated national circumstances.

If a pest is found in a relatively confined area, remote or protected from other host plants or the natural environment, then a relatively focused, short-term mitigation measure may be efficacious. A confined area is not limited to the natural environment but may include contained structures such as cargo ships, railway containers, trucking containers, greenhouses, or even warehouses. In such confined natural areas and structures, USDA may be able to apply quick responsive measures to control, manage, or eradicate the pest. Several examples follow, based in part on the nature of the site where the pest is detected:

- Environmental finds: an exotic pathogen species may be detected and eradicated. Delimitation surveys are conducted near the detection site, coupled with focused ground sprays, resulting in eradication over several months.
- Confined port location or shipping container: exotic pathogens may be detected in containers or packing material imported from foreign locations where the microbes originated. Treatments to quickly kill the pathogens may be conducted within a few days.
- Greenhouses: a host-specific exotic fungal disease, such as chrysanthemum white rust (46) may be detected in a greenhouse. Fungicides, host removal, and surface decontamination may effectively eradicate it.

In the above short-term response examples, the pests have not yet become established, widespread, or present in areas, making efficacious removal from urban or environmentally sensitive areas possible. Several situations may result in a short term response evolving into a longer term mitigation effort. Several examples follow, although these are not exhaustive of all possibilities:

- The pest is found in locations beyond where it was first detected. Additional resources and time are required to determine the full extent of its distribution.
- Surveillance efforts are hampered due to lack of tools or methods to afford early detection in noninfested areas, or the biology of the pest impedes detection at certain stages of the life cycle.
- Treatment, through chemical, biological control, regulatory, or other measures, is unavailable or not efficacious for the pest. Additional research for efficacy or EPA registration of a pesticide take time and additional resources to acquire the needed tools to mitigate the pest.
- It becomes clear to federal and state agencies, growers, and affected industries that the pest cannot be eradicated in the short term. It may make sense to recognize the pest as established and potentially widespread. Long-term research efforts, monitoring, and learning about the best means to mitigate the pest are components of a strong strategy.

The Long Term: the NPDRS

Plant diseases that are new to our agroecosystems threaten U.S. agriculture. The National Plant Disease Recovery System (NPDRS) was created in 2004 by HSPD-9 to ensure that the tools, infrastructure, communication networks, and capacity required to mitigate the impact of high-consequence plant disease outbreaks are such that a reasonable level of crop production is maintained in the United States.

Long-term strategies for plant disease management usually rely upon basic and applied research. NPDRS strives to identify the most promising research needed to overcome each identified pathogen.

The NPDRS' main vehicle for identifying and preparing for the most threatening diseases is through recovery plans. Each recovery plan provides a brief primer on a threatening disease, assesses the status of critical recovery components, and identifies disease management research, extension, and education needs. The recovery plans are not intended to be stand-alone documents or to address all aspects of a plant disease outbreak, the decisions that must be made, and the actions that must be taken to achieve effective response and recovery. They are, rather, documents to help USDA and others guide efforts to prepare for and recover from new plant diseases in the United States. The real work is accomplished by plant pathologists working through federal, state, university, and private organizations.

The recovery plans are a cooperative effort of universities, industry, and the USDA. Pathogens discussed in these plans have been nominated as critical threats to U.S. agricultural production and reviewed at workshops of the American Phytopathological Society (APS) and USDA held at annual meetings since April 2006. The content and recommendations of those meetings can be viewed at http://www.apsnet.org/members/npdrs/default.asp. Completed recovery plans (Table 1) can be viewed at http://www.ars.usda.gov/research/npdrs.

Two overriding concerns of the NPDRS program are how to deal with the thousands of documented exotic pathogens that may enter the United States and how to prepare for those that are yet unknown. We believe that the solution is to prepare for all diseases by developing a core group of recovery plans that represent every major type of pathogen that could arrive or develop. When an unexpected pathogen does arrive or emerge, one of the

Table 1. NPDRS recovery plans completed or under development

Disease	Etiologic agent
Citrus leprosis	Citrus leprosis virus
Citrus variegated chlorosis	*Xylella fastidiosa*
Cyst and rootknot nematode diseases	*Heterodera* spp. and *Meloidogyne* spp.
Downy mildews of corn	*Sclerophthora rayssiae* var. *zeae* and *Peronosclerospora philippinensis*
Huanglongbing of citrus	"*Candidatus* Liberibacter asiaticus," "*Candidatus* Liberibacter africanus," and "*Candidatus* Liberibacter americanus"
Late wilt of corn	*Harpophora maydis*
Laurel wilt of avocado	*Raffaelea lauricola*
Laurel wilt of redbay	*Raffaelea lauricola*
Plum pox or sharka	PPV
Potato wart	*Synchytrium endobioticum*
Ralstonia bacterial wilt of potato and carnation	*Ralstonia solanacearum*, race 3, biovar 2
Red leaf blotch of soybean	*Phoma glycinicola*
Rice bacterial blights	*Xanthomonas oryzae* pathovars
Scots pine blister rust	*Cronartium flaccidum*
Slime disease of grasses	*Rathayibacter toxicus*
Stem rust of wheat (Ug99)	*Puccinia graminis* f. sp. *tritici*
Tree-ornamental diseases caused by *Phytophthora* spp.	*Phytophthora* spp.
Tree and shrub diseases caused by *P. kernoviae*	*Phytophthora kernoviae*
Walnut canker of thousands	*Geosmithia* sp.
Wheat blast	*Magnaporthe grisea*
Wheat rusts	*Puccinia* spp.

representative plans can be used as a model to quickly assemble a new recovery plan for the unexpected pathogen. Using this strategy, we can better prepare for and react to expected and unexpected new, high-consequence plant diseases.

The Long Term: Development and Deployment of Resistant Germplasm

While short-term disease management strategies are deployed to mitigate seasonal losses from disease outbreaks, long-term strategies for durable resistance to constantly mutating pathogens require the discovery of multiple resistance genes for breeding into elite lineages. Once elite lines are established, the genes can be introduced into crop varieties and cultivars that are adapted to regional and local conditions. This often entails screening pathogen genotypes on crop germplasm collections in attempts to find resistance genes that can be "pyramided" into elite lines. The discovery of new resistance genes has been streamlined with the development of techniques applying molecular markers to develop fine linkage maps of major crops, allowing one to more easily map genes that provide partial or full resistance to pathogen genotypes.

When new pathogens that break down existing resistance genes in major crops emerge, the most pressing need is often to collect representative pathogen genotypes from the country of origin and begin a coordinated screening effort. Virtually all seed companies breed varieties that are adapted to regional climates, photoperiods, pests, and pathogens. Thus, screening efforts may be coordinated so that university, state, and federal laboratories share the screening

for pathogens on locally adapted crops. However, new and emerging pathogens are often quarantined upon discovery, such that screening must be conducted inside a containment facility, where space restrictions limit the scope of the effort. In the case of Asian soybean rust, over 16,000 soybean lines in the USDA germplasm collection were screened inside a small containment greenhouse facility at Ft. Detrick, MD (27, 41). Subsequent field and greenhouse evaluations were conducted in Paraguay (42) and Nigeria (56) and in greenhouse studies in Stoneville, MS (34, 35), and Urbana, IL (45), with U.S. isolates of Asian soybean rust.

Once resistance gene phenotypes are discovered by classical screening in existing germplasm collections, or as sequences of novel resistance genes are found through molecular methods, the technology must be transferred to industry for introgression into elite breeding lines. Resistant crop varieties that are adapted to regional climates may then be developed based on the severity of the pathogen infestation. The breeding and marketing of resistant seed is a purely financial investment decision made by seed companies as new pathogens emerge and become established in growing areas. Once resistant seed is marketed for sale, growers and producers must weigh the benefits provided by pathogen resistance, which are often dictated by local weather, with the risks of using nonresistant seed, which may produce higher yields when disease pressure is low or absent. As discussed above, the NPDRS was established under HSPD-9 to drive the discovery of resistance genes against major emerging pathogens and develop stocks of resistant seed for deployment in the event of introduction of the pathogen. However, due to the complexity of the process of discovery of resistance genes, the requirement for development of regionally adapted germplasm, the speed at which new pathogens emerge and are introduced into growing regions, and the paucity of federal funding for such a massive effort, it is likely that the emergence of new pathogens will remain ahead of the development of resistant varieties.

Eradication

Conceptually, eradication is simple: remove diseased plants more rapidly than new ones become diseased. The more rapid and efficient the removal of diseased individuals, the less the chance of continued pathogen spread, and the quicker the disease can be eliminated. However, because a latent period between infection and symptom expression is common, it is not always easy to recognize newly infected plants. Some plants are subclinically infected, and some latent infections can persist for days to years without symptoms. Diseased plants may not always be aggregated into convenient groups for easy eradication. The disease is often distributed diffusely within an otherwise healthy population. Thus, to achieve eradication, both diseased and nearby asymptomatic but potentially latently infected plants must be removed. Furthermore, if newly affected plants are asymptomatic, then eradication will require that plants at some distance to known infections may need to be removed as well (23, 52). Similar issues have occurred in the animal world; diseases such as foot and mouth or bovine spongiform encephalopathy may require culling of entire herds to preserve the health of other animals in a region (12, 16). Depending on the real, perceived, or esoteric value of individual plants or animals, farmers and ranchers, having large numbers, or residential homeowners, having only a few individuals, may disagree with and/or resist eradication policy.

Thus, although eradication theory is simple, a regulatory decision to initiate eradication is not. First, the extent of the disease must be delimited by survey, and the disease must not have exceeded the ability to eradicate it. Then, only if sufficient human and fiscal resources

exist, and the disease is still limited in distribution, should eradication be considered. Although regulatory agencies are sometimes mandated to protect agricultural commodities and authorized to use eradication if necessary, recent eradication programs have demonstrated that regulatory action must be accompanied by commodity group cooperation and political will, combined with a strategy that will achieve disease eradication without exceeding the tolerance of the affected populace (20). If eradication enforcement efforts exceed commodity, political, or populace tolerance, groups can become pitted against one another, resulting in resistance. Such resistance can quickly escalate to legal challenges that can halt eradication efforts, allowing the disease to continue unabated.

The Florida citrus canker epidemic and resulting eradication program mentioned above exceeded the social tolerance of residential homeowners, who resisted removal of their apparently healthy, but potentially asymptomatically affected, trees in support of the commercial citrus industry. This situation led to years of litigation and greatly reduced the effectiveness of eradication efforts (20). Conversely, the PPV eradication program in Pennsylvania, which affected both commercial and residential stone fruit tree owners but did not exceed the tolerance of either group, was successful within a few years (19).

In addition to adequate human and fiscal resources, a major key to eradication is early detection, typically by surveys (36), of new infections and rapid response to eliminate the disease and minimize further spread. Effective survey design is dependent upon knowledge of the pathogen, of pathways for distribution, and of distribution patterns. If eradication is deemed feasible and is initiated, then intensive detection surveys within the infected area are deployed to find all foci of infection for elimination. Simultaneously, outside the infected area commercial and residential sentinel surveys are often used to locate new outbreaks as early as possible. If spread is affected by weather patterns, then targeted surveys take advantage of known foci of infection, wind and rain direction, and wind speed to estimate dispersal vectors and distances and to define downwind areas for intensive survey. Discoveries from each of these survey types initiates immediate eradication protocol, deployment of eradication/removal teams, and quarantines based on risk analyses.

SUMMARY AND NEEDS

Pathogen Information Gaps

The major impediment to progress in detection and mitigation of any emerging disease is often the lack of scientifically credible information on the identity, biology, and epidemiology of the pathogen. New diseases emerge from many different centers of origin on plants that may or may not be their primary hosts and are often detected only after expanding into new agroecosystems on major host crops or ornamental plants in numbers high enough to be detected. The identification of a newly emerged or previously described disease on a major economical host often creates a crisis situation requiring immediate regulatory and mitigation effort without in-depth knowledge of factors controlling the pathogen's spread, survival, or adaptation to host and climate. The collection of such information then becomes a major priority of the research community in the country of introduction. In a more rational approach, diseases of high priority are identified as they are first detected and initial impacts are surveyed. Resources for research and education are deployed to bring the pathogen to culture collections and distribute the germplasm for study before the pathogen becomes

widespread. Experts in the country of origin are identified and contacted, and cooperative projects are developed for culture exchange, resistance screening, and transfer of resistant germplasm. While this proactive approach is the intent of biosecurity legislature in several countries, in practice, severe limits to research resources result in emerging plant diseases being studied intensely only after introduction and crises occur.

Worldwide Surveillance, Monitoring, and Communication Networking

New pathogens are customarily described in short report format in peer-reviewed journals such as *Plant Disease* (http://apsjournals.apsnet.org/loi/pdis), *New Disease Reports* (http://www.bspp.org.uk/publications/new-disease-reports/index.php), and other plant pathology journals globally. Volunteer members of the International Society for Infectious Disease scan reports of new disease findings and report to subscribers via the listserv ProMED Plant (http://www.promedmail.org/pls/otn/f?p=2400:1000:).

Although the European Plant Protection Organization (http://www.eppo.org/DATABASES/databases.htm) and the Commonwealth Agricultural Bureaux International (http://www.cabi.org/default.aspx?site=170&page=1028) maintain global databases of plant pathogens and published reports of new pathogen outbreaks are included in ProMED Plant listserv messages, no system for real-time capture and recording of new occurrences of disease outbreaks currently exists, due to the costs and degree of international cooperation associated with such efforts. As described previously (39), a unified system for global surveillance and reporting is needed to ensure accurate dissemination of information regarding disease outbreaks and dissemination. Such a system would collect credible information by experts into a centralized database, precisely record the distribution using Geographic Information System longitude/latitude data, apply graphical mapping of the presence and distribution of the pathogen, and include tiered, web-based access to the information by the research community, regulators, first responders, and regulatory officials. Such a system would mirror the IPM PIPE system described above on a global scale. While experts agree on the requirements and components of an effective early warning system, the sensitivities and potential economic and trade implications incurred in reporting new diseases on a local, regional, and international scale represent a major impediment to the creation of open surveillance reporting systems.

Committed Funding Efforts by Legislators

Emerging, infectious plant diseases have long been of concern not only to growers and plant pathologists but also to legislators and policy makers. It was only in the aftermath of 11 September 2001, however, that we were forced to consider the magnitude of our challenge. The establishment of DHS demonstrated the seriousness with which Congress and the President viewed the threats to our nation. Existing federal agencies, particularly the USDA, also stepped up to support effective existing programs and develop new ones (including both the NPDN and the NPDRS) and to design new strategies for resource allocation, interagency cooperation, and effective response. New funding programs were established by both the USDA and DHS, among others, to facilitate the generation of new research strategies and outcomes to more effectively respond to emerging pathogens and pests. These actions were—and are—timely and effective, but even today, they are not enough when

considered in light of the problem. Agencies already stressed to manage the sheer numbers and breadth of plant pathogens and pests entering this country via myriads of routes are often forced into a mode of firefighting, lacking the time, resources, and encouragement for thoughtful, long-range planning and preparation. That resources available to the emerging infectious human disease community are far greater than those to the agricultural community is both necessary and appropriate. However, issues, challenges, and solutions within the two communities are often so similar that crossover, collaboration, and integrated programs and practices between the two could significantly enhance the value of each dollar spent on emerging infectious diseases.

Information Sharing

Efforts to recognize, identify, and mitigate the effects of emerging infectious plant diseases are the responsibility of a number of different agencies, some of which have been established only recently as a result of new attention to the threats of invasive exotic agents and the shadow of bioterrorism. This chapter has presented the roles of many of these entities, and while their missions are distinct, their applications are, appropriately, often related and occasionally even overlapping. Their effectiveness, as well as the prudent use of monetary and personnel resources, is dependent upon trusted relationships, a culture of information-sharing, and a strong, encouraged communication network. The USDA's NPDN, a part of the larger Integrated Consortium of Laboratory Networks system, is a major success story in this regard, having successfully linked more than 50 disparate, unevenly funded and resourced state diagnostic laboratories. Communication and information sharing also is facilitated by the organization and resources of professional societies, in this case particularly APS, which provides the infrastructure to support active subgroups such as a committee on emerging pests and pathogens, a committee on plant biosecurity, and an interest group on microbial forensics. Because about a third of APS members are international, the society also offers opportunities for cross-border, multinational interactions and communication. Openness and sharing of information combined with the values inherent to plant pathologists whose lives are spent fighting plant diseases, helping farmers produce healthy, nutritious crops, and providing scientific research to underpin development of the next generation of disease resistant crops are the keys to a healthy world.

CONCLUSIONS

This chapter provides basic information, for informed readers who are interested in emerging diseases and pathogens but are not experts in plant pathology, on plant pathogens, plant diseases, and the nature and impact of issues related to emergence of new or modified phytopathogens within, or of concern to, the United States. Although plant diseases generally do not cause immediate, acute, or lethal consequences for humans, they can and do result in significant economic harm, as trade is affected and rural communities and downstream industries experience the impacts of crop quarantines, trade embargoes, and loss of income. Strategies for prevention, preparedness, response, and recovery are essential for ensuring the stability of our nation's agricultural enterprise and the constancy and quality of our food, feed, and fiber.

Dedication. This chapter is dedicated to our coauthor Dr. Larry McDaniel, who passed away on 4May 2010. He will be remembered professionally for his many contributions to plant pathology and personally for his commitment, kindness, and gentle humor.

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