Forensic Phytopathology: a Critical Review

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ABSTRACT Forensic phytopathology is the application of plant pathology to legal or criminal matters. It is an emerging field. The existing literature focuses mainly on potential agricultural bioterrorism threats to the United States. Here we try to take a broader view including agricultural bioterrorism, mycoherbicide applications to eradicate plants used for illegal drugs, civil cases involving charges of sale or movement of diseased plants, and mycotoxins. In several of the examples given the evidence is inconclusive, but the examples are no less interesting for that.

DEFINITIONS AND EXISTING LITERATURE

If forensic science is any science used for the purposes of the law (as defined by the American Academy of Forensic Sciences) or for solving a crime, then forensic phytopathology is the application of plant pathology to purposes of the law. In other words, it is the interface between plant pathology and civil and criminal legal affairs. It is a largely unexplored field and is still developing.

The existing literature on forensic phytopathology is limited in several ways. First, it is limited in historical trajectory: most of the articles have been published in the past 20 years. Second, it is limited in scope: previous reviews in this field have focused almost exclusively on bioterrorism and much less on civil issues. Third, much of the relevant information is not in peer-reviewed scientific journals but in less reliable sources, such as the popular press. And fourth, it is limited in perspective: the approach to bioterrorism has been one-sided, focusing mostly on potential threats to U.S. agriculture by foreign agents and ignoring some of the most interesting and important examples.

One of the strengths of the existing literature is that it describes the use of forensic phytopathology to teach basic principles of plant pathology. An interesting example is a lab exercise that uses the idea of crime scene evidence to teach taxonomy of plant-pathogenic fungi (1). We try to follow that model here. To understand forensic phytopathology, it is necessary to keep in mind the classic dictum of our field: plant disease is an interaction between a pathogen, a host, and the environment. This is represented in the form of a triangle with the three players at the points and the sides representing pairwise interactions (Fig. 1). More recently, it is often represented as a tetrahedron, with time as the fourth point (2, 3). The presence of a pathogen is not enough to cause disease without a susceptible host, a propitious environment, and sufficient time. Of course, these models are conceptual tools that cannot fully account for the complexity of some of the examples below.

In this chapter, we review examples of forensic phytopathology, grouped in four sections: bioterrorism, biocontrol of narcotic plants with mycoherbicides, civil cases, and mycotoxins. Some of these examples are illustrative of important concepts in plant pathology, and all are interesting.

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BIOTERRORISM ATTACKS ON CROP PLANTS

A number of reviews provide concise and well-written summaries of the potential use of plant pathogens as agents of bioterrorism against crops in the United States (4–9). Other reviews summarize historical evidence for the use of plant pathogens as bioweapons, mostly in Europe in World Wars I and II and during the Cold War (10–12). Others describe the different methodologies and types of evidence available, and how they interact with the needs of the legal and criminal justice systems (4, 6, 13). These publications are essential reading for anyone interested in this field.

Many of these articles were published shortly after the 9/11 attacks and address post-9/11 homeland security concerns. The fact that fewer articles have been published recently might suggest that they overestimated risks of plant pathogens as agents of agricultural bioterrorism—or, alternatively, that society has become complacent and let down its guard.

Invasive plant pathogens that are believed to pose serious threats to U.S. agriculture are listed as select agents under the Agricultural Bioterrorism Protection Act of 2002. Intended to prevent or deter agroterrorism, this act also puts serious bureaucratic obstacles in the path of researchers who want to work on these pathogens, thus discouraging potential studies (14). In one case, a plant pathology group had to travel 225 km to work on “Candidatus Liberibacter asiaticus” (causal agent of huanglongbing, or citrus greening) because of these legal requirements, even though the pathogen was already infecting citrus trees near their lab in Florida (14). Seven plant pathogens are currently listed as select agents (http://www.selectagents.gov/SelectAgentsandToxins.html). In the case of “Candidatus Liberibacter,” the organism reached the United States by unintentional or natural introduction and eventually was removed from the select agent list.

Another example is Asian soybean rust, caused by the fungus *Phakopsora pachyrhizi* (and, to a lesser extent, by *Phakopsora meibomiae*). It is an extremely destructive pathogen, capable of causing up to 80% yield loss in some areas (15). Given the importance of soy to U.S. agriculture, Asian soybean rust was considered a potential bioterrorism agent post-9/11 and was included on the select agent list. It was found in Louisiana in 2004, apparently introduced as windborne spores in a hurricane or tropical storm, and has since been found in eight states. A National Association of State Departments of Agriculture report recommended that the U.S. Department of Agriculture (USDA) and Department of Homeland Security take soybean rust off the select agent list, because its listing might impel trade partners to block importation of U.S. soybeans (16).

A positive consequence of the post-9/11 focus on preventing agricultural bioterrorism was the establishment of the National Plant Diagnostic Network, linking diagnostic laboratories at universities in each state into a system to detect, diagnose, and report pathogens and pests (5). A National Plant Disease Recovery System compiles reports on specific pathogens viewed as critical threats to U.S. agriculture (http://www.ars.usda.gov/News/docs.htm?docid=14271).

MYCOHERBICIDES AS WEAPONS IN THE WAR ON DRUGS

The concept of what constitutes bioterrorism appears to vary with the perspective of the viewer. The following cases involve efforts, sponsored largely by the U.S. government, to develop fungi as mycoherbicides to spray on drug crops in other countries. In the scientific literature these cases are not usually referred to as bioterrorism, but in the eyes of many people in the target countries they are as much bioterrorism as deliberately
infesting the U.S. soybean crop with *Phakopsora pachyrhizi* would be. In this section we also address the alleged use of mycoherbicides against crop plants in Cuba.

**Fusarium as a Mycoherbicide To Kill Coca and Marijuana**

*Fusarium oxysporum* f. sp. *erythroxyl*ii, known as FoxyE, was isolated as a soilborne pathogen of *Erythroxylon coca* at a research center in Hawaii in the 1980s (17). It causes a vascular wilt that killed seedlings grown from coca seeds imported from Peru; the same fungus caused heavy losses in coca plantations in the Huallaga Valley in Peru (18). Certain strains of FoxyE were shown to cause vascular wilt on *E. coca* and *Erythroxylon novogranatense* under greenhouse conditions (19, 20). FoxyE strain En-4 was developed by the U.S. government as a bioherbicide to eradicate coca plants. It was intended to be an alternative to glyphosate (trade name Roundup), which was sprayed from airplanes over large areas of Colombia as part of Plan Colombia (17, 18).

The use of *F. oxysporum* f. sp. *erythroxyl*ii to kill coca was proposed by the U.S. Congress in the Plan Colombia program in 2000 but was blocked by President William Clinton because it could be considered biological warfare. Peru subsequently passed a law banning the use of biological agents in coca eradication in 2000, and similar laws were passed in Bolivia, Colombia, and Ecuador. However, Congressman Dan Burton and other War on Drugs supporters were still arguing for its inclusion in Plan Colombia in 2005 (21).

Its supporters argued that *F. oxysporum* f. sp. *erythroxyl*ii was highly host specific, less destructive to nontarget plants than glyphosate, and endemic to coca-growing areas in Peru (12, 17, 18, 22). Its detractors objected for several reasons. (i) It is unclear if *F. oxysporum* f. sp. *erythroxyl*ii would have been effective as a mycoherbicide under field conditions. (ii) Twenty-six plant genera were evaluated in greenhouse experiments, and FoxyE was pathogenic only on *E. coca* and *E. novogranatense* (species used to produce cocaine) (20). However, the other 283 *Erythroxylum* species in the tropics and subtropics were not included in the virulence experiments, so the degree of host specificity was never established (17, 22). (iii) FoxyE and *Fusarium oxysporum* were compared using random amplified polymorphic DNA analysis (23). This technique successfully distinguished FoxyE from nonpathogenic isolates of *F. oxysporum* from *E. coca*. However, the technique could not differentiate between races of FoxyE from different areas and hosts or fingerprint specific genotypes to follow them in the field. This means that the spread of the applied mycoherbicide would be difficult to evaluate. (iv) *F. oxysporum* includes serious pathogens of many crops, and recombination or mutation could lead to host switching or increases in virulence. (v) Some strains of *F. oxysporum* can produce mycotoxins that affect human health, including diacetoxyscirpenol, T-2 toxin, and zearalenone (24–27). Studies on FoxyE as a mycoherbicide did not test for mycotoxin production, and it is unclear if its application to coca plants could represent a health risk for consumers. Coca leaves have been used by indigenous groups in South America (Quechus, Aymaras, and Chibchas among them) for religious and medicinal purposes for thousands of years; the potential contamination of coca with mycotoxins is viewed by some people as a threat to their way of life.

*Fusarium oxysporum* also attacks *Cannabis* (28). *F. oxysporum* f. sp. *cannabis* and *F. oxysporum* f. sp. *vasinfectum* cause damping off, stem canker, root rot, and wilt (28, 29). Although morphologically these two *formae speciales* are very similar, they can be distinguished because *F. oxysporum* f. sp. *cannabis* infects only *Cannabis*, whereas *F. oxysporum* f. sp. *vasinfectum* has a wider host range (30). *F. oxysporum* f. sp. *cannabis* was used successfully to infect *Cannabis* plants in greenhouses, growth chambers, and fields in Italy and Kazakhstan (30, 31).

*F. oxysporum* f. sp. *cannabis* was proposed as a mycoherbicide to control Florida’s outdoor marijuana industry by Jim McDonough, a former top aide to then-U.S. Drug Czar Barry McCaffrey, in 1999 (21). This plan was strongly opposed by David Struhs, head of Florida’s Department of Environmental Protection. In April 1999, he wrote: “It is difficult if not impossible to control the spread of the *Fusarium* species. *Fusarium* species are capable of evolving rapidly... Mutagenicity is by far the most disturbing factor in attempting to use a *Fusarium* species as a bioherbicide. The mutated fungi can cause disease in a large number of crops, including tomatoes, peppers, flowers, corn and vines” (21).

**Pleospora papaveracea, a Pathogen of Opium Poppies**

A similar story unfolded with *Pleospora* (Crivellia) *papaveracea*, a pathogen of opium poppies, *Papaver somniferum* and *Papaver bracteatum*. Afghanistan is the world’s leading producer of opium and its derivative, heroin. The use of *P. papaveracea* as a mycoherbicide has been proposed. The fungus was first isolated in the 1980s by the Institute of Genetics in Tashkent,
Uzbekistan. In 1999 a “highly virulent” isolate was found that caused 50 to 75% losses in poppy crops (18). Symptoms on adult plants included leaf and stem necrosis, stem girdling, stunting, necrotic leaf spots, and foliar and pod blight. Symptoms on seedlings included wire stem, damping-off, and root rot (32).

In 1999 and 2000, the governments of the United Kingdom and the United States funded a project implemented through the Institute of Genetics in Tashkent to produce spores of *P. papaveracea* and develop field tests in four neighboring countries (http://www.sunshine-project.de/infos/archiv/hintergrund/nr_04.pdf). In addition, in 2000 the USDA conducted tests with *P. papaveracea* in its laboratories in Beltsville, MD. *Pleospora papaveracea* and *Brachycladium papaveris* were isolated from seeds, diseased leaves, and pods of opium poppy from Iran, Colombia, Venezuela, Sweden, India, and the United States (32). A highly virulent transgenic strain of *P. papaveracea* was made by inserting the gene for the Nep1 protein from *Fusarium oxysporum* (33). Nep1 induces production of ethylene and causes extensive necrosis on leaves of dicotyledons such as poppies. However, according to Eric Rosenquist, USDA-ARS Senior National Program Leader, the USDA opposed the use of mycoherbicides in Afghanistan to control poppies because of environmental and possible human health implications (21).

In 2006, President George W. Bush signed the Office of National Drug Control Policy Reauthorization Act, which required an efficacy study of mycoherbicides on the opium poppy and coca (http://www.gpo.gov/fdsys/pkg/PLAW-109publ469/html/PLAW-109publ469.htm). According to section 1111a, no more than 90 days after the date of enactment of this Act, the Director of the Office of National Drug Control Policy shall submit to the Congress a report that includes a plan to conduct, on an expedited basis, a scientific study of the use of mycoherbicide as a means of illicit drug crop elimination by an appropriate Government scientific research entity, including a complete and thorough scientific peer review. The study shall include an evaluation of the likely human health and environmental impacts of mycoherbicides derived from fungus naturally existing in the soil.

In response, the Office of National Drug Control Policy requested that the National Academy of Science’s National Research Council form an expert committee to assess the use of naturally occurring mycoherbicide fungi as a means of eradicating illicit cannabis, coca, and opium poppy crops. The Committee on Mycoherbicides for Eradicating Illicit Drug Crops included distinguished scientists from academia and various government agencies. Their 2011 report, *Feasibility of Using Mycoherbicides for Controlling Illicit Drug Crops* (18), concludes that more research is needed to evaluate toxicological effects, inoculum production and delivery, persistence of the fungi, effects on nontarget plants and organisms, and mutations—in short, a conclusion in which nothing is concluded. However, their report is the definitive work on the topic and is available online (http://www.nap.edu/catalog.php?record_id=13278).

**Were Mycoherbicides Used in the “Dirty War” against Cuba?**

Tobacco blue mold (*Peronospora tabacina*) attacked Cuba’s tobacco fields, destroying 25% of the crop in 1979 and 90% in 1980 (34). The Cuban government claimed this was part of the “dirty war” by the Central Intelligence Agency (CIA) to cause the overthrow of Fidel Castro. However, evidence to support this claim was apparently never published. Although the claim was repeated by other sources, most scientific accounts appear to have concluded that *Peronospora* spores reached Cuba on wind currents from other parts of the Caribbean.

A similar case is sugarcane rust, caused by *Ustilago scitaminea*. It reached Cuba in 1979 and was also claimed to have been intentionally introduced by the CIA (34). The most likely explanation is that windborne spores crossed the Atlantic from Cameroon. This explanation is supported by the fact that *U. scitaminea* arrived in the Dominican Republic at the same time (35).

Similar claims were made for a variety of other plant pathogens and pests, including black sigatoka of bananas, the coffee berry borer, thrips, and rice mites (34). Commentators have noted that every time production of a crop was intensified in Cuba, a new disease appeared that attacked it. This was assumed to be evidence that the CIA was monitoring Cuban agriculture and continually mounting new attacks (e.g., http://www.afrocubaweb.com/biowar.htm). However, plant pathology teaches us that naturally dispersed pathogens and pests are more likely to become problematic as crop area increases (2), so human intervention is not necessarily the explanation for the appearance of these pathogens.

**CIVIL OR UNINTENTIONAL CASES**

The existing literature on forensic phytopathology focuses on plant diseases that could be—or could have been—intentionally caused. However, in most cases the introduction of pathogens is unintentional (13), and these cases have been of far greater practical importance.
They are forensic in the sense that it is often necessary to establish legal liability.

These cases often involve one or more of the following:
- appearance of a novel pathogen or host range expansion to a new host species
- appearance of known pathogen in a new area
- attempts to limit the spread of a pathogen
- uncertainty about when a plant was infected
- uncertainty about who was responsible

A few examples will illustrate the complexity of these cases. They also show the complexity of the interface between science and the legal system. Of course, there are economic aspects as well: in cases of quarantine imposed to limit spread of plant diseases, producers in the embargoed areas lose business, and competitors in other areas will potentially gain business. This may lead to allegations of commercial considerations in what are supposed to be decisions based on science (36, 37).

Many of these diseases (along with others) are discussed by Fletcher et al. (6).

Vine Decline, or Black Goo Disease of Grapevine

The case of vine decline, or black goo disease of grapevine, involves transactions in which buyers claimed they were sold infected plant material or supplies; the sellers claimed that plants and materials they sold were clean, and the fact that plants later became diseased was not their fault. For plant diseases with a long latent period, it can be very difficult to determine which party is correct.

Phaeoacremonium and Cylindrocarpon fungi are the causal agents of vine decline. Symptoms include stunted growth, chlorosis, unsuccessful grafts, and a diagnostic sticky ooze from the phloem when vines are cut. These symptoms can take months or years to develop, so it can be difficult to determine when and where plants became infected. Even the universally admired and well-maintained University of California—Davis grapevine collection was found to be infected (38).

Many wineries in northern California replaced vines susceptible to the Phylloxera root louse in the 1990s. Some of the new vines developed vine decline, which the growers in some cases blamed on the nurseries from which the plants were bought. In one such case, the grower sued Sonoma Grapevines, claiming that the company knowingly sold him infected vines; the company countersued for slander (39).

Sudden Oak Death

Phytophthora ramorum is an emerging pathogen. It was first described in 1995 as the causal agent of die-off of oaks (Quercus spp.) and tanoaks (Notholithocarpus densiflorus) in northern California. Named sudden oak death, this epidemic caused great alarm for several reasons: the suddenness with which it started, the number of host plants affected, and the environment in which it prospered. Other genotypes of the same pathogen were found in Europe (http://www.dontmovefirewood.org/gallery-of-pests/sudden-oak-death-syndrome.html). Phytophthora species cause many serious plant diseases, but they are typical of wet climates; in this case the disease apparently started in the mostly dry, Mediterranean climate of the Central Valley and Coast Range mountains. Within a few years, P. ramorum was found as a pathogen in the Pacific Northwest as well, and transport of plants was being restricted.

Uncertainty about which plants were diseased and efforts to restrict their movements resulted in numerous regulations and lawsuits. For example, in 2004 Kentucky banned shipment of plant material and soil from California; the California Association of Nurseries & Garden Centers sued Kentucky, claiming that the ban was illegal because it went beyond USDA regulations and thereby violated the Plant Protection Act of 2000 (40). Similarly, in 2009 South Carolina imposed restrictions on shipments of nursery plants from California, Oregon, and Washington (the states known to harbor sudden oak death).

Citrus Canker

Citrus canker is a serious disease of citrus leaves, fruits, and twigs caused by the bacterium Xanthomonas campestris pv. citri. It is thought to have originated in Southeast Asia (41). Citrus canker was introduced to Florida in 1933 and 1986 and was successfully eliminated both times. It appeared again in 1995. To limit its spread and damage to Florida’s citrus industry, the Florida Department of Agriculture ordered eradication of all citrus trees within 1,900 ft of an infected tree (http://www.crec.ifas.ufl.edu/extension/canker/history.shtml). Many trees were removed in residential areas from 2002 to 2006. Over 40,000 homeowners sued, claiming that the trees removed were healthy, and they deserved higher compensation than the state of Florida had provided them. Courts ruled in favor of the plaintiffs (even though the state’s actions were scientifically justified), but nearly a decade later the amount of damages was still in dispute. In one case $20 million was awarded to a group of plaintiffs in 2014 (42). In another
case in 2014, a judge refused to award the damages because the state legislature had not allocated the money (43). Most disturbing from a plant pathologist’s perspective was a judge’s ruling that the science of tree disease could not be mentioned as evidence during the trial (44).

Witches’ Broom of Cacao
Intentional introduction of a disease is claimed to have caused widespread losses to cacao in Brazil. The disease is witches’ broom of cacao, caused by the fungus Crinipellis perniciosa (2). An outbreak in Bahia in northeastern Brazil starting in 1989 was alleged to have been intentional. The epidemic caused a 50% decline in cacao production in Brazil and cost 200,000 jobs (45).

Initially, fingers were pointed at the Ivory Coast and Ghana, both cacao-producing nations (43). It is now believed that the pathogen was brought from Rondônia in northwestern Brazil, where it is endemic. The evidence included diseased cacao branches found tied to trees, presumably to disperse the spores. The federal police investigated but did not reach a conclusion.

Seventeen years later, a technician with the Ministry of Agriculture allegedly confessed to have participated in the intentional spread of the pathogen. He said it was politically motivated, to attack the power of the cacao barons in the region and destabilize the local government. Comparison of DNA fingerprints of the pathogen from both regions is consistent with this story (46) but of course does not exclude the possibility of unintentional introduction. These claims are presented in a 2012 documentary called O Nó, Ato Humano Deliberado by Dilson Araújo, available online with English subtitles (https://www.youtube.com/watch?v=0mi3Yocm-4 or http://www.filmesbrasileiros.net/o-no-ato-humano-deliberado/). The documentary also addresses the human and environmental costs of agricultural bioterrorism. However, the claims have not been proved; in fact, none of the people implicated had been charged as of 2014, and several continue working with cacao for the Brazilian government.

An interesting but unaddressed question is this: given the large scale of cacao cultivation in Bahia, and the tremendous flux of people and goods in Brazil, how much longer would it have taken the pathogen to arrive on its own?

MYCOTOXINS
Some plant pathogens are problematic because of the toxins they produce rather than because of the diseases they cause. Several species of Aspergillus, Penicillium, and Fusarium are opportunistic pathogens of living plants and also infect crop products postharvest. They can produce toxic secondary metabolites that make plant products unfit for human or animal consumption. Other fungi, such as the Epichloë/Neotyphodium group, are obligate, mutualistic endosymbionts of grasses, producing alkaloids that are toxic to herbivores, including livestock.

Aflatoxins
Aflatoxin and other mycotoxins are regulated in many commodities, with levels as stringent as the parts per billion (or microgram per kilogram) levels set by the FDA, European Union, and food safety agencies of other countries. The stringent limits mean that hundreds of millions of dollars in losses are incurred when contaminated commodities are rejected. The regulatory and ensuing legal aspects of mycotoxins make them among the most important examples of forensic phytopathology.

Although the most common consequence is rejected lots of commodities, growers, processors, exporters, and their insurers may be subject to criminal and civil demands if their products exceed legal limits for mycotoxins. The threat of potential lawsuits adds to the burden of testing for mycotoxins (36). Sampling is extremely complex because a single highly contaminated grain or seed can cause a whole shipment to exceed the established limits, if by chance it is included in the sample (47).

Three examples will illustrate the type of legal cases arising from claims of mycotoxin contamination.

In 1990 the FDA warned the Peanut Corporation of America (PCA) that some of its shipment levels contained aflatoxins above the 20-ppb limit (http://www.foodhaccp.com/1news/020409p.html). Several candy-makers subsequently sued the PCA, even though the aflatoxin content of their products was well below the legal level. The PCA, in turn, sued a supplier of peanuts. The PCA later went bankrupt, and its president was convicted in federal court after the company was linked to Salmonella poisoning (https://en.wikipedia.org/wiki/Peanut_Corporation_of_America#cite_note-pca-3).

In 2008 a scandal broke in Japan when Mikasa Foods was accused of selling 400 metric tons of rice contaminated with aflatoxins and the pesticide methamidophos for human consumption (48). A criminal investigation was launched, and one rice dealer committed suicide.

A 2015 class action lawsuit by dog owners alleged that Beneful dog food, produced by Nestlé Purina Petcare, contained mycotoxins and propylene glycol that...
killed several thousand dogs (49). However, the news stories on this case do not mention whether the lots of dog food in question were ever tested and shown to contain mycotoxins above permitted limits, or even which mycotoxins were believed to be involved.

The presence of detectable levels of mycotoxins in commodities is not necessarily dangerous; it reflects the analytical power of chromatography and detection methods, which are increasingly sensitive, rather than reflecting risks to public health (50, 51). Methods used to detect mycotoxins in commodities have been reviewed extensively (see, e.g., reference 47).

Speaking of aflatoxins, UN Secretary General Kofi Annan said in 2001 (52):

All of these [regulations] are ostensibly designed to protect consumers, and ensure that they know what they are buying. I am not saying that is unnecessary. But the requirements are often absurdly complex.

Let me give one example: the European Union regulation on aflatoxins. A World Bank study has calculated that this regulation costs Africa $750 million each year in exports of cereals, dried fruit and nuts.

And what does it achieve? It may possibly save the life of one citizen of the European Union every two years.

Please do not misunderstand me. I am the last person to undervalue even one human life.

But here many African lives are at stake – the lives of those whom the chance to export those products might save from an early death, caused by malnutrition or endemic disease.

Surely these regulations need to be reviewed with a sense of proportion! Surely a more reasonable balance can be found.

Two Mycotoxin Mysteries
Two interesting—and mysterious—examples of forensic phytopathology involve mycotoxins. The first is the “yellow rain” controversy. In 1981 the U.S. government accused the former Soviet Union and its allies of using mycotoxins as biological weapons in Laos, Kampuchea (Cambodia), and Afghanistan, in violation of the Geneva Protocol and the Biological and Toxin Weapons Convention (53). The mycotoxins in question are T-2 and other trichothecenes, produced by Fusarium species. Multiple lines of evidence were presented: (i) interviews with refugees in Thailand and with Vietnamese and Laotian combatants, many of whom reported low-flying aircraft spraying mists, yellow and other colors; (ii) symptoms including lesions, blistering, necrosis, dizziness, blurred vision, nausea, and death in people exposed to the sprays; (iii) detection of mycotoxins in environmental samples, including sticky spots associated with the yellow mists; and (iv) detection of mycotoxins in tissue samples from exposed individuals (53, 54).

However, a group of influential scientists proposed an alternative explanation: the yellow rain was excrement from mass migrations of bees, and the mycotoxins came from plant products the bees had consumed (55, 56). The anecdotal evidence was attributed to hysteria and leading questions from investigators.

The claims are difficult to evaluate because most were published in reports and news stories rather than in peer-reviewed scientific journal articles and it is not always clear whether appropriate controls were used. Much of the evidence remains classified, and it is not clear if the controversy will ever be resolved (54).

The second example is that of biological weapons in Iraq. Between 1985 and 1991 (when the first U.S. invasion of Iraq occurred), Iraq developed and produced missiles containing anthrax spores, botulism toxin, and aflatoxin (9). It is not clear or logical how a weapon containing aflatoxin would be useful, since the health effects of aflatoxins are mostly long-term; a biological weapon that causes liver cancer in a few of its victims 20 years later will not win any wars. Several hypotheses have been advanced to explain why aflatoxins were used: they may have been easier to produce than other bioterrorism weapons, thus helping program managers fulfill their quotas, or they may have been intended to cause panic in Iran (Iraq’s principal enemy at the time) (9).

CONCLUSIONS
So let us consider these examples in light of the classic triangle (or tetrahedron) model of plant disease. The bioterrorism examples cited above show that the presence of the pathogen is not sufficient to cause disease: one can spray a field with spores, but if the host is not susceptible and the environment is not propitious, nothing will happen. In fact, the most remarkable—and fortunate—aspect of these agricultural bioterrorism (and antinarcotic mycoherbicide) cases is that despite multiple research efforts and millions of dollars invested in developing, detecting, and preventing them, there is very little evidence they have ever been applied successfully, except perhaps in the case of witches’ broom of cacao mentioned above.

There is a common element in the examples of soybean rust, blue mold of tobacco, and sugarcane rust mentioned above: bioterrorism was anticipated or
alleged, whereas the pathogen probably arrived unassisted. A classic dictum of microbial ecology, postulated by Lourens Baas Becking in the 1930s, is “everything is everywhere; the environment selects” (57). (This dictum does not apply equally to all types of pathogens and does not take into account the quantity of inoculum necessary to establish an initial infection, but it is relevant to the three examples cited here.) For a microorganism that produces very large quantities of very small propagules, dispersal is not a limiting factor; wind, water, or other agents can move them just about anywhere. What determines where they will colonize is the combination of a suitable host population, a suitable environment, and sufficient time. Given the enormous scale of cultivation of many important crops, many such potential examples of agricultural bioterrorism, even if they were successfully introduced, might just be accelerating the inevitable. However, delaying the arrival of a serious crop pathogen by even a few years may gain valuable time in preparing management and control strategies.

A society without the threat of agricultural bioterrorism and lawsuits involving forensic phytopathology is probably unrealistic to hope for. However, a society in which politicians, government officials, and judges have a basic grasp of science is not an unreasonable wish—although it seems like a very remote possibility.

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