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Invasive Pest Species: Impacts on Agricultural Production, Natural Resources, and the Environment

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INTRODUCTION

Agriculture in the United States relies on a myriad of native and non-native species of plants, insects, fish, and animals. Throughout the past 250 years, non-native organisms have been introduced both accidentally and intentionally. Economic, sport, or aesthetic introductions have capitalized on available habitats and markets. For example, most U.S. pets and some species sought by hunters and anglers are non-native. Most cultivated crops (eight of the nine most economically important U.S. plants) and many domesticated animals of economic importance originated outside the United States (Simberloff 2000). Even the staple crops corn (maize, *Zea mays*) and potatoes (*Solanum tuberosum*) were brought from subtropical areas of the American continents. The introduction of food sources such as cattle, wheat, honeybees, kiwi fruit, and soybeans and of ornamental plants such as tulips, chrysanthemums, and dawn redwoods has produced sizeable economic benefits. Some non-native insects have been instrumental in limiting the destructive effects of other insects and of native and non-native weeds. The intentional introduction of each of these species is more or less controllable. Of greater concern are the non-native species that are prone to escape human control or to carry undesirable species with them (e.g., insect-transmitted viruses).

Because of the large volume of commerce and travel taking place within and across its borders, the continental United States has been, and continues to be, especially prone to pest introduction. The United States is a "melting pot" of ethnic groups and likewise a "stew" of crops and pests. In the past, there was a low potential for inadvertent introductions of detrimental species because of the relatively slow and deliberate introduction of beneficial new plants, animals, and insects. The extended transit time, limited distribution, and small volumes involved also decreased the potential for survival and establishment of non-native pests. Often, however, pests came along with intentionally introduced crops and livestock. The once formidable geographic barriers posed by the Atlantic and the Pacific Oceans have been breached through increased travel, trade, and transportation. The ecology of the Western Hemisphere has been changed by agricultural, social, and industrial activities. Consequently, throughout the twentieth century a great number of extremely damaging pests--insects, weeds, pathogens, arthropods, mollusks, other invertebrates, reptiles, amphibians, and mammals--became established in the United States as the result of both accidental and intended introductions. There have been economic losses to food and fiber industries, export markets, natural resource uses, and native species' habitats regardless of the method of entry. A greater volume of global trade without more stringent controls will only expand and increase these risks.

Increases in the introduction of non-native (also termed *introduced*, *nonindigenous*, *exotic*, *alien*, or sometimes *invasive*) species constitute a global change of great magnitude (NRC 2000). And the intracontinental migration of introduced non-native species places U.S. agriculture and natural resources at increased risk. These pests impose an enormous economic burden--estimated at $137 billion/year--on the United States (Pimentel et al. 2000). They constitute the second leading cause of species endangerment and recent extinctions (Wilcove et al. 1998), cause grave medical problems (CDC 1993; McMichael and Bouma 2000), and damage human enterprises and ecosystems in countless ways (Simberloff 2000).

Natural movements of non-native species into the United States are uncommon. But over the past three decades the rate of detrimental introductions has accelerated greatly as a result of exponentially increasing air travel, growing numbers of ports of entry, expanding export/import markets, and improved access to foreign ecosystems. Hundreds of non-native species are brought into the United States each year through commercial air cargo, shipping ballast water, and private travel (U.S. Congress, OTA 1993). The risk is compounded by decreasing diversification in production systems, international trade agreements that limit the exclusion of products that might carry non-native species, and restrictions on the use of chemical controls (Simberloff 2000). Several factors may cause the global threat of pestilence, which historically brought famine, to reach a new economic potential: (1) further restrictions on chemical control research, germplasm development, and management flexibility; (2) failure to train taxonomists and other diagnostic and control personnel; and (3) concentration of holdings and resources in financial markets remote from producers, which could increase response time. In addition, bioterrorism introduces another unknown risk factor into the already unstable mix of detrimental exotic species.

Natural development of new strains of fungi, bacteria, and viruses, as well as accidental introduction of new pests through commerce and immigration, requires an alert and aggressive response to prevent economic disruption of our stable supply of food, fiber, and industrial raw products. The potential damage from an overt introduction of a new pest, more virulent strain of pathogen, or timely distribution of many existing disease organisms could overwhelm the response capabilities necessary to contain that threat. Increased production efficiency is essential to maintain competitiveness in a global economy. New pest control strategies--including integrated chemical, cultural, and biological approaches to ecosystem management--depend on the availability of resources and trained personnel in pest management disciplines.

This paper presents information on the current status of non-native species in the United States; discusses possible human health risks, economic costs, and ecological effects from non-native pests; and offers recommendations to minimize risks. Appendix tables list some damaging non-native pests already introduced into the United States as well as non-introduced pests that are potentially damaging to U.S. animals and plants.

WHAT ARE NON-NATIVE PESTS?

Exotic pests include non-native microorganisms, plants, insects, and other animals that cause or transmit diseases, displace native species, or diminish the economic or aesthetic value of a product or the environment. By producing toxins or acting as a vector for plant, animal, or human diseases, these pests may affect domestic animals, cultivated crops, forests, ornamentals, pets, wildlife and their habitats, and humans. In addition to affecting production efficiency and product quality directly, alien pests may be a nuisance in one environment while beneficial in another (e.g., Asian lady bird beetles invade homes for winter refuge in the midwestern United States but provide biological control of the pecan aphid in Georgia). The mere presence of certain pests (e.g., Karnal bunt in wheat) may restrict a product's export market potential greatly, even though these pests do not significantly damage domestic production. When production becomes uneconomical, crops are not produced and industries dependent on that raw product are forced to relocate or to close. The economic and ecological damage caused by some non-native plants has been recognized for years and was the topic of a recent report from the Council for Agricultural Science and Technology (CAST 2000).

WHY BE CONCERNED ABOUT NON-NATIVE PESTS?

Many non-native species have affected U.S. industry and the natural environment significantly (see Appendix A). Approximately 6,000 known insect species, 51 animal pathogens, and 2,000 plant pathogens are recognized as established pests in other countries. If introduced into the United States, these organisms might adapt to similar ecological conditions (McGregor et al. 1973; Thurston 1973). As many as 25% of the world's pathogens and 10% of its insect species pose significant risks to U.S. agriculture. Non-native pests also may raise concerns about environmental quality and aesthetics. McGregor and colleagues (1973) identified 22 animal diseases, 551 plant diseases and nematodes, and 760 insects and mites that constitute a significant threat to plants and animals in the United States (see Appendix B). Well-known introduced non-native pests include the mosquito, gypsy moth, Japanese beetle, Asian long-horned beetle, fire ant, Africanized honeybee, and zebra mussel. Since their introductions in the early 1900s, Dutch elm disease and chestnut blight have destroyed almost all American elm and chestnut trees, respectively. White pine blister rust, introduced around 1900, causes extensive losses and makes white pine unprofitable to grow in many areas of the United States.

In some instances, the source of introduction is either known or strongly suspected. Those persons who introduced certain species intended their imports to proliferate as beneficials. Their purposes ranged from the practical (e.g., nutria as furbearers) to the quixotic (e.g., starlings because Shakespeare mentioned them). Introductions of non-native species may be intentional (e.g., swine to Hawaii) or accidental (e.g., zebra mussels to the eastern and midwestern United States and eastern Canada). Either means of introduction, however, can have catastrophic results through direct or indirect effects on the economy, native species, and/or ecosystems.

Introduced species evolve as part of the dynamic process of life. Sometimes this evolution can modify the effects of an introduced pest greatly. Changes in host range, pest virulence, pesticide resistance, or environmental adaptation are well documented (Williamson 1996). A European weevil introduced into North America by Agriculture Canada for control of some

Eurasian thistles is harming populations of a geographically restricted native thistle in Nebraska and of Suisun thistle in California (Louda et al. 1997; USDI 1997). Selection pressures on an introduced species may be fairly mild because natural predators, parasites, or other controls are frequently absent in its new habitat. The occurrence of different selection pressures in the new habitat and geographical isolation from populations in the original range of the species prevent competition with those newly evolving genotypes. This isolation permits extensive hybridization, development, and segregation of genetically diverse species at the expense of native species. Introduced species also may have a greater competitive ability than native species, as demonstrated by the seven-spot lady bird beetle, which was introduced and distributed widely to control Russian wheat aphid and now outcompetes native lady bird beetles in several locations (Obrycki, Elliott, and Giles 2000).

The United States already has suffered incursions of bovine pleuropneumonia and Venezuelan equine encephalitis. The "new pest on the block" is West Nile virus, which can be fatal to humans, birds, and horses. Current tests to screen incoming animals may be inadequate to detect subclinical or dormant infections. For example, serodiagnostic tests for heartwater infections are insufficiently sensitive to identify infected carrier animals of certain African wildlife species (Burridge 1997); only more-sophisticated, nonstandard tests have this capability (Kock et al. 1995; Peter et al. 1998).

Heartwater, an acute disease of domestic ruminant animals that has significant mortality rates even in endemic countries, has the potential to infect white-tailed deer. When presented with infected or carrier hosts, the native Gulf Coast tick (*Amblyomma maculatum*) has been shown in the laboratory to transmit this disease at rates similar to those of its usual vectors--the African bont tick and the Caribbean tropical bont tick (Mahan et al. 2000). Cattle egrets have been shown to move tropical bont ticks readily over considerable distances (Corn et al. 1993). Similar scenarios may have played out in the southern United States, with disaster averted only by the intervention of another exotic pest, the fire ant, which preys very effectively on ground-living ticks. As these ants acquire their own enemies, this protection may be lost.

WHAT DAMAGES ARE POSSIBLE?

Introduced species have many potential direct and indirect effects, which can be categorized as deleterious to (1) human health, (2) agricultural and forest production, (3) aesthetics, or (4) ecosystems and natural resources. Introduced diseases, parasites, and insects have decreased greatly the production efficiency of many agricultural crops, animals, and trees. For example, the presence of Karnal bunt in durum wheat in the southwestern United States has prevented exports of the commodity to noninfested countries and entailed extensive sanitation costs, even though the disease is not known to cause a significant decrease in grain yield. The introduction of new strains of a pathogen that are virulent on resistant U.S. cultivars could have a devastating effect on production, as well as on the economics of the agricultural industry. One example is the recent, rapid spread throughout the major growing areas of the eastern and central United States of new fungicide-resistant strains of *Phytophthora infestans*, the cause of late blight of potato, after their introduction from Mexico.

Infestations or outbreaks of foreign pests or diseases disrupt the normal movement of people and commodities and lead to complaints about government interference in travel, trade, and marketing practices. Entire herds infected with foot-and-mouth virus must be destroyed if this disease is introduced. To eliminate citrus canker or to prevent its spread, millions of citrus trees in Florida have been destroyed at a tremendous cost to the industry, and confidence in a disease-free product for export has been shattered.

Some species can change the structure and functioning of entire ecosystems. For example, introduced mammals that graze, burrow, and root can devastate plant communities and the animals that depend on those communities (Groombridge 1992; Ricciardi, Neves, and Rasmussen 1998; Simberloff 2000). Introduced species can act synergistically with one another or with an indigenous pest, thereby exacerbating the effects of both species (Simberloff and Von Holle 1999). This interaction can be especially damaging when a disease is introduced and its vector is already present. An example is the recent introduction of the West Nile virus into New York state, where a mosquito vector already was in place. Hybridization of native species with introduced related species can result in genetic extinction of the native species due to differences in population sizes (Rhymer and Simberloff 1996). Examples of this phenomenon are the hybridization of Hawaii’s native duck with introduced mallards, and of Apache and Gila trout with introduced rainbow trout.

WHAT ARE THE ECONOMIC COSTS?

If non-native species become pests, the economic risks include lost production, diminished quality, increased production costs, decreased flexibility in production/management decisions, and increased risk of human disease. For those species that prove to be detrimental, costs can be calculated.[1] Severe pest infestations (such as beet necrotic yellow vein virus in Texas sugar beets) have caused industries to relocate because they can no longer produce the necessary raw materials efficiently. Environmental and aesthetic effects can be just as damaging. Yet it is difficult to estimate the economic effect of harmful, non-native species because no one maintains a comprehensive compilation of costs incurred. Thousands of acres of rangeland are lost daily to the onslaught of invasive, non-native weeds (CAST 2000; Westbrooks 1998). Insects such as the

Mediterranean fruit fly (the "medfly") pose a constant threat to important fruit production systems in the western United States and Florida. From 1982 to 1983, medfly eradication cost approximately $100 million in California alone. In this eradication campaign, the state also had to pay $3.7 million to settle 14,000 claims of car paint damaged by the spraying of insecticide (Getz 1989). To compound the loss, eight foreign countries and some U.S. states embargoed fruit shipped from California (Eden et al. 1985). At the same time, the cost of insecticidal sprays, as well as public concern about chemical exposure, made effective eradication difficult.

Another non-native pest that has caused economic loss is the rapidly invading zebra mussel, a freshwater bivalve introduced into the Great Lakes in the late 1980s. By clogging water lines for power plants and industry, and by fouling hulls, docks, and other structures, this pest has caused losses of hundreds of millions of dollars during its brief residence in the United States (U.S. Congress, OTA 1993). Between 1989 and 1994, utility companies along Lake Michigan spent $120 million to keep zebra mussels out of water intake pipes (Goetz 2000). If this species crosses into the western states and invades the area’s thousands of miles of irrigation systems, its natural lakes, and the Sacramento/San Joaquin Delta, water sources for more than 30 million people will be threatened. Similarly, the recent introduction of the Asian long-horned beetle near New York City has a tremendous potential to cause extensive losses throughout eastern hardwood forests (USDA 2000).

Pimentel and colleagues (2000) estimated annual non-native pest damage to the U.S. economy at $137 billion. This figure includes $2 billion for the fire ant, $1 billion each for the Formosan termite and the Asian river clam, $310 million for the zebra mussel, $44 million for the European green crab, $10 to $15 million for the sea lamprey, and $1 million for the brown tree snake (in Guam). The Nature Conservancy estimates that the 79 most invasive exotic weeds have cost the U.S. economy $97 billion since their introductions (U.S. Congress, OTA 1993).

When citrus canker was found in Florida in 1980, all fruit markets had to be closed temporarily, fruit had to be covered from harvest time until processing, and meticulous cleaning requirements for harvesting and processing equipment were imposed by regulatory agencies. Eradication of citrus canker (1980 introduction) cost $160 million but was necessary to protect the $8.5 billion Florida citrus industry. At least 8.7 million plants in the initial infestation and an additional 2 million in follow-up efforts were destroyed (Eden et al. 1985). Recent estimates of potential losses from tree pests introduced on solid wood packing materials range from several hundred dollars to more than one thousand dollars per tree. Losses from a specific pest could be as great as $1 billion in the first year of introduction (USDA 2000). It is even more difficult to measure the monetary losses from such pests as honeybee mites and plant pathogens.

Thus, the damage effects from non-native pests span an enormous range. These effects include loss of power; loss of farmland; depreciation of property value; contamination of grain for export; spread of disease; increased cost of operation; decreased efficiency of production and irrigation; economic annihilation of agricultural producers; collapse of buildings; competition with native species; loss of sport, game, and endangered species; and disturbance of ecosystems.

WHAT ARE THE ECOLOGICAL EFFECTS?

Non-native plants, animals, insects, and pathogens can change ecosystem structure and function through direct damage, competition, hybridization, infestation, and/or disease. Some introduced mammals that dig or graze (e.g., rats, European wild boar, feral swine, and their hybrids) have destroyed plant communities and the animals that depend on them in Florida, Hawaii, Tennessee’s Great Smoky Mountains National Park, and California’s Santa Cruz Island (Cox 1999). Goats have played a similar destructive role on islands (Groombridge 1992), and nutria have destroyed many acres of productive land in Louisiana and Maryland by digging out and consuming the marsh plants that provide soil stability and prevent erosion (Bounds 1998). The Japanese hemlock woolly adelgid has devastated hemlocks in many forests of the eastern United States (McClure and Cheah 1999). The cactus moth, introduced into the Lesser Antilles to control prickly pear, spread to Florida where it has already eliminated the native semaphore cactus (Johnson and Stiling 1998) and threatens many cactus species grown as economic crops in the United States and Mexico. Gypsy moths were introduced from Europe into Massachusetts in 1869, in the hope that these oak-eating insects could be crossed with silkworms to spin silk. Since their escape from a backyard colony, gypsy moths have spread throughout the Northeast and the upper Midwest at the rate of about 13 miles a year, defoliating an additional three million acres of forest annually (Goetz 2000). Because the moth has few natural enemies and because each insect can eat 11 square feet of foliage in its lifetime, this pest can do much damage.

The predatory rosy wolf snail, brought to Hawaii and other islands to control the introduced giant African snail, already has caused the extinction of more than 30 native terrestrial and arboreal snails (Civeyrel and Simberloff 1996). Also in Hawaii, avian pox and malaria, transmitted by introduced mosquitoes, pose a major threat to many native songbirds, whose numbers and environmental ranges already have been greatly diminished as a result of habitat destruction (van Riper et al. 1986). The brown tree snake introduced into Guam has rapidly extinguished 10 of the 12 native forest bird species; the remaining two are rare (Williamson 1996). And since its introduction into Pennsylvania in frozen rainbow trout imported from Europe, whirling disease has spread and all but eliminated rainbow trout fishery from Montana and a large part of Colorado (Bergersen and Anderson 1997).

HOW ARE NON-NATIVE PESTS INTRODUCED AND SPREAD?

New pest species may be introduced accidentally or intentionally (see Appendix A, Tables A.1 and A.2). They can originate from any area of the world but commonly come from areas whose ecological conditions are similar to those of the United States. Many harmful nonindigenous species were brought over inadvertently as "hitchhikers" on commercial commodities. The Asian long-horned beetle arrived in New York and Chicago on untreated wooden packing material from China (University of Illinois 1998), and Dutch elm disease and its bark beetle vector came over on infected Asian timber (von Broembsen 1989). Various tick species have arrived on kudu and other African wildlife imported for zoos and game ranches. The brown tree snake reached Guam in cargo transported from the Admiralty Islands during World War II (Rodda, Fritts, and Chiszar 1997; Rodda, Fritts, and Conry 1992), and fire ants came north from southern Brazil (Jemal and Hugh-Jones 1993).

Discharged bilge water from ships is another source of inadvertent introduction. The Australian spotted jellyfish now swarming in the Gulf of Mexico may have arrived in ballast water from a ship coming through the Panama Canal (Raines 2000). Contaminated water is an increasing risk for introducing marine pests and pathogens such as the bacteria that cause cholera (CDC 1993). Potting soils used for introduced plants also can serve as active reservoirs for pests. Latent or symptomless infections on plants or animals are difficult to identify, and predicting damage is difficult because many damaging introduced pests did not constitute a problem in their native areas due to natural biological controls.

Many pest species were introduced deliberately--for aesthetic, economic, sport, or environmental reasons--rather than inadvertently (Lever 1992; Long 1981; Tenner 1996). But some biological control introductions have gone awry. Examples of such introductions include a European weevil introduced to control thistles; the seven-spot lady bird beetle, to control Russian wheat aphid; the Indian mongoose, to control rats in sugarcane fields (Simberloff and Stiling 1996); and grass carp, to control aquatic weeds (Taylor, Courtenay, and McCann 1984). Goats and pigs have been released on islands worldwide as food, as has the giant African snail, which was introduced as a food item into the Hawaiian islands.

Acclimatization societies (organizations formed to establish populations of exotic animals) introduced many birds onto islands around the world (Lever 1992), and individuals with a taste for exotics have imported such pestiferous species as the house sparrow. The starling was brought to the United States in 1890 by New Yorker Eugene Schieffelin, an eccentric drug manufacturer, as part of a plan to introduce all birds mentioned by Shakespeare (Long 1981). Large numbers of fish species have been brought to the United States as game (Fuller, Nico, and Williams 1999; Moyle 1995); some subsequently have become significant pests. Introduced game animals that have become environmentally and economically disastrous include nutria and European boar (Singer, Swank, and Clebsch 1984). Pet ferrets and cats released to the wild can establish populations that cause major damage to birds and small rodents (Jurek 2000; Pimentel et al. 2000).

Intentionally introduced species often do not stay where they are wanted. The Asian lady bird beetle, introduced into Georgia, is now a widely distributed nuisance throughout the Midwest. The cactus moth, brought to the Lesser Antilles, later arrived in Florida. After the grass carp was introduced into Arkansas in 1968, it spread to the Mississippi River, carrying a parasitic Asian tapeworm that infested fish such as the red shiner (*Notropis lutrensis*), a popular bait fish. Fishers or bait dealers then introduced infested red shiners into the Colorado River, and by 1984 the tapeworms had reached the Virgin River, a Utah tributary of the Colorado River, where they infected the woundfin (*Plagopterus argentissimus*), causing population numbers to crash (Moyle 1995).

Recently, freshly arrived African spurred tortoises (*Geochelone sulcata*) and leopard tortoises (*G. pardalis*) have been found infested with *Amblyomma marmoreum* ticks. Although it has yet to be shown that the tortoises are effective carriers of *Cowdria ruminantium*, which causes the lethal disease heartwater in cattle, DNA of *C. ruminantium* has been demonstrated in these tortoises and ticks (Burridge et al. 2000). This tick vector has been long suspected, although not directly established, as a carrier (Oberem and Bezuidenhout 1987). Contemporaneously, the African tortoise tick, *A. marmoreum*, has been found in significant numbers in some reptile importing and breeding facilities in Florida, with strong evidence that it is not a recent infestation (Allan, Simmons, and Burridge 1998; Burridge, Simmons, and Allan 2000). In one recent shipment to Florida from Zambia, 38 *A. sparsum* male ticks were collected off leopard tortoises and were found to be positive for *C. ruminantium*. This large reptile tick is found on both reptiles and large mammals, infesting not only tortoises but also large mammals such as the African buffalo (*Syncercus caffer*), a known carrier of heartwater (Andrew and Norval 1989). This occurrence indicates that the components exist in Florida for the establishment of heartwater, and they have been there for an extended period. Release of tick-infested and possibly infected tortoises into the wild by former owners is likely, just as happens when owners tire of other exotic pets. In the wild, the infested tortoises would spread the pathogen and compete with native species for habitat. Although further importation has been banned, only time will tell whether the action to ban was taken quickly enough.

A new species can exist in an area for decades without its presence being noticed. After introduction, there often is a long lag during which a nonindigenous species remains harmless and relatively rare. The lag before population growth and spread ranges from 3 to 99 years after introduction until serious infestation is observed (Corn et al. 1999; Crooks and Soulé 1996; McGregor et al. 1973). Although this phenomenon is recorded more commonly for introduced plants than for animals, many examples exist in both kingdoms. Reasons for lag times depend on species. The wood-boring isopod *Limnoria tripunctata* arrived in the Long Beach-Los Angeles Harbor before 1900, perhaps on wooden ship hulls, but it remained innocuous for many years, probably because pollution from industrial, domestic, and storm wastes created a nearly sterile environment.

Pollution abatement in the late 1960s led to rapid *Limnoria* population growth and subsequent damage to wooden structures (Crooks and Soulé 1996).

For many years, fire ants were limited to counties adjoining Mobile, Alabama. Eventually this pest reached inland commercial nurseries and was rapidly and widely disseminated by means of potted plants (Tschinkel 1993), as far west as southern California and as far north as Tennessee. This tropical ant has breached the frost line and can be expected to move even farther north. Some lag time may be due to the fact that population sizes are too small to be detected at first or that a genetic change such as pesticide resistance or some other unknown condition has not occurred yet (Shigesada and Kawasaki 1997).

DO ALL INTRODUCED ORGANISMS BECOME PESTS?

A succession of events must transpire before a newly arrived organism becomes established as a pest. These events constitute the overcoming of important obstacles, and each event has its own probability of occurrence. When a species is introduced into a new site, it must find conditions adequate for its needs and must avoid predators, parasites, and diseases. Most introduced organisms fail to become established because they do not fit into the new ecological environment required for survival, reproduction, and spread. These same limitations on establishment hold true for organisms introduced intentionally for commerce or biological control. Although many species cannot survive and become established in the United States, there are sufficient numbers of other species that can, and they create continuing threats to an already pest-burdened crop production system and to invaluable natural resources. Pests compatible with new surroundings and lacking in natural biological controls or natural resistance can colonize and multiply rapidly to reach damaging levels quickly.

HOW VULNERABLE ARE UNITED STATES AGRICULTURE, NATURAL RESOURCES, AND URBAN ENVIRONMENTS?

Long lists of potential exotic pests have been compiled for the United States; many of the species identified are considered of quarantine importance (McGregor et al. 1973; Thurston 1973). To become established, an exotic pest not only must survive transit but also find a favorable environment and host population. This process provides a selective filter through which a new pest may pass more readily than its parasites, predators, and pathogens. Because quarantine programs tend to make the filter more impervious to both pests and their natural enemies, the probability of a pest being introduced without its natural controls is enhanced. This selective filter may explain why a study comparing the behaviors of exotic organisms in their original habitats with their effects when introduced into the United States was able to predict accurately the risk of damage after importation only 18 to 35% of the time, with the calculated risk being much lower than the actual loss experienced after introduction (McGregor et al. 1973). This inability to predict the consequences of introducing a given pest highlights the difficulty of making program decisions and thus defines one topic in which additional research is needed.

Intensified farming, which involves limited diversification of crop and cultivar genetics over large areas, typical cultural practices, and economic constraints on pest control implementation in an already economically stressed environment, presents an ideal environment for new pest establishment. Prohibitively high development and registration costs have limited development of new emergency response materials, and diminishing public acceptance of chemical pesticide application (Williams 1997) makes use of the few remaining available chemicals even more difficult. Because cost/benefit considerations are focused on short-term economic return, the concentration of financial resources and land ownership at locations far from production areas also jeopardizes the rapid response to new pest introductions that is crucial for effective containment and/or eradication. New international treaties limit the ability to restrict importation of potentially infested products. A declining number of personnel trained in applied pest disciplines makes it difficult to inspect thoroughly the large volume of imported products.

Each newly introduced pest requires that societal resources be expended to combat the pest through eradication, control, and/or management. In an increasingly competitive global environment for agricultural products, additional costs for pest control could result in loss of market potential as production is shifted to areas of decreased pest pressure or increased accessibility to effective and economical controls, such as pesticides (U.S. Congress, OTA 1979). Additional costs for increased pest control could pose an unmanageable economic burden on many producers whose credit and operating capital already are limited because of low commodity prices.

WHAT ARE SOME THREATENING PESTS?

Numerous pests known or anticipated to be damaging should they enter the United States (or be reintroduced after eradication programs) are listed in Appendix B. Of the 6,000 insect species that are not currently present in the United States but that pose potential risks, 600 may be regarded as high risk. Of the 135 potentially damaging alien animal diseases, 22 can be considered high risk to animals, and several can be considered high risk to humans (AHA 1998; Bram and George 2000; McGregor et al. 1973; Office International des Épizooties 1998). The situation for plant pathogens is similar: 551 of the 2,000 known potentially damaging alien plant pathogens are believed to pose significant new risks to U.S. agriculture (McGregor et al. 1973; Thurston 1973; Watson 1971).

Various lists of pests exist, and the differences among them are sometimes difficult to reconcile, except as reflections of the lack of essential knowledge and of the difficulty in predicting pests' behavior after introduction. For example, of 212 introduced, economically damaging insect pests, 139 would not have been anticipated to be damaging based on their behaviors in their native lands (McGregor et al. 1973). It would be fool-hardy to ignore classes of pests that present significant potential dangers even though individual members may not seem important. Both prediction and identification become even more difficult when pest variability is considered. Therefore, even though a particular pest already may be present in the United States, introduction of a new race or strain may be as damaging as if the pest were a newly introduced organism. For example, introduction from Australia of the new strain of *Fusarium* causing cotton wilt, which is virulent to current U.S. cotton varieties, could be very damaging even though a more benign strain of the cotton wilt *Fusarium* is already present here.

UNDERSTANDING THE CHALLENGE OF NON-NATIVE SPECIES

The efficient movement of beneficial plants, plant products, biological control organisms, or other articles into, out of, or within the United States is vital to the nation's economy and should be facilitated to the extent possible and reasonable. At the same time, it should be recognized that unregulated movement of organisms can present unacceptable risks. Current regulatory constraints on the movement, sale, and possession of exotic organisms must be evaluated. The total resources directed at intervention, quarantine, removal, and enforcement of existing federal statutes are woefully inadequate.

Geographically isolated from the world biota until 250 years ago, Hawaii has attempted to keep out unwanted pests by means of an intensive quarantine effort. Still, the rate of pest establishment in Hawaii is 500 times the rate in the continental United States (McGregor et al. 1973). Ecological differences account for the disproportionately smaller number of immigrant pests present in the contiguous states. At the same time, the effectiveness of Hawaii's quarantine is limited by the physical impossibility of inspecting all entrants. The probability of discovering agricultural contraband in air passenger baggage is 50% or lower. The increased volume of passenger traffic entering the United States by air and land routes from Mexico and Canada places severe stress on existing inspection operations. The common practice of containerized shipping, with cargoes assembled well within the boundaries of the exporting country and delivered to widely diffused, inland U.S. destinations remote from traditional inspection sites at ports, poses additional obstacles to effective exclusion and interception of non-native pest species.

Even after an introduced pest or pathogen is documented, it takes time for a response to be implemented fully. One example is the heartwater disease threat to ruminants that was introduced through animals imported from Africa (Trevor et al. 1998). Control of the disease is now one of the four major goals cited in the 2001-2003 strategic plan of the Veterinary Services Division of the Animal and Plant Health Inspection Service, whose mission is to "safeguard the U.S. from the occurrence of adverse animal health events." Objective 1.2 is directed specifically at safeguarding against nonindigenous invasive species. To achieve this objective, the service will establish regulations to prevent introduction and establishment of known or potential vectors of heartwater and other vector-borne diseases stemming from the importation of reptiles. A draft of a proposed rule for this regulation was expected during 2001, publication of the proposed rule is expected during 2002, and implementation of the final rule is expected during 2003 (AHA 1998; APHIS 2001).

If a pest *can* enter the United States, over time, it *will* find a way here, so a means must be found to develop appropriate, feasible, economic, and cost-effective quarantine procedures. Improved early detection and identification, as well as eradication or control when exclusion has been ineffective, are required. Anticipation of a problem can minimize risk further if such anticipation leads to development of resistant varieties, treatments, and vaccines for future mobilization when delaying tactics no longer are appropriate. If these activities are coupled with an aggressive agricultural defense policy in foreign nations where high-risk pests for the United States are known to exist, U.S. aid and research programs in these nations will be of great benefit to this country.

WHAT IS NEEDED TO MINIMIZE THE THREAT?

Major problems in protecting against non-native pests include (1) public indifference, (2) ease of introduction and movement (e.g., postal regulations on confidentiality), (3) lack of effective emergency pesticides, (4) claims by international partners that U.S. sanitary barriers are economic barriers, (5) lack of research addressing prevention and control needs, (6) inadequate inspection techniques and procedures, and (7) inadequate coordination and cooperation among state and federal agencies and industry (Eden et al. 1985). Public indifference, lack of knowledge, and opposition to governmental "interference" greatly complicate response efforts. Complaints from various sources are voiced widely, and magnified by the press, about restricted movement or aggressive actions taken to contain and to eradicate a non-native pest. Many people, especially parents of school children, were upset about the potential effects of the aerial spray program for medfly eradication in California. Applications in treated areas had to coincide with times when children were absent from those areas. Additionally, people with organic gardens protested in large numbers, and visits to physicians by people with allergies greatly increased (Eden et al. 1985). Public complaints about restrictive actions frequently are based on special interests or lack of public understanding of the pest risks involved. Either way, pest containment and control are delayed unnecessarily and an unreasonable burden may be placed on control efforts.

A coordinated, internet-based data network with basic information on introduced species is needed urgently (Ricciardi et al. 2000; Simberloff 1999). Although many web sites carry key information on various introduced species, there is no way to acquire that information rapidly and be assured that it is credible and necessary for a particular potential problem-invader. Furthermore, databases and web sites generally are restricted both taxonomically and geographically (e.g., introduced fishes in the continental United States, or major weeds of natural areas in Tennessee). The fact that different species can interact in many ways to exacerbate one another's effects and that they can move rapidly from one location to another means that limited databases will be unable to identify many potential problems, or possible means of dealing with them, in a timely manner. A coordinated network of professional societies and state and national governmental entities would help solve this problem.

The early warning and rapid-response mechanisms associated with a coordinated network are needed to cut across jurisdictional lines and to permit timely response to reported invasions. Contrary to popular belief, many introduced species have been eradicated, but the keys to success have been informed personnel, rapid-response capacity, sufficient resources, and the legal authority necessary to deal with issues that often arise in eradication projects (Myers et al. 2000; Simberloff 2002). These multifaceted projects include a search and destroy component to contain and then eradicate non-native pests.

Risk assessment procedures for introduced species are incompletely developed (Simberloff and Alexander 1998) and tend to be drawn from models for chemical stressors that fail to account for unique traits of living species (e.g., species evolution, independent reproduction, or dispersal method--often for long distances). The unpredictable nature of each of these three traits makes it extremely difficult to assess risks posed by planned introductions of species or by pathways that might transport species inadvertently. Methods used to date are versions of the U.S. Department of Agriculture's (USDA) Generic Non-Indigenous Pest Risk Assessment Process (Orr, Cohen, and Griffin 1993) and are an important start because they necessitate consideration of the different steps (arrival, survival, population growth, spread, and effect) leading to establishment of an introduced pest. Well-developed procedures have not been created, however, to estimate probabilities in any of these steps, and statistical confidence limits are lacking. Thus, risk assessment for introduced species is currently only as accurate as the inputs from experts who subjectively assess the component probabilities.

HOW SHOULD PROGRAMS BE PRIORITIZED TO MINIMIZE RISKS?

Prioritization of programs for the control of non-native pests should reflect the following recommendations (Eden et al. 1985; McGregor et al. 1973):

1. **Implement aggressive public information programs emphasizing global movement controls.** For example, public service television announcements and airport information stations would aid in a public education process. Informational programs are essential because once pests have been introduced, domestic control and eradication efforts are almost always a less desirable alternative.

2. **Adopt balanced, coherent, and realistic approaches to protecting plant, animal, and environmental resources.** Maintain a constant monitoring system with prompt feedback to exporting countries and receiving states. Ensure that exporting countries have a vested interest in minimizing pest introductions to the United States by discounting commodity prices or denying access to U.S. markets, and include forward-looking activities such as pest control assistance in source countries to minimize initial commodity exposure to pests.

3. **Concentrate on the highest-risk pests--and define them--so that information is readily available about host commodities, world regions where these pests are located, and seasonal and environmental factors important for their introduction and establishment.** Actual or potential pathways for their introduction need to be defined clearly. A nationally coordinated, internet-based data network is needed urgently.

4. **Decrease biological uncertainties related to pests' present distribution, transit survival, establishment, and characteristics of potential losses.** Coordinate efforts of federal, state, and private entities to ensure adequate support for research on high-risk pests' biology and taxonomy, economic effects, detection technologies, and interdiction pathways.

5. **Emphasize voluntary compliance more than enforcement, through an effective information and education campaign, especially one to decrease risk of introductions through passenger baggage and mail services.** Resolve, either by regulation or legislation, the problem of inspection of first-class mail as a route of entry for non-native pests.

6. **Encourage private efforts, with the view that protection is a shared responsibility.** Communicate the importance of quarantine programs to the public, as well as to transportation and production industry personnel. Encourage continued education and training of specialists in pest diagnosis, interception, eradication, and management.

7. **Establish risk standards for proposed introductions, with a scientific basis for the standard regarding how much risk will be tolerated.** Implement regular training of regulatory personnel to ensure unity of purpose between preclearance international personnel and receiving port personnel.

8. **Maintain and support emergency "strike force" capability, including vigorous investigation of the sources and pathways of infestations of exotic pests and an adequate supply of materials necessary to eradicate high-priority pests** (see item 3). Assign high priority to the development of new pesticides and new use patterns for current pesticides available to treat imports and those needed for effective response to new introductions.

9. **Develop an active, ongoing process for periodic evaluation and assessment of risks and regulatory programs, with regular updates and reassessments in light of new knowledge and events.**

APPENDIX A: SOME DAMAGING NON-NATIVE PESTS INTRODUCED INTO THE UNITED STATES

Table A.1. Damaging non-native pests cited in the current study

Scientific name	Common name	Known or suspected route of introduction or origination
Pests Damaging to Animals		
Aedes albopictus and many others	Mosquitoes	Introduced mosquito, shipping containers
Amblyomma hebraeum	Bont tick	Infested leopard tortoise and African spurred tortoise
Boiga irregularis	Brown tree snake	Hitchhiker in cargo
Bothriocephalus acheilognathi	Asian tapeworm	Grass carp introduced for weed control
Coccinella septempunctata	Seven-spot lady bird beetle	Introduced biocontrol of Russian wheat aphid
Cowdria ruminantium	Heartwater of ruminant	Tick on infected zoo animal or pet turtle
Euglandina rosea	Rosy wolf snail	Intentional biocontrol of giant African snail
FMD virus	Foot-and-mouth disease virus	Infected animal or material
Mycoplasma mycoides mycoides (small colony)	Bovine pleuropneumonia	African wildlife and cattle
Myxosoma cerebralis	Whirling disease	Imported frozen rainbow trout
Varroa destructor	Honeybee mite	Introduced from Asia
Vibrio cholerae	Cholera	Bilge water of ships
West Nile virus	West Nile virus	Infected human immigrant
Pests Damaging to Plants		
Adelges tsugae	Japanese hemlock wooly adelgid	Wood products
Anoplophora glabripennis	Asian long-horn beetle	Contaminant in wood packing material

Beet necrotic yellow vein virus (BNYVV)	Rhizomania of sugar beet	Infected seed or soil
Cactoblastis cactorum	Cactus moth	Intentional biocontrol of prickly pear
Ceratitis capitata	Mediterranean fruit fly	Contaminant with fruit or material
Ceratocystis ulmi	Dutch elm disease	Contaminant in imported logs
Cronartium ribicota	White pine blister rust	Contaminant in imported logs
Cryphonectria parasitica	Chestnut blight	Contaminant in imported logs
Hylurgopinus rufipes	European elm bark beetle	Contaminant in imported logs
Lymantria dispar	Gypsy moth	Intentional attempt to cross with silkworm
Popillia japonica	Japanese beetle	Agricultural products suspected
Rhinocyllus conicus	European weevil	Intentional biocontrol of Eurasian thistle
Tilletia indica	Karnal bunt of wheat	Contaminant on durum seed wheat
Xanthornonas campestris var. *citri*	Citris canker	Contaminated nursery stock or fruit
Pests Damaging to Agriculture or the Environment		
Achatina fulica	Giant African snail	Introduced into Hawaii as a food item
Aedes albopictus	Mosquito	Introduced from South China
Apis mellifera scuteltata	Africanized honeybee	Hybrid with accidental release of African bee
Carcinus maenas	European green crab	Introduced from Europe
Coptotermes formosanus	Formosan termite	Contaminant on imported material
Corbicuta fluminea	Asian river clam	Unknown
Ctenopharyngodon idella	Grass carp	Introduced for aquatic weed control
Dreissena polymorpha	Zebra mussel	Contaminant on ship hulls or in ballast water
Harmonia axyridis	Asian lady bird beetle	Intentional biological control of pecan aphid
Herpestes javanicus	Indian mongoose	Introduced biocontrol for rat in sugarcane
Limnoria tripunctata	Wood-boring isopod	Hitchhiker on ship hulls
Myocaster coypus	Nutria	Intentional from South America
Petromyzon marinus	Sea lamprey	From the Atlantic Ocean
Phyllorhiza punctata	Australian spotted jellyfish	Ballast water of ships
Solenopsis invicta	Fire and	In dunnage from Brazil
Stumus vulgaris	Starling	Intentional, due to mention by Shakespeare
Sus scrofa	European wild boar	Introduced as a sport animal

Table A.2. Introduced higher vertebrate species that can affect U.S. agricultural or ecological systems

Scientific name	Common name	U.S. habitat range	Origination
CLASS MAMMALIA			
Artiodactyla			
Bos taurus, B. indicus	Cattle	All	Brazil, Europe, India
Capra hircus	Wild goat	Scattered, coastal islands (San Clemente Island, CA; many FL islands)	Europe
Sus scrota		Scattered	Europe

	European wild boar		
Carnivora			
Canis familiaris	Wild dog	All	Europe
Felis catus	Feral cat	All	Europe
Herpestes javanicus	Mongoose	Hawaii, Caribbean Islands (including Puerto Rico)	Indoa
Lagomorpha			
Oryctolagus cuniculus	European rabbit	Scattered	Europe
Perissodactyla			
Equus asinus	Burro	Scattered (mainly western)	Eurasia
Equus caballus	Wild horse	Scattered (mainly western; eastern coastal islands)	Eurasia
Rodentia			
Mus musculus	House mouse	All	Europe
Myocaster coypus	Nutria	Coastal FL, LA, MD	South America
Rattus norvegicus	Norway rat	All	Asia
Rattus rattus	Black rat	All	Europe
CLASS AVES			
Anatidae (duck, goose, swan)			
Cygnus olor[1]	Mute swan	Mid-Atlantic, Great Lakes	Europe
Ardeidae (heron, egret)			
Bubulcus ibis[2,3]	Cattle egret	South and central (from the Carolinas to CA, north to KS, MO, and UT)	Africa
Columbidae (pigeon, dove)			
Columba livia	Rock dove	All	Europe
Streptopelia decaocto	Eurasian collared-dove	Coastal Southeast (AL, FL, GA, LA, MS, SC, TX)	Europe
Icteridae (blackbird)			
Molothrus bonariensis	Shiny cowbird	Coastal Southeast (FL to NC and TX)	South America
Passeridae (Old World sparrow)			
Passer domesticus	House sparrow	All	United Kingdom
Passer montanus	Eurasian tree sparrow	Midwest (IL,MO)	Eurasia
Phasianidae (partridge, grouse, turkey)			
Alectoris chukar[1]	Chukar	Rocky Mountains, Great Basin	Eurasia
Phasianus colchicus[1]	Ring-necked pheasant	Scattered	China

Psittacidae (parrot, parakeet)			
Myiopsitta monachus	Monk parakeet	FL and many cities (e.g., Chicago, Houston)	Temperate South America (Bolivia, Argentina)
Sturnidae (starling)			
Stumus vulgaris	European starling	All	Europe
CLASS REPTILIA			
Reptilia			
Boiga irregularis	Brown tree snake	Guam	Asia (New Guinea)
CLASS AMPHIBIA			
Amphibia			
Bufo marinus	Cane toad	FL, HI	South America
Xenopus laevis	African clawed frog	Parts of CA	Africa
CLASS OSTEICHTHYES			
Osteichthyes			
Clarias batrachus	Walking catfish	FL	Southeast Asia
Ctenopharyngodon idella	Grass carp	Mississippi River drainage	China
Cyprinus carpio	Common carp	All (except AK)	Eurasia
Gymnocephalus cemuus	Ruffe	Western Great Lakes (Superior, Huron)	Europe
Monopeterus albus	Asian swamp eel	FL, GA	Asia
Neogobius melanostomus	Round goby	Great Lakes, MI	Black/Caspian Sea
CLASS AGNATHA			
Petromyzon marinus[2]	Sea lamprey	Great Lakes	Atlantic Ocean

1 Hunted species
[2] Non-native, but arrived naturally in the United States
[3] Considered a Migratory Bird Treaty Act species

Appendix B: Some Non-Native Pests Potentially Damaging to U.S. Animals and Plants

Table B.1. Non-native pests potentially damaging to animals if introduced or reintroduced

Scientific name	Common name	Potential source
Insects		
Cochliomyia hominivorax	New World screwworm	South America
Chrysomya bezziana	Old World screwworm	Europe
Hippobosca longipennis	Louse fly	Africa
Musca vitripennis	Licking fly	Europe
Psoroptes ovis	Sheep scab mite	Global

Arachnids		
Amblyomma hebraeum	Bont tick	Africa
Amblyomma variegatum	Tropical bont tick	Caribbean, Africa
Boophilus annulatus	Cattle tick	Mexico
Boophilus microplus	Southern cattle tick	Australia, the Caribbean, Central and South America, Mexico
Ixodes riciuns	European castor bean tick	Europe, Middle East, North Africa
Rhipicephalus appendiculatus	Brown ear tick	Africa
Fungi		
Aphanomyces astaci	Crayfish plague (Crustaceans)	Europe
Histoplasma farciminosum	Epizootic lymphangitis	Africa, Asia, Middle East
Bacteria		
Burkholderia mallei	Glanders	Global
Burkholderia pseudomallei	Melioidosis	Asia
Mycoplasma capricolum capripneumoniae (Mccp)	Contagious caprine pleuropneumonia	Africa, Middle East, Turkey
M. mycoides mycoides (Large colony) *(MmmLC)*	Cont. caprine pleuropneumonia	France, India, Israel, U.S.
M. mycoides mycoides (Small colony)	Cont. bovine pleuropneumonia	Africa, Asia, Australia, Europe
Pasteurella cholerae-gallinarum	Hemorrhagic septicemia	Africa, Latin America
Rickettsias		
Cowdria ruminantium	Heartwater	Africa, Caribbean
Cytoecetes phagocytophilia	Tick borne fever	Europe
Ehrlichia bovis	Bovine ehrlichiosis	Africa, Mediterranean, South America
Ehrlichia (Cytoecetes) ondiri	Bovine infectious petechial fever	East Africa
Ehrlichia ovina	Ovine ehrlichiosis	Africa, Middle East, Sri Lanka
Piscirickettsia salmoninarum	Piscirickettsiosis	Chile
Viruses (and Virus-Like Particles)		
African horse sickness virus (AHS1, AHS2 ... AHS9)	African horse sickness	Africa
African swine feverlike virus	African swine fever	Africa, Italy
Classical swine fever virus	Classical swine fever	Asia, Europe, Latin America
Enteroviruses serotypes 1-3	Teschen-Talfan disease	Europe, Madagascar
Epizootic haematopoietic necrosis virus	Epizootic haematopoietic necrosis	Australia
Equine herpesvirus Type A	Horse pox	Mozambique
Flavivirus	Japanese encephalitis	Asia
Foot-and-mouth virus	Foot-and-mouth disease	Global

Hendra virus	Hendra virus disease	Australia
Influenzavirus A	Fowl plague	Africa, Asia, Eastern Europe
Influenzavirus A	Highly pathogenic avian influenza	Italy, Pakistan
Jembrana disease virus	Jembrana	Indonesia
Louping ill virus	Louping ill	Bulgaria, Norway, Spain, Turkey, United Kingdom
Lumpy skin disease virus	Lumpy skin disease	Africa
Maedi-visna virus (tentative)	Maedi-visna	Canada, Europe
Nairobi sheep disease virus	Nairobi sheep disease	East Africa
Nipah virus (tentative)	Nipah virus	Malaysia
Ovine pulmonary adenomatosis virus	Ovine pulmonary adenomatosis	Africa, Canada, Europe, Middle East
Onchorhynchus masou herpesvirus	Onchorhynchus masou disease	Japan
Peste des petits ruminants virus	Peste des petits ruminants	Africa, Asia
Rhadovirus (unclassified)	Ephemeral fever	Australia
Rift valley fever virus	Rift valley fever	Africa, Saudi Arabia, Yemen
Rinderpest virus	Rinderpest	Pakistan, Russia
Sheeppox virus	Sheep and goat pox	Africa, Asia, Europe
Spring viremia of carp virus (tent.)	Spring viremia of carp	United Kingdom
Swine vesicular disease virus	Swine vesicular disease	China, Italy
Viral haemorrhagic septicaemia virus	Viral haemorrhagic septacaemia	Europe, Japan
Protozoa		
Babesia spp.	Babesiosis	Global
Besnoitia besnoti	Besnoitiosis	Africa, Europe
Theileria spp.	Theileriosis	Africa, Asia, Middle East
Trypanosoma congolense, T. vivax, T. brucei brucei, T. simiae	Trypanosomoses (African)	Africa, Central and South America
Trypanosoma equiperdum	Dourine	Africa, Asia, Southeastern Europe, South America
Trypanosoma evansi	Surra	Central and South America

Table B.2. Non-native pests potentially damaging to plants if introduced or reintroduced

Scientific name	Common name	Potential source
Insects		
Adelges japonicus	Spruce gall aphid	Japan
Agriotes obscurus	Dusky wire worm	Canada, Europe
Agriotes sputator	Common click beetle	Canada, Northern Europe
Anoplophora glabripennis[1]	Asian long-horned beetle	China, Japan, Korea
Aradus cinnamomeus	Pine flat bug	Europe

Calliteara pudibunda	Dog hop	Europe
Cerambyx cerdo	Great capricorn beetle	Europe
Ceratitis capitata[2]	Mediterranean fruit fly	Africa, Central and South America, Europe
Cryptomermes spp.	Drywood termite	Africa, Asia, Central America
Dendroctonus spp.	Bark beetle	China
Eutetranychus orientalis	Citrus brown mite	Africa, Asia, Australia, Middle East
Helicoverpa armigera	Cotton bollworm	Africa, Asia, Australia, Europe, Middle East, Pacific Islands
Hylurgops major	Pine bark beetle	China
Hylurgus ligniperda	Red-haired pine bark beetle	Africa, Asia, Australia, Brazil, Europe
Ips typographus	Spruce bark beetle	Asia, Europe
Lesidosaphes newsteadi	Pine pest	Cuba
Lymantria dispar (Asian)	Asian gypsy moth	Eurasia
Lymantria monacha	Nun moth	Asia, Europe
Orthotomicus erosus	Mediterranean pine engraver	Asia, Chile, Europe, Middle East, South Africa
Panolis flammea	Pine beauty	Europe
Pityogenes charcographus	Bark beetle	Asia
Sarsina violascens	Purple moth on eucalyptus	Argentina, Brazil, Mexico
Scolytus intricatus	European oak bark beetle	Africa, Asia, Europe, North Africa
Sirex noctilio	Wood wasp, pine	Asia, Australia, Europe, North Africa, South America
Targionia vitis	Pest on grape	Mediterranean area
Tomicus piniperda	Bark beetle	Asia
Trogoderma granarium	Khapra beetle	Africa, Asia, Brazil, China, Europe, India, Japan, Philippines
Xyleborus spp.	Bark beetle	China
Zabus tenebrioides	Corn ground beetle	Europe
Fungi		
Armillaria spp. (exotic)	Root and heart rots of trees	Africa, Asia, Australia, Europe, South America
Ceratocystis autographa	Wood rot of conifers	Europe
Chrysomyxa deformans	Rust on Picea spp.	Asia
Chrysomyxa himalensis	Rust on rhododendron	India
Colletotrichum zeae	Anthracnose	Africa, Europe, Nepal
Cronartium himalayense	Pine rust	Asia, India
Ganoderma spp. (exotic)	Root and wood rots of trees	Africa, Asia, South America
Helicobasidium mompa	Wood rot of fruit trees	India, Japan
Heterobasidium spp. (exotic)	Root, butt, heart rots of trees	Asia, Australia, Europe
Lachnellula willcommi	Larch canker	Europe
Lophodermella sulcigena	Needle cast of pines	Eastern Europe
Melampsora pinitorqua	Twist rust of pines	Europe

Microcyclus ulei	Leaf blight of rubber	Central and South America
Moniliophthra (Monilia) rorei	Pod rot of cacao	Central and South America
Mycosphaerella sojae	Soybean brown spot	Asia
Ophiostoma spp. (exotic)	Wilt and wood rot of tree	Asia, Europe
Peronosclerospora maydis	Java downy mildew, corn	Australia, Indonesia
Peronosclerospora philippinensis	Philippine downy mildew	India, Indonesia, Philippines
Peronosclerospora sacchari	Downy mildew	Australia, Fiji, India, Japan, Philippines, Taiwan
Phakopsora pachyrhiza	Soybean rust	Africa, Asia, Australia, Central and South America, Mexico, Pacific Islands
Phellinus spp. (exotic)	Root and wood rots of trees	Africa, Asia, Australia, Europe, South America
Physopella zeae	Tropical rust, corn	Central and South America, Caribbean
Phytophthora cambivora	Root rots of trees	Australia, Europe
Pucciniastrum areolatum	Cherry spruce rust	Europe
Pythium volutum	Root rots of barley, ginger	Europe
Sclerophthora raysiae	Downy mildew	India, Nepal, Thailand
Sclerospora spontanea	Sugarcane downy mildew	Asia
Septoria maydis	Ear and stalk rots of corn	Central and South America
Synchytrium dolichi	Gall on Fabiaceae	Africa, Asia, Central America, Philippines
Synchytrium umbilicatum	Gall on Fabiaceae	Sri Lanka, India
Bacteria and phytoplasmas		
Corynebacterium tritici (C. rathayi)	Yellow slime disease	Australia, Europe, India, Middle East
Flavescence doree (maladie du Buco 21)	Phytoplasma of grape	Europe
Liberobacter spp.	Citrus greening (Huanglongbin, HLB)	Africa, Asia
Phytoplasma	Apple proliferation	Europe
Xanthomonas axonopodis Pv. *citri*	Citrus canker	Asia, Australia, India, Indonesia, Mexico, South Africa
Xanthomonas axonopodis Pv. *vasculorum*	Sugarcane gumming disease	Africa, Australia, Central and South America, Philippines
Xylophilus ampelinus	Canker of grapevine	Mediterranean, South Africa
Viruses (and Virus-Like Particles)		
Banana bunchy top virus	Banana bunchy top virus	Africa, Asia, Australia
Begomovirus complex	Begomovirus complex (New types and vectors)	Asia, Caribbean, Worldwide
Citrus chlorotic dwarf virus	Citrus chlorotic dwarf virus	Turkey
Citrus ringspot virus	Citrus ringspot virus	Argentina
Citrus tristeza virus	Citrus tristeza virus (CTV, new strain)	Asia, Caribbean

Groundnut rosette virus	Groundnut rosette virus	Africa, Australia, Philippines
Plum pox virus[3]	Plum pox	Chile, Europe, India
Soybean stunt virus	Soybean stunt	Asia
Veinal necrosis virus	Potato virus Y necrotic strain for tobacco and potato, PVYN	South America
Virus complex	Citrus psorosis virus complex	Brazil, Cuba, India, Mediterranean, New Zealand
Nematodes		
Globodera rostochiensis	Golden nematode of potato	Africa, Canada, Central and South America, Europe, Japan

1 Eradication program in New York and Illinois
2 Eradication program in the United States
3 Under eradication in the United States

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1 | Cost estimates cited in this report are based generally on a simple calculation that the value of losses is equal to an average price multiplied by the quantity lost due to the pest. The authors caution that such calculations, although common in pest loss literature, do not estimate correctly the economic cost of the pest to society. Valid estimates must take into account more-appropriate economic concepts and allow for price, demand, supply, export, and import adjustments. The authors also caution that the cost estimates cited here do not indicate in any way to whom the costs (or benefits) of non-native pests accrue. Additional information on more-appropriate economic concepts for calculating aggregate economic effects can be found in Taylor (1978). These concepts are beyond the scope of the present report. Although the estimates cited here are not theoretically or conceptually valid, they may be useful for indicating the magnitude of importance of various pests. The estimates also may be used to provide a rough ranking of pests' relative importance.

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