Annu. Rev. Public Health 2003. 24:153–74
doi: 10.1146/annurev.publhealth.24.090302.155542

First published online as a Review in Advance on December 2, 2002

ONE FOOT IN THE FURROW: Linkages Between Agriculture, Plant Pathology, and Public Health

Karen-Beth G. Scholthof
Department of Plant Pathology and Microbiology, Texas A&M University, College Station, Texas 77843-2132; email: kbgs@tamu.edu

Key Words genetically modified crops, mycotoxigenic fungi, biological control, environmental health, disease triangle

■ **Abstract** Plant pathology is a field of biology that focuses on understanding the nature of disease in plants as well as on more practical aspects of preventing and controlling plant diseases in crop plants that are important to agriculture. Throughout history, plant diseases have had significant effects on human health and welfare. Several examples, in both historical and contemporary contexts, are presented in this review to show how plant pathogens, biotechnology, and farming practices have affected public health. Specific topics illustrating clear linkages between agriculture and human health include allergens in the environment, food-safety and agricultural practices, mycotoxigenic fungi, agrobioterrorism, and the biological control of plant diseases. The further argument is made that in order to monitor and ensure that good health and safety practices are maintained from "farm to fork," public health specialists may benefit from the resources and expertise of agricultural scientists.

Man does not live by bread alone—but he must have bread. And he must have bread that is truly a staff of life, not a scepter of death (44).

INTRODUCTION

Agriculture is an indispensable part of the lives of people living in economically stable countries, ensuring that nutritious inexpensive food is readily available. Yet the methods of food production and the importance of agriculture are increasingly invisible in our society. With the development of modern farm implements, the labor-intensive practices associated with food production were eased, and in the post–World War II economy, emigration from farms and rural communities to major metropolitan areas became the norm. In the early 1900s, more than 40% of the U.S. population lived and worked on farms. Today, 25% of the population is rural (farm and non-farm) and only 2.5% of the U.S. labor force is in farming occupations (Figure 1) (83). Coincident with this, the day-to-day knowledge of how agriculture affects our health and welfare has diminished. My intent is to show that these relationships deserve continued attention and that agricultural specialists can

0163-7525/03/0505-0153$14.00

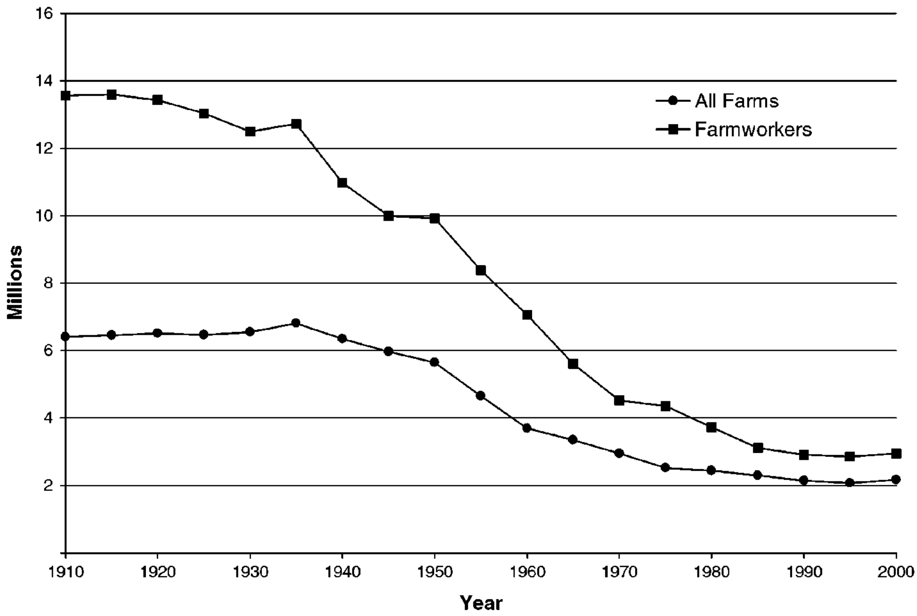

Figure 1 Farms and farmworkers in the United States (1910–2000), National Agricultural Statistical Service, USDA.

contribute to the evaluation of occupational safety and public health and related policy-making programs.

As has been the case throughout the history of agrarian-based societies, conquering famine, drought, pests, and diseases are the goals of science, medicine, and agriculture. Over half of the world's population will live in cities by 2005, placing an added burden on farmers to produce and harvest a sustainable and safe food supply. Because increases in suitable land for cultivation are unlikely, improvements in crop yield and quality are therefore the most realistic strategies to meet the ongoing demand for food, especially cereals, a food staple worldwide. The processing, transport, and storage of foods are political and economic challenges that must be met as food quality and security, or the perceptions of such, are primary determinants of the health and welfare of individuals and societies (32, 74). Improved resource management and applications of agricultural technology will be needed to ensure an abundance of affordable, nutritious foods for all.

A HISTORICAL PERSPECTIVE OF HOW PLANT DISEASES AFFECT PUBLIC HEALTH

The study and understanding of plant diseases to improve plant health broadly defines the area of plant pathology. However, the importance of plant disease control and management extends beyond plant health to have an enormous impact

on the global economy as well as the health of humans, domestic animals, and the environment. As a formal area of study, plant pathology developed at the turn of the twentieth century, with the detailing of an understanding of germ theory and the formalized aspects of modern science (10, 38, 39). Plant pathology has historic roots, dating back thousands of years, which include prohibitions of certain agricultural practices in order to prevent crop losses. Artifacts such as coins and synagogue floor mosaics in Israel dating from the first to the sixth centuries C.E. show malformed Etrog citron fruits with shapes suggesting that the plants were infected with viroids, small infectious circular RNAs (2). There also were horticultural prohibitions of "close cultivation of related plant species in vineyards and the grafting of non-related species," presumably to prevent the spread of grape diseases (2). In the Middle Ages, Hildegard von Bingen [1098–1176] in Germany described diseases of plants, animals, and man (53). Similarly, the extant literature of the Moors, representing the Arabs who had moved into Spain, reveals an interest in plant diseases and remedies dating to the twelfth century (53).

Hieronymus Fracastorius [1478–1553], a respected physician in Verona, Italy, was known to have enjoyed botany and studied the use of plants as medicinals. In 1546 he published *Contagion, Contagious Diseases and Their Treatment* to outline his perceptions of the principles of disease transmission, especially the etiology of known human diseases (88). Fracastorius' observations about plants and plant diseases were equally illuminating. He wrote that "an especially good instance of the contagion that infects by contact only is that which occurs in fruits, as when grape infects grape, or apple infects apples. . . . It is evident that they are infected because they touch, and that some one fruit decays first, but what is the principle of the infection? Since the first fruit from which all the infection passes to the rest, has putrefied, we must suppose that the second has contracted a precisely similar putrefaction, seeing that we defined contagion as *a precisely similar infection of one thing by another*. We must therefore suppose that hot moist particles . . . that evaporate from the first fruit are the principle and germ of the putrefaction that occurs in the second fruit. . . . We must therefore suppose that it is by means of these principles that contagion occurs in fruits. . . . Now the principle is those imperceptible particles . . . in what follows they are called Germs of Contagions" (88). His thoughts were manifested as a prescient idea of germ theory, which would be formally developed in the nineteenth century.

In the 1500s, rye bread was a main source of calories and nutrition in Europe (24, 44). It can be grown in cool, wet climates in many soil types. However, rye is very susceptible to infection by *Claviceps purpurea*, a fungus that produces ergot sclerotia. The effects of ergotism or "St. Anthony's Fire" include seizures, hallucinations, and gangrene (3, 17, 24). The poor ate the worst-quality grain, and children and the elderly were most susceptible to the disease. Europeans, at least those of the upper or ruling classes, were aware of the danger of rye, even if they did not associate the fungi with toxicity. Therefore, the wealthy bought wheat if they could afford it, and they probably had more varied diets than the poor who would eat the cheaper ergot-infested grain as a primary source of calories.

When New World crops such as maize and potatoes were brought to Europe, the dietary transformation often improved the health of the lower classes, especially as potatoes became a primary component of the Irish diet (39, 52).

American colonists settling in New England in the early 1600s planted familiar European cereal crops, including oats, wheat, barley, and rye. Wheat did not thrive in the cool New England climate, and the plants were also very susceptible to wheat rust disease caused by the fungus *Puccinia graminis* (57). Rye, better adapted to cool, wet climates, became a substitute cereal. Weather conditions from 1664–1689 did not favor infection of rye flowers by *C. purpurea*, but in 1690 a cold trend resulted in an outbreak of ergotism and by 1692 ergotism was endemic (44). Matossian (44) has made the controversial argument that ergotism was the trigger for the Salem witch trails. In all, 20 people, mostly women, were tried and executed. At the time, physicians could not determine a source of the illness and decided that the afflicted were under the influence of Satan or bewitched. Signs of bewitchment (in the 1690s) included temporary blindness, deafness, speechlessness, burning sensations, the sense of flying "out of body," feeling sick, or weak; all these are classic symptoms of ergotism (44).

Today, government standards prohibit the sale of grain containing more than 0.3% ergot by weight. The ergot sclerotia can be removed from the grain either with cleaning machinery or by soaking the grain to float the sclerotia. Since sclerotia do not survive for more than a year in the ground, crop rotation and plowing are effective control measures. On a related note, ergot alkaloids and their derivatives have been of great benefit to human health when used as medicines to treat migraine headache, or to induce labor and reduce postpartum bleeding (3, 17).

Until the mid-1800s, manuscripts about plant diseases were descriptive, but rapid advances occurred in parallel with the development of germ theory (39). The origins of modern plant pathology are closely linked to the Great Famine in Ireland, where more than 1.5 million Irish perished and an equal number migrated to North America or Australia (39, 52). The famine was a political and economic event that manifested itself as unimaginable suffering caused by the destruction of the potato by *Phytophthora infestans*, the late blight fungus (52). During the famine [1847–1852], Berkeley and deBary classified the blight as a fungus (a mold) and thus synthesized the then-radical concept that fungi cause disease (39). This discovery predated the results of Pasteur's germ theory and Koch's postulates. In 1898, infectious agents smaller than bacteria were first described by Beijerinck (72), resolving the causal agent of the economically important tobacco mosaic disease as a virus, *Tobacco mosaic virus*.

THE DISEASE TRIANGLE: A MODEL FOR PLANT PATHOLOGY

What were the causes of the imbalances that resulted in disease, as illustrated in the previous section? In plant pathology, the disease triangle provides a model to investigate and understand the parameters associated with plant disease epidemics

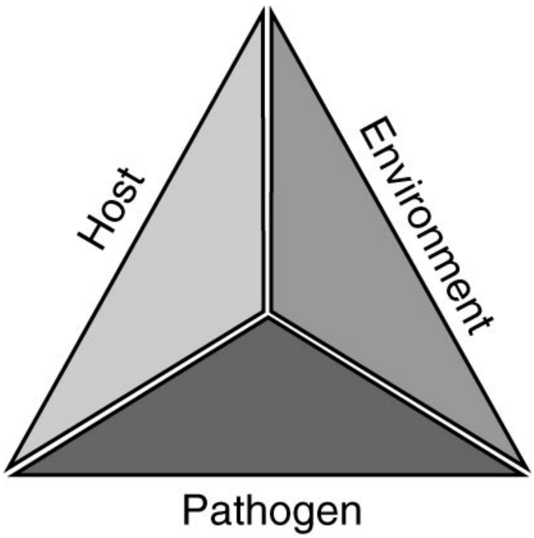

Figure 2 The confluence of interactions between the host/society, pathogen or agent, and the environment leading to reportable or economically significant diseases as represented by the disease triangle model.

(Figure 2). Plant disease development is dependent upon favorable environmental conditions, as well as the presence of a pathogen and a susceptible host plant on which it can elicit disease (45). If any one of these conditions or features is slightly modified it can tip the balance: a bumper harvest or a crop of reduced or no economic value. With the globalization of trade and travel, plants, seeds, and pathogens can rapidly move into new environments, sometimes with devastating effects. Pathogens can also mutate, often resulting in the selection of variants in response to changes in the environment or the host plant.

For plants, the outcome of the disease process can be altered with chemical treatments (fungicides, pesticides, herbicides), disease-resistant stock, and/or plants that are genetically modified to resist disease. Precision agriculture is a more recent all-encompassing technology that improves plant health and reduces the environmental impact of large-scale farming. This new approach uses global positioning systems, satellite imagery, local and historic weather data, and disease forecasting to monitor and control plant diseases and weeds. This is particularly important with modern agriculture, when huge areas are devoted to monoculture, providing the perfect environment for pathogens to rapidly sweep through a crop. Precision agriculture helps farmers to increase crop yields while reducing their real costs and the oftentimes detrimental effects on the land and aquifers that are caused by the overuse of pesticides and water.

One example of the economic and potential food security impact of monoculture was revealed during an epidemic of southern corn leaf blight in the United States in

1970 caused by the fungus *Cochliobolus heterostrophus*. At this time, about 80% of the hybrid corn in the United States had Texas male-sterile cytoplasm (CMS-T), which was an advantage for hybrid corn production since these lines did not produce viable pollen (82). This resulted in cheaper production of hybrid maize because workers were not needed to hand-emasculate the plants. However, the CMS-T maize was preferentially susceptible to this fungal pathogen, especially T-toxin producing strains. This disease outbreak resulted in 80% to 100% yield losses in fields planted with maize hybrids with a CMS-T genetic background (62, 82). This lesson in plant pathology caused the industry to abandon the use of CMS-T maize, and it was a wake-up call to agriculturists of the dangers of planting a genetically uniform crop across a broad swath of the United States. As we continue to depend on only a few major crops for most of our foods, it is particularly important that we understand the impact of diseases on cereals (wheat, rice, maize) and potatoes. There are many lessons in the history of plant pathology that demonstrate the fragility of food security—lessons to remember as we look to technology to improve yields and the nutritional quality of food.

PLANT DISEASES THAT CURRENTLY AFFECT AGRICULTURAL PRODUCTION

In the past decade many pathogens of plants, animals, and humans have been described as emerging or re-emerging. In the scientific literature there are suggestions that these pathogens are finding new hosts as part of taking advantage of new or changing environmental conditions. This requires a multidimensional evaluation of the disease triangle (Figure 2) in an attempt to develop effective control measures.

Although emerging human pathogens and their associated diseases have an immediate emotional and social impact, the plant pathogens should not be overlooked in terms of their potential effect on the human health. With the increasing globalization of agriculture and changes in the environment, phytopathogens and their vectors may represent a greater concern for society than in any recent time.

Late Blight Disease of Potato and Tomato

Potatoes are an important food and make up a substantial source of calories for subsistence farmers around the world (20, 43, 48). More than 150 years after the Irish Famine, late blight disease has reemerged as an economically important disease on potato and tomato due to new and more aggressive strains of *Phytophthora infestans* that are resistant to the systemic fungicide metalaxyl and the worldwide migration of exotic strains since the 1980s (23). The A2 mating type has recently become widely distributed in the Americas, Europe, and Asia; previously it was thought that only the A1 mating type existed outside of Mexico (23, 26). The coincidence of the two mating types allows for the establishment of genetically diverse *P. infestans* populations, making it more difficult to develop resistant potato

varieties and to effectively use fungicides to control the disease. Poor management practices, such as leaving infected tubers in the field or in cull piles after harvest, improper storage of tubers, and diseased tomato cuttings and transplants, can provide an inoculum source for the next growing season if the mycelium produce sporangia and the weather remains cool and damp (35).

Most control strategies focus on good cultivation practices combined with the use of potato lines that limit crop losses associated with *P. infestans* infections (23). Although no potato is immune to the late blight fungus, there are cultivars with some resistance that can keep disease to a minimum, particularly when grown under relatively dry conditions. In addition, prophylactic use of fungicides and killing the plants before harvest can greatly reduce disease and the build up of inoculum in the field. The reemergence of this significant disease calls into question the effectiveness of quarantines and forces us to rethink how new strains or lineages of a fungus can so quickly adapt and displace known clonal lineages that were used in breeding programs to select for pathogen-resistant potatoes (23, 26). It also points out the importance of being able to genetically "fingerprint" pathogens to rapidly diagnose disease and to monitor pathogens in the field and foods that are imported.

Citrus Canker

In Asia, North Africa, and the Americas (81), citrus canker is an economically important disease, causing leaf spotting and blemishes on citrus fruits, defoliation, and fruit drop that results in reduced marketability and quarantine restrictions (73). In time, the health of the tree will decline to such an extent that it no longer produces fruit. The causal agent of citrus canker disease is the bacterium *Xanthomonas axonopodis* pv. *citri*, which is spread by wind and rain (73). Citrus canker was reported in the United States in the early 1910s and in 1984 and was considered eradicated in both instances. It reemerged in 1995 in residential citrus in Florida, threatening the state's $8.5 billion commercial citrus industry (27, 73). More than 2 million trees have been destroyed in an effort to prevent the further spread of the disease into commercial citrus areas of Florida as well as to protect the citrus crops in Texas and California (27, 73). In addition to the potential of citrus canker to ruin citrus production, much political and social ill will has been caused by this disease (73). A single infected orange or grapefruit tree in a neighborhood sparks mandatory eradication of every citrus tree within a 1 km radius (27). Citrus canker disease has provided Florida homeowners with a lesson in the destructiveness and socioeconomic repercussions of plant diseases (27).

Black Sigatoka of Banana

This disease, caused by the fungus *Mycosphaerella fijiensis*, is the most important disease of banana because the fruit is a vital food source in developing countries, and also a valuable export food, ranking fourth after rice, wheat, and milk (76, 81). However, exports account for 10%–20% of banana production, with the remainder

of the crop being used by poor subsistence farmers in Africa, the Americas, and Asia. The Cavendish variety is exported to North American and European markets. The black Sigatoka fungus infects plantains, dessert, and cooking bananas, causing disease everywhere bananas are grown (76). *M. fijiensis* has recently emerged as an important pathogen in the Americans and Caribbean. Black Sigatoka disease causes significant reductions in leaf area and premature ripening, a serious defect in exported fruit. Resistance or tolerance has been reported on banana by growers using systemic fungicides to control the disease, so they often combine these with protectant fungicides. Since natural resistance to *M. fijiensis* is poor and resistant cultivars are not as productive or desirable as marketed varieties, the most important control strategy is disease management, following the disease triangle model (Figure 2). Such practices include removing obviously diseased leaves, increasing the spacing between plants, and providing good irrigation drainage (81). Disease forecasting, using epidemiological modeling and monitoring weather conditions that are favorable for fungal infections, also has been useful to reduce the need for 25 to 40 fungicide treatments per year.

Commercial fungicides are usually too expensive for subsistence farmers to use; most applications are generally limited to multinational corporate farms that can afford up to $1000 per hectare per year to control fungal diseases on banana as a commodity targeted for international food markets. To prevent yield losses of 20%–50% that are associated with this aggressive plant pathogen, weekly applications of fungicide are usually required for adequate control of *M. fijiensis* in commercial fields (81, 86). Intersecting concerns of agriculture, plant pathology, and public health are environmental and quality-of-life issues such as contamination of groundwater and the long-term negative health effects to farmworkers routinely exposed to pesticides.

Plant Viruses and Their Insect Vectors

Plant viruses, especially tospoviruses and geminiviruses, cause economically important losses throughout most of the world (63). Part of the success of *Tomato spotted wilt virus* (TSWV) as a rapidly expanding economically important crop pathogen is the cosmopolitan occurrence of its primary insect vector, western flower thrips (*Frankliniella occidentalis*). Thrips are notoriously difficult to control, in part owing to their small size (<2 mm) and their ability to complete their lifecycle in the soil, which often precludes chemical control measures until an outbreak is under way. In recent years thrips have developed resistance to many commonly used insecticides, confirming the need for improved biological control organisms for the greenhouse and field. The additive effect of thrips damage and TSWV infection often results in significant economic plant losses. The broad host range of TSWV and its ability to recombine with related virus strains of tospoviruses make it difficult to develop long-term stable resistance strategies (63, 64). Genetically engineered plants offer an effective disease strategy for controlling TSWV infections of ornamental plants by reducing the need for expensive chemicals to control the insect vectors, especially in commercial greenhouses and horticultural nurseries.

Like tospoviruses, geminiviruses and their vectors have been broadly distributed as a result of global trade and transport of plants (31, 61). This has become particularly important with the recent findings that different strains of geminiviruses readily recombine in the plant host. In the Americas, *Tomato yellow leaf curl virus* (TYLCV) has devastated tomato production in the Dominican Republic, and the virus has recently been detected in the United States (61). TYLCV was introduced from the Middle East to the Caribbean in the early 1990s and is now established in Florida and Texas. Insecticide applications are generally not effective because of the nearly impossible task of controlling the enormous whitefly populations that are associated with virus outbreaks and rapid transmission of TYLCV by its whitefly vector to host plants. If a grower observes symptoms of virus of infection, such as leaf curling and yellowing, there is no benefit in using pesticides, as pesticides do not lessen these effects. However, it is not uncommon for farmers in developing countries to make several unnecessary applications of insecticides even when total crop loss is a near certainty, resulting in overexposure to pesticides and the pollution to the ecosystem and groundwater (31, 61).

Other strategies, such as crop rotation, altering planting dates or a break in the cropping cycle to remove the food source for whiteflies, can be effective control measures if an entire agricultural production area follows the guidelines. As it takes from five to ten years for plant breeders to develop resistant plants, new strategies to combat the rapid evolution/mutation of the geminivirus genomes and the rapid reproduction rates of whiteflies and their tolerance to pesticides need to be investigated. Genetically engineered resistance, surveillance, and biological control of the vector are strategies that are being tested and deployed in the Americas and Middle East.

In each of these cases, deployment of new technology or modifications of familiar practices to affect the outcome of the disease triangle are dependent upon a close relationship between plant pathologists, farmers, and the public. The current trend in agriculture, coinciding with the needs and wishes of the public and farmers, is to find new and better biological control agents for plant pathogens and insects to reduce pesticide and fungicide applications. A melding of good farm practices to reduce inoculum loads in the field or greenhouse and the application of modern plant breeding and biotechnology are necessary if we are going to produce quality food, forage, and fiber for the world's growing population.

KEY TRENDS AND INTERFACES WITH THE PUBLIC HEALTH SYSTEM

We expect to have ready access to wholesome, inexpensive food, yet most of us lack basic knowledge about farming, where food is produced, and how it reaches the marketplace. Filling in such gaps is one essential component of evaluating the relationships between plant pathology, agriculture, and public health. The following examples focus on farm practices and plant diseases that are known to have beneficial or detrimental effects on community health.

Genetically Engineered Plants and Food

Plant pathologists are using biotechnology to develop disease- and insect-resistant crops to increase yield and quality and to produce added value products in plants. Plants also can be used as platforms to produce pharmaceuticals, particularly vaccines. Some of the public health issues associated with deploying genetically modified plants include food safety and allergens, environmental risks and benefits, pesticide and herbicide use, and distribution of biotechnology in developed and developing countries.

In 1996, ∼8 million acres in the United States were planted with genetically engineered crops, which rapidly increased to more than 67 million acres in 1998 (83). By 2000, ∼41% of the major crop acreage, which includes soybean, cotton, and maize, was genetically modified (49) with a trend of yearly increases (Table 1) (49, 50, 83). One of the goals of developing genetically engineered field crops was to reduce the use of herbicides and pesticides. This has been realized for soybeans based on data provided by the United States Department of Agriculture (USDA) (83). From 1996 to 1998, there was a net decrease in herbicide use in the

TABLE 1 Percentage of genetically modified (GM) major crop acreage in the United States (2000–2002)[a]

		Percentage of specific crop acreage with GM-derived resistance			
Year	**Crop**	**Herbicide**	**Insect (Bt)**	**Multigene**	**Total**
2000	Cotton[b]	26	15	20	61
	Soybean[c]	54	—[e]	—[e]	54
	Maize[d]	6	18	1	25
2001	Cotton[b]	32	13	24	69
	Soybean[c]	68	—[e]	—[e]	68
	Maize[d]	7	18	1	26
2002[f]	Cotton[b]	36	13	22	71
	Soybean[c]	75	—[e]	—[e]	75
	Maize[d]	9	22	2	34

[a]References 49, 50, 83.

[b]Estimates of total (GM and conventional) upland cotton planted in 2000–2002 were 15.5, 15.5, and 14 million acres each growing season, respectively.

[c]Estimates of total (GM and conventional) soybeans planted in 2000–2002 were 74.5, 74, and 73 million acres each growing season, respectively.

[d]Estimates of total (GM and conventional) maize planted in 2000–2002 were 79.5, 76, and 79 million acres each growing season, respectively.

[e]Genetically modified crop not developed or not available for commercial production.

[f]Estimates through June 2002.

United States as the percentage of glyphosate-resistant soybean acreage increased from 7% to 45% (83). Glyphosate-resistant soybeans allow farmers to spray their fields on an "as needed" basis to reduce weeds, a strategy that has the further effect of reducing the input of fertilizer and water. Glyphosate is considered to be relatively environmentally safe since it is readily absorbed to soil where it is degraded and has little potential to contaminate groundwater. From 1996 to 1998, the total amount of herbicide used by farmers who planted glyphosate-resistant soybeans increased from 0.17 to 0.43 pounds per acre (83). At first glance this may seem to be counterintuitive, but glyphosate has a half-life of 47 days versus 60–90 days for herbicides that it replaces. The application of less environmentally friendly herbicides, which are 3.6 to 16.8 times more toxic than glyphosate, has decreased by ∼1 pound per acre, for a net decrease in chemical application of ∼10% (83). Based on these measures and other current scientific results, there will likely be benefits to agriculture and society in developing genetically engineered crops, but more data are needed, including studies on long-term environmental effects and the risks and benefits to public health and the global economy (70, 75, 80).

Modification of plants used for food and forage may be especially useful for the development of foods that are more nutritionally complete (30). This potential has been demonstrated with transgenic rice plants expressing two proteins that complete the carotenoid biosynthetic pathway (90). The strategy behind "golden rice" is to allow the body to synthesize the last step of the pathway from ß-carotene to vitamin A. If the breeding lines of rice hold up to further research, a single serving of rice could provide the recommended dietary allowance of vitamin A to millions of at-risk people worldwide. This would be a first step toward producing more healthful, nutritionally complete foods. Vitamin A–deficient diets cause vision impairment affecting up to 3 million children annually, of whom 250,000 to 500,000 become blind, and at least 60% die within one year (12). The Centers for Disease Control (CDC) estimate that in Southeast Asia alone, between one to two million pregnant women may be at risk from subclinical vitamin A deficiency (12).

Pathogen-derived resistance (68) is a strategy using plants genetically modified with a virus gene or portions of a virus genome to protect against a plant virus infection in the field or greenhouse. This has been one of the success stories of agricultural biotechnology (4, 36), and it is being used to protect squash and papaya plants from destructive plant viruses. As many economically important viruses are seed- and/or insect-transmitted, protecting the plants against infection can have the further benefit of protecting the subsequent crop or increasing the yield and quality of the plant and its seeds. Other goals of agricultural biotechnology include using plants to express pharmaceutical grade proteins and edible vaccines (15, 66, 71).

Mycotoxogenic Fungi

Plant pathogenic fungi of significant detriment to human and animal health are the mycotoxigenic producing species of *Aspergillus*, *Fusarium*, and *Claviceps*. Mycotoxins produced by these fungi as secondary metabolites include aflatoxin, trichothecenes, fumonisins, and ergot alkaloids (17, 58, 60). Some *Penicillium*

species, a familiar blue or green mold on fruits, also produce mycotoxins or carcinogens. Mycotoxin-producing fungi are plant pathogens, generally infecting plants in the field before the grain or seed is harvested. Postharvest damage to the seed coat, either by mechanical means or insect damage, or by poor environmental storage conditions, including high moisture, also provide good conditions for fungal infections (8, 19, 56, 58). Biologically significant amounts of toxin can accumulate even in the absence of obvious fungal contamination; therefore, casual inspection is not sufficient to determine if grain or feed is safe for human or animal use.

Human mycotoxicoses cause life-threatening disorders including human liver cancer, esophageal cancer, and gastrointestinal and pulmonary hemorrhage. In China, hepatitis B virus infections are endemic, and concomitant exposure to alfatoxin B1 is correlated with a 60-fold increased risk of liver cancer (85). Studies in China and South Africa have also shown a causal link between fumonisins and risk for esophageal cancer. The Food and Agriculture Organization (FAO) estimates that 25% of the world food crops are contaminated with mycotoxins.

Grain or seed storage in hot or humid conditions can increase aflatoxin accumulation, making it a particular concern for cotton, maize, and peanut growers in the southern United States (8, 19, 56). In Britain in 1960, the devastating effects of aflatoxin were evident when more than 100,000 turkeys died of turkey X disease, as a result of a diet of *Aspergillus*-contaminated peanut meal imported from Brazil (69). Today, maize, peanuts, and other feeds containing $>$20 ppb aflatoxin are not permitted for animal or dairy use or for human consumption. In Texas, the regulatory limit for aflatoxin in maize that is used by hunters for “deer corn” to attract whitetail deer and other wildlife is currently set at 50 ppb. Milk intended for human consumption is even more strictly regulated by the FDA with an action level of 0.5 ppb of aflatoxin M1. The action levels are based on unavoidable amounts of aflatoxin contamination. If the action level is exceeded, it is illegal to mix or blend clean grain or milk with the contaminated product in an attempt to reduce the final concentration of aflatoxin. One promising strategy to reduce or prevent aflatoxicosis is the use of an aflatoxin-binding dietary clay to block its bioavailability in the gastrointestinal tract of humans and animals (58).

Fusarium species can cause seedling diseases and rots in the field as well as damaging stored grain. As plant breeding approaches to develop *Fusarium*-resistant varieties of maize and wheat have not been successful, most control measures depend on reducing the level of mycotoxin contamination (46). The amounts of fumonisin B_1 (FB_1) toxin in feed are also strictly regulated, with maximum concentrations for horses set at 5 ug/g feed and allowances of ten times that amount for poultry.

In the United States, fumonisin-contaminated grain is ubiquitous, although the low levels of contamination have not been judged a health risk. For example, from 1988 to 1995, of 1300 maize samples collected in the midwestern United States, FB_1 averaged 1–3 ug/g, although amounts of 5–10 ug/g have occasionally been detected in U.S. samples and in grain from Brazil, Italy, and Kenya (46, 47). Milling, cooking, and storage have little effect on decreasing the toxicity of contaminated

grain, providing a historical explanation of how epidemics could continue for months, essentially until the grain reserves were depleted or when the diet became more varied.

F. graminearum, the causal agent of head blight or scab of wheat and barley, has emerged as a significant plant disease in the United States and Canada (87). In the 1990s, epidemics of Fusarium head blight in wheat and barley resulted in estimated losses of $3 billion in the United States and $500 million in Canada (87). In addition to the yield and grain quality losses sustained by small-grain growers, another economic problem associated with *F. graminearum* is that it can produce the mycotoxin deoxynivalenol (DON), commonly known as vomitoxin. The maximum allowable amounts of DON in grain destined for human consumption is 1 ppm (87).

Genetic engineering of maize may provide a strategy to reduce *Fusarium* and *Aspergillus* infections and, by extension, mycotoxin contamination of food and feed (8, 46, 47). Plants transformed with naturally occurring insecticidal genes (Cry), isolated from the bacterium *Bacillus thuringiensis* (Bt), account for ~18% of the maize planted in the United States (49, 50, 83) (Table 1). Bt-maize, expressing one or more of the Cry proteins, is used primarily to control the European corn borer and the corn rootworm beetle (75). These insects can move fungal spores of *Fusarium* and *Aspergillus* from plant surfaces to kernels or from plant to plant across longer distances. An unexpected, but beneficial by-product of deploying Bt-maize has been to reduce *Fusarium* and *Aspergillus* infections, and hence fumonisin and aflatoxin production, respectively (8, 46, 47). Bt-plants may provide one means to reduce the exposure of humans and animals to these harmful postharvest fungi (77). However, there is continuing research on the possible environmental effects of Bt-pollen on nontarget species and on the potential for resistance to develop in the target insect species continually exposed to the Bt-protein toxin during feeding (22, 28, 59, 77). Developing refuge areas with plants that are not genetically modified is one strategy being used to reduce the potential risk of Bt-resistance occurring in these insect pests (22, 75, 77).

Allergens

As indicated above, the control of *Fusarium* and *Aspergillus* are intertwined with public health (8, 46), as are questions about the allergenicity of Cry9C Bt-protein. The potential for this protein to induce an allergic response became a news topic in 1999, following the contamination taco shells and other foods with processed yellow corn that was allowed only for use as animal feed (21). Thus far, the data indicate a very low risk of the Cry9C protein being allergenic, but it has become a matter of public anxiety and incites a certain amount of fear—again related to limited knowledge of how our food is produced and how it gets from the farm to our dinner table (70).

Paradoxically, strategies being tested for reducing toxigenic fungi in grain and oilseed crops may in turn increase exposure of agricultural workers to allergens. Cotton, in addition to its use as a fiber, is an important oilseed crop. To reduce the

occurrence of mycotoxin-producing strains of *Aspergillus* in cotton, atoxigenic (low or no toxin–producing) forms of *Aspergillus flavus* have been produced (25) to out-compete the toxin-forming strains on cotton plants. *Aspergillus* spores are known airway irritants and can cause respiratory distress and allergic responses (14, 84). If the atoxigenic form is ecologically and genetically fit for survival in agricultural applications are there public health risks? In particular, will individuals working in the field during the growing season and harvest and those cleaning or storing grain or fibers be at increased risk for *Aspergillus* infections or other respiratory complications such as allergy or asthma?

The potential for genetically engineered plants to produce foreign allergens was demonstrated when the Brazil nut 2S albumin protein was expressed in soybean, which induced an allergic response in volunteers with sensitivity to this protein (51). The original intent of the research was not to test an allergen, but instead to improve the nutritional quality of soybeans by overexpressing the methionine and cysteine-rich 2S albumin protein (41, 51). This example highlights the need for assays that can determine if a peptide is allergenic (70, 80).

Genetic engineering can also be used to excise or mutate plant genes that are known to express allergenic proteins. A goal would be to produce hypoallergenic foods or to reduce the incidence of known pollen allergens (89). The potential of this approach was demonstrated using antisense mRNA technology to silence expression of the rye grass pollen Lol p 5 allergenic protein gene. Pollen from the genetically engineered rye grass plants was hypoallergenic compared to wild-type pollen when tested in sensitized patients (6). Clearly, there are many venues to discuss the risks and benefits of agricultural biotechnology, and the significant overlap of issues between public health and plant biology is amply illustrated.

Foodborne Illness and Farming Practices

Foodborne illnesses have major repercussions on the health and economy of the United States. It is estimated that 76 million cases of foodborne illness result in more than 300,000 hospitalizations and 5000 deaths each year, and cause economic losses of around $5 billion. Significant reductions might be realized if plant pathologists joined with public health officials to control foodborne microorganisms at their source: in the fields where the crops are produced, extending through postharvest handling and storage.

Given our global marketplace, the food we consume during one meal may originate from many countries. Therefore, agriculture and plant pathology are, by necessity, international concerns, with a blurring of the distinction between domestic and foreign production (78, 79). Although technology has been used to reduce foodborne illnesses in the United States, we are increasingly dependent on other countries for our food supply. For example, in the winter, many of our fruits and vegetables are imported from Chile, Mexico, Peru, New Zealand, and Australia. At certain times of the year, more than 75% of the fresh fruits and vegetables are imported. The USDA has taken a preemptive stance to educate

TABLE 2 Potential sources for microbial contamination of fresh market fruits and vegetables during production and processing[a]

Agricultural event	**Event features**	**Contamination sources**
Production and harvest	Growing, picking, bundling, boxing	Irrigation water, manure, lack of field sanitation
Initial processing	Washing, waxing, sorting, boxing	Wash water, handling, cutting equipment
Distribution	Trucking	Ice, dirty trucks, improper storage temperature
Final processing	Slicing, shredding, peeling, juicing	Wash water, handling, cross-contamination, improper storage temperature

[a]References 5, 79.

consumers about the need for correct preparation of meat, poultry, and eggs to avoid common foodborne microorganisms. However, hazards can be introduced anywhere in the food chain, from the farm to the table, and consequently there is a dire need for programs that are directed toward farm practices, production, and handling (Table 2) (5, 79).

Untreated or contaminated water is a common source of contamination of fruits and vegetables in the field or during packaging. Water used for irrigation, fungicide/fertilizer treatment, and washing fruits and vegetables prior to shipping must be microbiologically safe. After two large outbreaks of salmonellosis were attributed to imported cantaloupe in the early 1990s, the melon industry developed a 'Melon Safety Plan' and focused on using chlorinated water to wash melons and to make ice used for shipping the fruits (79). *Salmonella* contamination of tomatoes (16) has also reinforced the need for being proactive in the field and packing shed to reduce bacterial contamination of tomatoes destined for fresh market.

Outbreaks of *Escherichia coli* and *Salmonella* have also occurred throughout the world as a result of contaminated alfalfa, radish, and bean sprouts. Sprouting seeds are an excellent source of nutrients and are a common component of many cuisines. However, the frequent reports of outbreaks associated with sprouts, and the generally good nutritional status of most Americans who tend to eat raw sprouts, suggest that the risk outweighs the novelty of consuming such products (7, 78).

Alfalfa is produced as a perennial crop that is cut for 3 to 5 years, before plowing over a field to plant another crop, such as wheat, as part of a crop rotation strategy. During production, alfalfa seed destined for sprouts for human consumption is not discriminated from alfalfa seed produced for animal forage. Untreated irrigation water and manure-based fertilizer may be used in its production, and deer and livestock may enter alfalfa fields, contaminating plants with their feces (7). In one trace-back study it was determined that the alfalfa seed was harvested from a field adjacent to a cattle feedlot (7).

Following the CDC guidelines, in 1998 the FDA released a food advisory that children <5 years of age, the elderly, and persons with compromised immune systems should not eat raw sprouts. Guidelines for safe sprout production were also issued that include testing seeds for *E. coli* and *Salmonella*, treating seeds with calcium hypochlorite prior to sprouting, and microbial testing of sprout wastewater. Irradiation may offer another means to reduce bacterial contamination if the seeds are not compromised for germination following treatments: However, organic growers may be reluctant to pursue this strategy.

Nutrients that are released during seed germination provide rich substrate for the amplification of microorganisms. Water, nutrients, and bacteria can quickly spread across a large tray of sprouting seeds, resulting in the production of contaminated sprouts. Hazard analysis and critical control point (HACCP) programs have benefited the $250 million sprout-growing industry in the United States, yet spent waste water monitoring also needs to be implemented by growers. Organic farms, farm stands, and "U-Pick" farms also should develop and follow HACCP guidelines if manure and/or recycled water are used for field or greenhouse production of fresh fruits and vegetables.

Biological Control

Biological control involves the use of fungi and bacteria to control plant pathogens and the diseases they cause. The microorganisms must be shown to be effective and safe to use, including low impact on the ecosystem and no significant negative detriment to plant or human health. Biological control has the potential to reduce our need for fungicides and other agricultural chemicals while protecting plants from disease. Unfortunately, there are not many success stories associated with biological control of fungi that can consistently offer protection in the field, even though this is often a suitable means to control greenhouse pests.

Burkholderia cepacia, a bacterium, has been used as a biological control agent to prevent or suppress several soilborne plant pathogens that cause seedling diseases of plants (33, 55). The bacterium was first described as sour skin, a disease of onion (9, 34), and is considered cosmopolitan, being found worldwide in soil, water, and the air. The effectiveness of *B. cepacia* as a biological control agent is shown by improved seed germination, seedling vigor, and subsequent crop yields. The bacterium can be applied to seed or sprayed on crops; it is also used by the golf-course industry to prepare soil for turfgrass. In addition, the degradative properties of *B. cepacia* are of interest for potential use in the bioremediation of contaminated soils (13). Biological control is increasingly sought after as an environmentally friendly means of controlling plant diseases with the concomitant reduction of pesticide applications. However, human infections caused by *B. cepacia* have increased markedly in recent decades, and respiratory tract infections can be life-threatening for immunocompromised individuals (29, 34, 42). Since *B. cepacia* is a known health risk to patients with cystic fibrosis, new strains are unlikely to be approved for agricultural crops or environmental remediation (55). Furthermore, *B. cepacia* is resistant to a broad spectrum of medically useful antibiotics (55, 84).

On a positive note, the research on *B. cepacia* will provide better insight toward understanding how to use these bacteria as a tool for plant pathology. The challenge is to disarm them so that they no longer pose a risk to humans (54, 65). Research on plant pathogens also has a direct and significant consequence on our understanding of the pathogenesis of human pathogens. For example, *Pseudomonas aeruginosa* infects both humans and plants and likely uses similar strategies to infect both hosts (65, 84). *Yersinia pestis* (a bacterium causing human plague) and *Xanthomonas axonopodis* pv. *vesicatoria* (a bacterium causing black spot on tomato) also have been shown to share pathogenicity mechanisms (54).

Antibiotics

Bacterial diseases of plants are very difficult to manage, because the pathogen can systemically infect the host plants and the bacteria grow rapidly since good resistance genes to protect the crop are often lacking. For bacterial diseases such as fire blight of apple and pear trees, caused by *Erwinia amylovora*, streptomycin treatment is considered a suitable control strategy (37). Also, tetracyclines can be injected into the trunks of palm and elm trees to treat lethal yellows diseases (phytoplasma) (40). Despite these options, the use of antibiotics to control plant disease is unlikely to affect public health. Most growers cannot afford antibiotic applications, and they are aware that antibiotic-resistant strains of bacteria have been detected in orchards. About 0.1% of the total antibiotic use in the United States is for agricultural crop applications.

Biological Warfare and Terrorism

Wheat stem rust is historically one of the most devastating pathogens of wheat and even with decades of introducing and pyramiding resistance genes, it continues to be economically important and thus a possible weapon (57). Based on the limited documentation that is readily accessible, there are reports that stem rust (*Puccinia graminis*) is considered at least as a prototype for testing the dispersal of spores (67). Fungi such as *Fusarium* and *Aspergillus* are other possible agents to deploy; strains that are engineered to express enhanced or multiple forms of fumonisins or aflatoxin. *Fusarium* has been considered for use as an agent to eradicate coca plants in Columbia (1), suggesting that *Fusarium* species might be suitable for adaptation as biological warfare agents against food crops. Despite a great deal of speculation about the potential for using plant pathogens to disrupt or destroy agriculture (11, 18), there is little direct evidence of its practicality or successful deployment by rogue scientists. But as a preventative measure, and as a direct consequence of terrorism occurring on U.S. soil on September 11, 2001, the USA Patriot Act was legislated with strict controls on biological agents and toxins. This includes aflatoxin and T-2 toxin, produced by *Aspergillus* and *Fusarium* species, respectively. This legislation also includes genetically modified organisms and nucleic acid sequences coding for the listed toxins. Interestingly, other than the two mycotoxins produced by plant pathogenic fungi, all of the selected biological agents (bacteria, viruses, rickettsiae, fungi) on the CDC list are

pathogens of humans and livestock. The Agricultural Bioterrorism Act of 2002 lists several plant pathogens that are considered threats to plant health or products. Although "a bioterrorism attack on U.S. agriculture is highly unlikely to result in famine or malnutrition, it could harm people, disrupt the economy, and cause widespread public concern and confusion" (50a). Clearly there is a need for better communication between veterinary, plant, and medical infectious disease experts as a part of improving surveillence and detection networks to reduce the potential threat posed by bioagents.

CONCLUSION

Agriculture links people both locally and globally. Plant health and the environmental conditions associated with growing crops are and will continue to be important indicators for human health. Direct health implications that link agriculture, plant pathology, and public health include emerging and reemerging plant diseases, mycotoxigenic fungi, agricultural biotechnology, allergens, and food safety. Integrating agricultural expertise and education into public health programs (and vice versa) offers an additional means to improve environmental and human health.

ACKNOWLEDGMENTS

I thank Arthur Frank, Randy Ploetz, and Herman Scholthof for their helpful criticism and suggestions during earlier drafts of this manuscript. I also appreciate the generous funding provided by the Program for Scholarly and Creative Activities at Texas A&M University in support of this work during my faculty development leave as a Visiting Scholar at the Department of the History of Science at Harvard University.

LITERATURE CITED

1. Bailey BA, Hebbar KP, Strem M, Lumsden RD, Darlington LC, et al. 1998. Formulations of *Fusarium oxysporum* f.sp. *erythroxyli* for biocontrol of *Erythroxylum coca* var. *coca*. *Weed Sci.* 46:682–89
2. Bar-Joseph M. 1995. A contribution to the natural history of viroids. In *Proc. 13th Conf. Int. Organ. Citrus Virol.*, ed. JV da Graça, P Moreno, RK Yokomi, pp. 226–29. Fuzhu, China
3. Barger G. 1931. *Ergot and Ergotism*. London: Gurney & Jackson. 279 pp.
4. Beachy RN. 1997. Mechanisms and applications of pathogen-derived resistance in transgenic plants. *Curr. Opin. Biotechnol.* 8:215–20
5. Beuchat LR, Ryu J-H. 1997. Produce handling and processing practices. *Emerg. Infect. Dis.* 3:459–65
6. Bhalla PL, Swoboda I, Singh MB. 1999. Antisense-mediated silencing of a gene encoding a major ryegrass pollen allergen. *Proc. Natl. Acad. Sci. USA* 96:11676–80
7. Breuer T, Benkel DH, Shapiro RL, Hall WN, Winnett MM, et al. 2001. A multistate outbreak of *Escherichia coli*

O157:H7 infections linked to alfalfa sprouts grown from contaminated seeds. *Emerg. Infect. Dis.* 7:977–82

8. Brown RL, Chen Z-Y, Cleveland TE, Russin JS. 1999. Advances in the development of host resistance in corn to aflatoxin contamination by *Aspergillus flavus*. *Phytopathology* 89:113–17
9. Burkholder WH. 1950. Sour skin, a bacterial rot of onion bulbs. *Phytopathology* 40:115–17
10. Campbell CL, Peterson PD, Griffith CS. 1999. *The Formative Years of Plant Pathology in the United States*. St. Paul, MN: Am. Phytopathol. Soc. Press. 427 pp.
11. Casagrande R. 2000. Biological terrorism targeted at agriculture: the threat to US national security. *Nonprolif. Rev.* 7(Fall/Winter):92–105
12. Cent. Dis. Control Prev. 1999. Global disease elimination and eradication as public health strategies. *MMWR* 48(Suppl.):154–203
13. Chen W, Bruhlmann F, Richins RD, Mulchandani A. 1999. Engineering of improved microbes and enzymes for bioremediation. *Curr. Opin. Biotechnol.* 10: 137–41
14. Cockrill BA, Hales CA. 1999. Allergic bronchopulmonary aspergillosis. *Annu. Rev. Med.* 50:303–16
15. Cramer CL, Boothe JG, Oishi KK. 1999. Transgenic plants for therapeutic proteins: linking upstream and downstream strategies. *Curr. Top. Microbiol. Immunol.* 240: 95–118
16. Cummings K, Barrett E, Mohle-Boetani JC, Brooks JT, Farrar J, et al. 2001. A multistate outbreak of *Salmonella enterica* serotype Baildon associated with domestic raw tomatoes. *Emerg. Infect. Dis.* 7:1046–48
17. De Costa C. 2002. St. Anthony's fire and living ligatures: a short history of ergometrine. *Lancet* 359:1768–70
18. Deen WA. 1999. Trends in American agriculture: their implications for biological warfare against crop and animal resources. *Ann. NY Acad. Sci.* 894:164–67
19. Dowd PF. 2000. Indirect reduction of ear molds and associated mycotoxins in *Bacillus thuringiensis* corn under controlled and open field conditions: utility and limitations. *J. Econ. Entomol.* 93: 1669–79
20. Economic and Social Dep. 2000. *Agriculture: Towards 2015/30, Technical Interim Report*. Rome: UN FAO
21. Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) Scientific Advisory Panel. 2000. *Assessment of Scientific Information Concerning StarLink Corn, SAP Report No. 2000–06*. Rosslyn, VA: US EPA. 28 pp.
22. Ferre J, Van Rie J. 2002. Biochemistry and genetics of insect resistance to *Bacillus thuringiensis*. *Annu. Rev. Entomol.* 47: 501–33
23. Fry WE, Goodwin SB. 1997. Re-emergence of potato and tomato late blight in the United States. *Plant Dis.* 81:1349–57
24. Fuller JG. 1968. *The Day of St. Anthony's Fire*. New York: MacMillian. 310 pp.
25. Garber RK, Cotty PJ. 1997. Formation of sclerotia and aflatoxins in developing cotton bolls infected by the S strain of *Aspergillus flavus* and potential for biocontrol with an atoxigenic strain. *Phytopathology* 87:940–45
26. Goodwin SB, Smart CD, Sandrock RW, Deahl KL, Punja ZK, Fry WE. 1998. Genetic change within populations of *Phytophthora infestans* in the United States and Canada during 1994 to 1996: role of migration and recombination. *Phytopathology* 88:939–49
27. Gottwald TR, Hughes G, Graham JH, Sun X, Riley T. 2001. The citrus canker epidemic in Florida: the scientific basis of regulatory eradication policy for an invasive species. *Phytopathology* 91:30–34
28. Gould F, Anderson A, Jones A, Sumerford D, Heckel DG, et al. 1997. Initial frequency of alleles for resistance to *Bacillus thuringiensis* toxins in field populations of

Heliothis virescens. *Proc. Natl. Acad. Sci. USA* 94:3519–23
29. Govan JRW, Vandamme P. 1998. Agricultural and medical microbiology: a time for bridging gaps. *Microbiology* 144:2373–75
30. Grusak MA, DellaPenna D. 1999. Improving the nutrient composition of plants to enhance human nutrition and health. *Annu. Rev. Plant Physiol. Plant Mol. Biol.* 50:133–61
31. Harrison BD, Robinson DJ. 1999. Natural genomic and antigenic variation in whitefly-transmitted geminiviruses (Begomoviruses). *Annu. Rev. Phytopathol.* 37:369–98
32. Hertzman C. 2001. Health and human society. *Am. Sci.* 89:538–45
33. Heungens K, Parke JL. 2000. Zoospore homing and infection events: effects of the biocontrol bacterium *Burkholderia cepacia* AMMDR1 on two oomycete pathogens of pea (*Pisum sativum* L.). *Appl. Environ. Microbiol.* 66:5192–200
34. Holmes A, Govan J, Goldstein R. 1998. Agricultural use of *Burkholderia (Pseudomonas) cepacia*: a threat to human health? *Emerg. Infect. Dis.* 4:221–27
35. Hudler GW. 1998. *Magical Mushrooms, Mischievous Molds*. Princeton, NJ: Princeton Univ. Press. 248 pp.
36. Iyer LM, Kumpatla SP, Chandrasekharan MB, Hall TC. 2000. Transgene silencing in monocots. *Plant Mol. Biol.* 43:323–46
37. Johnson KB, Stockwell VO. 1998. Management of fire blight: a case study in microbial ecology. *Annu. Rev. Phytopathol.* 36:227–48
38. Jones LR. 1914. Problems and progress in plant pathology. *Am. J. Bot.* 1:97–111
39. Large EC. 1962. *The Advance of the Fungi*. New York: Dover. 488 pp.
40. Lee I-M, Davis RE, Gundersen-Rindal DE. 2000. Phytoplasma: phytopathogenic mollicutes. *Annu. Rev. Microbiol.* 54:221–55
41. Lehrer SB, Horner WE, Reese G. 1996. Why are some proteins allergenic? Implications to biotechnology. *Crit. Rev. Food Sci. Nutr.* 36:553–64
42. LiPuma JJ. 1998. *Burkholderia cepacia* epidemiology and pathogenesis: implications for infection control. *Curr. Opin. Pulm. Med.* 4:337–41
43. Manning R. 2000. *Food's Frontier: The Next Green Revolution*. New York: North Point Press
44. Matossian MK. 1989. *Poisons of the Past: Molds, Epidemics, and History*. New Haven: Yale Univ. Press. 190 pp.
45. McNew GL. 1960. The nature, origin, and evolution of parasitism. In *Plant Pathology: An Advanced Treatise*, Vol. 2, ed. JG Horsfall, AE Dimond, pp. 19–69. New York: Academic
46. Munkvold GP, Desjardins AE. 1997. Fumonisins in maize: Can we reduce their occurrence? *Plant Dis.* 81:556–65
47. Munkvold GP, Hellmich RL, Rice LG. 1999. Comparison of fumonisin concentrations in kernels of transgenic Bt maize hybrids and nontransgenic hybrids. *Plant Dis.* 83:130–38
48. Myers N, ed. 1993. *Gaia: an Atlas of Planet Management*. New York: Anchor Books. 272 pp.
49. Natl. Agric. Stat. Serv. 2001. *Acreage, June 29, 2001*. Washington, DC: US Dep. Agric. 43 pp.
50. Natl. Agric. Stat. Serv. 2002. *Acreage, June 28, 2002*. Washington, DC: US Dep. Agric. 41 pp.
50a. Natl. Res. Counc. 2002. *Countering Agricultural Bioterrorism.* Comm. Biol. Threats to Agric. Plants and Animals, Board on Agric. and Nat. Resour., Board on Life Sci., Board on Radioact. Waste Manag. Washington, DC: Natl. Acad. Press, p. 194
51. Nordlee JA, Taylor SL, Townsend JA, Thomas LA, Bush RK. 1996. Identification of a Brazil-nut allergen in transgenic soybeans. *N. Engl. J. Med.* 334:688–92
52. Ó Gráda C. 1999. *Black '47 and Beyond:*

The Great Irish Famine in History, Economy, and Memory. Princeton, NJ: Princeton Univ. Press. 302 pp.

53. Orlob GB. 1971. History of plant pathology in the Middle Ages. *Annu. Rev. Phytopathol.* 9:7–20
54. Orth K, Xu Z, Mudgett MB, Bao ZQ, Palmer LE, et al. 2000. Disruption of signaling by *Yersinia* effector YopJ, a ubiquitin-like protein protease. *Science* 290:1594–97
55. Parke JL, Gurian-Sherman D. 2001. Diversity of the *Burkholderia cepacia* complex and implications for risk assessment of biological control strains. *Annu. Rev. Phytopathol.* 39:225–58
56. Payne GA, Brown MP. 1998. Genetics and physiology of aflatoxin biosynthesis. *Annu. Rev. Phytopathol.* 36:329–62
57. Peterson PD, ed. 2001. *Stem Rust of Wheat: From Ancient Enemy to Modern Foe*. St. Paul, MN: Am. Phytopathol. Soc. Press. 168 pp.
58. Phillips TD. 1999. Dietary clay in the chemoprevention of aflatoxin-induced disease. *Toxicol. Sci.* 52:118–26
59. Pimentel DS, Raven PH. 2000. Bt corn pollen impacts on nontarget Lepidoptera: assessment of effects in nature. *Proc. Natl. Acad. Sci. USA* 97:8198–99
60. Pitt JI. 2000. Toxigenic fungi and mycotoxins. *Br. Med. Bull.* 56:184–92
61. Polston JE, Anderson PK. 1997. The emergence of whitefly-transmitted geminiviruses in tomato in the western hemisphere. *Plant Dis.* 81:1358–69
62. Pring DR, Lonsdale DM. 1989. Cytoplasmic male sterility and maternal inheritance of disease susceptibility in maize. *Annu. Rev. Phytopathol.* 27:483–502
63. Prins M, Goldbach R. 1998. The emerging problem of tospovirus infection and nonconventional methods of control. *Trends Microbiol.* 6:31–35
64. Qiu WP, Geske SM, Hickey CM, Moyer JM. 1998. Tomato spotted wilt Tospovirus genome reassortment and genome segment-specific adaptation. *Virology* 244:186–94
65. Rahme LG, Ausubel FM, Cao H, Drenkard E, Goumnerov BC, et al. 2000. Plants and animals share functionally common bacterial virulence factors. *Proc. Natl. Acad. Sci. USA* 97:8815–21
66. Richter L, Kipp PB. 1999. Transgenic plants as edible vaccines. *Curr. Top. Microbiol. Immunol.* 240:159–76
67. Rogers P, Whitby S, Dando M. 1999. Biological warfare against crops. *Sci. Am.* 280:70–75
68. Sanford JC, Johnston SA. 1985. The concept of parasite-derived resistance–deriving resistance genes from the parasite's own genome. *J. Theor. Biol.* 113:395–405
69. Sargeant K, O'Kelly J, Carnaghan RBA, Allcroft R. 1961. The assay of a toxic principle in certain groundnut meals. *Vet. Record* 73:1219–23
70. Scholthof K-BG. 2001. The chimerical world of agricultural biotechnology: food allergens, labeling, and communication. *Phytopathology* 91:524–26
71. Scholthof K-BG, Mirkov TE, Scholthof HB. 2002. Plant viral gene vectors: biotechnology applications in agriculture and medicine. In *Genetic Engineering: Principles and Methods*, ed. JK Setlow, 24:67–86. New York: Plenum
72. Scholthof K-BG, Shaw JG, Zaitlin M, eds. 1999. *Tobacco Mosaic Virus: One Hundred Years of Contributions to Virology*. St. Paul, MN: Am. Phytopathol. Soc. Press. 256 pp.
73. Schubert TS, Rizvi SA, Sun X, Gottwald TR, Graham JH, Dixon WN. 2001. Meeting the challenge of eradicating citrus canker in Florida—again. *Plant Dis.* 85:340–56
74. Sen AK. 1982. *Poverty and Famines: An Essay on Entitlement and Deprivation*. Oxford: Oxford Univ. Press. 257 pp.
75. Shelton AM, Zhao J-Z, Roush RT. 2002. Economic, ecological, food safety, and social consequences of the deployment of

Bt transgenic plants. *Annu. Rev. Entomol.* 47:845–81
76. Stover RH. 1986. Disease management strategies and the survival of the banana industry. *Annu. Rev. Phytopathol.* 24:83–91
77. Tabashnik BE, Patin AL, Dennehy TJ, Liu Y-B, Carriere Y, et al. 2000. Frequency of resistance to *Bacillus thuringiensis* in field populations of pink bollworm. *Proc. Natl. Acad. Sci. USA* 97:12980–84
78. Taormina PJ, Beuchat LR, Slutsker L. 1999. Infections associated with eating seed sprouts: an international concern. *Emerg. Infect. Dis.* 5:626–34
79. Tauxe RV. 1997. Emerging foodborne diseases: an evolving public health challenge. *Emerg. Infect. Dis.* 3:425–34
80. Taylor SL. 2002. Protein allergenicity assessment of foods produced through agricultural biotechnology. *Annu. Rev. Pharmacol. Toxicol.* 42:99–112
81. Thurston HD. 1998. *Tropical Plant Diseases*. St. Paul, MN: Am. Phytopathol. Soc. Press. 200 pp.
82. Ullstrup AJ. 1972. The impacts of the southern corn leaf blight epidemics of 1970–1971. *Annu. Rev. Phytopathol.* 10:37–50
83. US Dep. Agric. 2000. *Agriculture Fact Book 2000*. Washington, DC: GPO. 314 pp.
84. Vidaver AK, Tolin S. 2000. Laboratory, growth chamber, and greenhouse microbial safety: plant pathogens and plant-associated microorganisms of significance to human health. In *Biological Safety: Principles and Practices*, ed. DO Fleming, DL Hunt, pp. 27–33. Washington, DC: ASM Press
85. Wang JS, Huang T, Su J, Liang F, Wei Z, et al. 2001. Hepatocellular carcinoma and aflatoxin exposure in Zhuqing Village, Fusui County, People's Republic of China. *Cancer Epidemiol. Biomarkers Prev.* 10:143–46
86. Washington JR, Cruz J, Lopez F, Fajardo M. 1998. Infection studies of *Mycosphaerella fijiensis* on banana and the control of black Sigatoka with chlorothalonil. *Plant Dis.* 82:1185–90
87. Windels CE. 2000. Economic and social impacts of Fusarium head blight: changing farms and rural communities in the Northern Great Plains. *Phytopathology* 90:17–21
88. Wright WC. 1930. *Hieronymus Fracastorius: Contagion, Contagious Diseases and Their Treatment*. New York: Putnam Press. 356 pp.
89. Yaklich RW, Helm RM, Cockrell G, Herman EM. 1999. Analysis of the distribution of the major soybean allergens in a core collection of *Glycine max* accessions. *Crop. Sci.* 39:1444–47
90. Ye X, Al-Babili S, Kloti A, Zhang J, Lucca P, et al. 2000. Engineering the provitamin A (ß-carotene) biosynthetic pathway into (carotenoid-free) rice endosperm. *Science* 287:303–5

Annual Review of Public Health
Volume 24, 2003

CONTENTS

ERRATA

An online log of corrections to *Annual Review of Public Health* chapters (if any have yet been occasioned, 1997 to the present) may be found at http://publhealth.annualreviews.org/