ENVIRONMENTAL AND ECONOMIC COSTS ASSOCIATED WITH NON-INDIGENOUS SPECIES IN THE UNITED STATES

David Pimentel, Lori Lach, Rodolfo Zuniga, and Doug Morrison
College of Agriculture and Life Sciences
Cornell University
Ithaca, NY 14850-0901
June 12, 1999

phone: (607) 255-2212
fax: (607) 255-0939
email: dp18@cornell.edu

ABSTRACT

Invading non-indigenous species in the United States cause major environmental damages and losses adding up to more than $138 billion per year. There are approximately 50,000 foreign species and the number is increasing. About 42% of the species on the Threatened or Endangered species lists are at risk primarily because of non-indigenous species.

In the history of the United States, approximately 50,000 non-indigenous (non-native) species are estimated to have been introduced into the United States. Introduced species, such as corn, wheat, rice, and other food crops, and cattle, poultry, and other livestock, now provide more than 98% of the U.S. food system at a value of approximately $800 billion per year (USBC 1998). Other exotic species have been introduced for landscape restoration, biological pest control, sport, pets, and food processing. Some non-indigenous species, however, have caused major economic losses in agriculture, forestry, and several other segments of the U.S. economy, in addition to harming the environment. One recent study reported approximately $97 billion in damages from 79 exotic species during the period from 1906 to 1991 (OTA 1993).

Estimating the full extent of the environmental damages caused by exotic species and the number of species extinctions they have caused is difficult because little is known about the estimated 750,000 species in the United States, half of which have not even been described (Raven and Johnson 1992). Nonetheless, about 400 of the 958 species that are listed as threatened or endangered under the Endangered Species Act are considered to be at risk primarily because of competition with and predation by non-indigenous species (Nature Conservancy 1996; Wilcove et al. 1998). In other regions of the world, as many as 80% of the endangered species are threatened due to the pressures of non-native species (Armstrong 1995). Many other species worldwide

that are not listed are also negatively affected by alien species and/or ecosystem changes caused by alien species. Estimating the economic impacts associated with non-indigenous species in the United States is also difficult; nevertheless, enough data are available to quantify some of the impacts on agriculture, forestry, and public health. In this article, we assess as much as possible the magnitude of the environmental impacts and economic costs associated with the diverse non-indigenous species that have become established within the United States. Although species translocated within the United States can also have significant impacts, this assessment is limited to non-indigenous species that did not originate within the United States or its territories.

ENVIRONMENTAL DAMAGES AND ASSOCIATED CONTROL COSTS

Most plant and vertebrate animal introductions have been intentional, whereas most invertebrate animal and microbe introductions have been accidental. In the past 40 years, the rate of and risks associated with biotic invaders have increased enormously because of human population growth, rapid movement of people, and alteration of the environment. In addition, more goods and materials are being traded among nations than ever before, thereby creating opportunities for unintentional introductions (Bryan 1996; USBC 1998).

Some of the approximately 50,000 species of plants and animals that have invaded the United States cause many different types of damage to managed and natural ecosystems (Table 1). Some of these damages and control costs are assessed below.

Plants. Most alien plants now established in the United States were introduced for food, fiber, or ornamental purposes. An estimated 5000 introduced plant species have escaped and now exist in U.S. natural ecosystems (Morse et al. 1995), compared with a total of about 17,000 species of native U.S. plants (Morin 1995). In Florida, of the approximately 25,000 alien plant species imported mainly as ornamentals for cultivation, more than 900 have escaped and become established in surrounding natural ecosystems (Frank and McCoy 1995a; Frank et al. 1997; Simberloff et al. 1997). More than 3000 plant species have been introduced into California, and many of these have escaped into the natural ecosystem (Dowell and Krass 1992).

Some of the 5000 non-indigenous plants established in U.S. natural ecosystems have displaced several native plant species (Morse et al. 1995). Non-indigenous weeds are spreading and invading approximately 700,000 ha/yr of the U.S. wildlife habitat (Babbitt 1998). One of these pest weeds is the European purple loosestrife (*Lythrum salicaria*), which was introduced in the early 19th century as an ornamental plant (Malecki et al. 1993). It has been spreading at a rate of 115,000 ha/yr and is changing the basic structure of most of the wetlands it has invaded (Thompson et al. 1987). Competitive stands of purple loosestrife have reduced the biomass of 44 native plants

and endangered wildlife, including the bog turtle (*Clemmys muhlenbengil*) and several duck species, that depend on these native plants (Gaudet and Keddy 1988). Loosestrife now occurs in 48 states and costs $45 million per year in control costs and forage losses (ATTRA 1997).

Many introduced plant species established in the wild are having an effect on U.S. parks (Hiebert and Stubbendieck 1993). In Great Smoky Mountains National Park, 400 of approximately 1,500 vascular plant species are exotic, and 10 of these are currently displacing and threatening other species in the park (Hiebert and Stubbendieck 1993).

The problem of introduced plants is especially significant in Hawaii. Hawaii has a total of 2690 plant species, 946 of which are non-indigenous species (Eldredge and Miller 1997). About 800 native species are currently endangered (Vitousek 1988).

Sometimes one non-indigenous plant species competitively overruns an entire ecosystem. For example, in California, yellow star thistle (*Centaurea solstitalis*) now dominates more that 4 million ha of northern California grassland, resulting in the total loss of this once productive grassland (Campbell 1994).

Similarly, European cheatgrass (*Bromus tectorum*) is dramatically changing the vegetation and fauna of many natural ecosystems. This annual grass has invaded and spread throughout the shrub-steppe habitat of the Great Basin in Idaho and Utah, predisposing the invaded habitat to fires (Kurdila 1995; Vitousek et al. 1996; Vitousek et al. 1997). Before the invasion of cheatgrass, fire burned once every 60 - 110 years, and shrubs had a chance to become well established. Now, fires occur about every 3 - 5 years; shrubs and other vegetation are diminished, and competitive monocultures of cheatgrass now exist on 5 million ha in Idaho and Utah (Whisenant 1990). The animals dependent on the shrubs and other original vegetation have been reduced or eliminated.

An estimated 138 non-indigenous tree and shrub species have invaded native U.S. forest and shrub ecosystems (Campbell 1998). Introduced trees include salt cedar (*Tamarix pendantra*), eucalyptus (*Eucalyptus spp.*), Brazilian pepper (*Schinus terebinthifolius*), and Australian melaleuca (*Melaleuca quenquenervia*) (OTA 1993; Miller 1995; Randall 1996). Some of these trees have displaced native trees, shrubs, and other vegetation types, and populations of some associated native animal species have been reduced in turn (OTA 1993). For example, the melaleuca tree is competitively spreading at a rate of 11,000 ha/yr throughout the vast forest and grassland ecosystems of the Florida Everglades (Campbell 1994), where it damages the natural vegetation and wildlife (OTA 1993).

Exotic aquatic weeds are also a significant problem in the United States. For example, in the Hudson River basin of New York, there are 53 exotic aquatic weed species (Mills et al. 1997). In Florida, exotic aquatic plants, such as hydrilla (*Hydrilla verticillata*), water *hyacinth (Eichhornia crassipes*), and water lettuce (*Pistia straiotes*), are altering

fish and other aquatic animal species, choking waterways, altering nutrient cycles, and reducing recreational use of rivers and lakes. Active control measures of the aquatic weeds have become necessary (OTA 1993). For instance, Florida spends about $14.5 million each year on hydrilla control (Center et al. 1997). Nevertheless, hydrilla infestations in just 2 Florida lakes have caused an estimated $10 million in recreational losses in the lakes annually (Center et al. 1997). In the United States as a whole, a total of $100 million is invested annually in non-indigenous species aquatic weed control (OTA 1993).

Mammals. About 20 species of mammals have been introduced into the United States; these include dogs, cats, horses, burros, cattle, sheep, pigs, goats, and deer (Layne 1997). Several of these species have escaped or were released into the wild; many have become pests by preying on native animals, grazing on vegetation, or intensifying soil erosion. For example, goats (*Capra hirus*) introduced on San Clemente Island, California, are responsible for the extinction of 8 endemic plant species as well as the endangerment of 8 other native plant species (Kurdila 1995).

Many small mammals have also been introduced into the United States. These species include a number of rodents, (the European [black or tree] rat [*Rattus rattus*)], Asiatic [Norway or brown] rat [*Rattus norvegicus*], house mouse [*Mus musculus*], and European rabbit *[Oryctolagus cuniculus*] (Layne 1997).

Some introduced rodents have become serious pests on farms, in industries, and in homes (Layne 1997). Rats and mice are particularly abundant and destructive on farms. On poultry farms, there is approximately 1 rat per 5 chickens (D. Pimentel, unpublished, 1951; Smith 1984). Using this ratio, the total rat population on U. S. poultry farms may easily number more than 1.4 billion (USDA 1998). Assuming that the number of rats per chicken has declined because of improved rat control since these observations were made, we estimate that the number of rats on poultry and other farms is approximately 1 billion. With an estimated additional 1 rat per person in homes and related areas (Wachtel and McNeely 1985), there are an estimated 250 million rats in the United States (USBC 1998).

If we assume, conservatively, that each adult rat consumes and/or destroys stored grains (Chopra 1992; Ahmed et al. 1995) and other materials valued at $15/yr, then the total cost of destruction by introduced rats in the United States is more than $19 billion per year. In addition, rats cause fires by gnawing electric wires, pollute foodstuffs, and act as vectors of several diseases, including salmonellosis and leptospirosis, and, to a lesser degree, plague and murine typhus (Richards 1989). They also prey on some native invertebrate and vertebrate species like birds and bird eggs (Amarasekare 1993).

One of the first cases of the failure of biological control is the use of the Indian mongoose (*Herpestes auropunctatus*). It was first introduced into Jamaica in 1872 for biological control of rats in sugarcane (Pimentel 1955). It was subsequently introduced

to the territory of Puerto Rico, other West Indian Islands, and Hawaii for the same purpose. The mongoose controlled the Asiatic rat but not the European rat, and it preyed heavily on native ground nesting birds (Pimentel 1955; Vilella and Zwank 1993). It also preyed on beneficial native amphibians and reptiles, causing at least 7 amphibian and reptile extinctions in Puerto Rico and other islands of the West Indies (Henderson 1992). In addition, the mongoose emerged as the major vector and reservoir of rabies and leptospirosis in Puerto Rico and other islands (Everard and Everard 1992). Based on public health damages, killing of poultry in Puerto Rico and Hawaii, extinctions of amphibians and reptiles, and destruction of native birds, we estimate that the mongoose is causing approximately $50 million in damages each year in Puerto Rico and the Hawaiian Islands.

Introduced cats have also become a serious threat to some native birds and other animals. There are an estimated 63 million pet cats in the United States (Nassar and Mosier 1991), plus as many as 30 million feral cats (Luoma 1997). Cats prey on native birds (Fitzgerald 1990), plus small native mammals, amphibians, and reptiles (Dunn and Tessaglia 1994). Estimates are that feral cats in Wisconsin and Virginia kill more than 3 million birds in each state per year (Luoma 1997). Based on the Wisconsin and Virginia data, we assume that 5 birds are killed per feral cat/year; McKay (1996) reports that pet cats kill a similar number of birds as feral cats. Thus, about 465 million birds are killed by cats per year in the nation. Each adult bird can be valued at $30. This cost per bird is based on the literature that reports that a bird watcher spends $0.40 per bird observed, a hunter spends $216 per bird shot, and specialists spend $800 per bird reared for release; in addition, note that EPA fines polluters $10 per fish killed, including small, immature fish (Pimentel and Greiner 1997). Therefore, the total damage to U.S. bird population is approximately $14 billion/yr. This figure does not include small mammals, amphibians, and reptiles that are killed by feral and pet cats (Dunn and Tessaglia 1994).

Like cats, most dogs introduced into the United States were introduced for domestic purposes, but some have escaped into the wild. Many of these wild dogs run in packs and kill deer, rabbits, and domestic cattle, sheep, and goats. Carter (1990) reported that feral dog packs in Texas cause more than $5 million in livestock losses each year. Dog packs have also become a serious problem in Florida (Layne 1997). In addition to the damages caused by dogs in Texas, and conservatively assuming $5 million for all damages for the other 49 states combined, total losses in livestock kills by dogs per year would be approximately $10 million per year.

Moreover, an estimated 4.7 million people are bitten by feral and pet dogs annually, with 800,000 cases requiring medical treatment (Sacks et al. 1996). Centers for Disease Control estimates medical treatment for dog bites costs $165 million/yr, and the indirect costs, such as lost work, increase the total costs of dog bites to $250 million/yr (Colburn 1999; Quinlan and Sacks, 1999). In addition, dog attacks cause between 11 and 14 deaths per year, and 80% of the victims are small children (CDC 1997).

Birds. Approximately 97 of the 1,000 bird species in the United States are exotic (Temple 1992). Of the approximately 97 introduced bird species, only 5%, including chickens, are considered beneficial. Most (56%), though, are considered pests (Temple 1992). Pest species include the pigeon, which was introduced into the United States for agricultural purposes.

Introduced bird species are an expecially severe problem in Hawaii. A total of 35 of the 69 non-indigenous bird species introduced between 1850 and 1984 in Hawaii are still extant on the islands (Moulton and Pimm 1983; Pimm 1991). One such species, the common myna (*Acridotheres tristis*), was introduced to help control pest cutworms and armyworms in sugarcane (Kurdila 1995). However, it became the major disperser of seeds of an introduced serious weed, *Lantana camara*. In the continental United States, the English or house sparrow (*Passer domesticus*) was introduced in 1853 to control the canker worm (Laycock 1966; Roots 1976). By 1900, the had become pests because they damage plants around homes and public buildings and consume wheat, corn, and the buds of fruit trees (Laycock 1966). Furthermore, English sparrows harass native birds, including robins, Baltimore orioles, yellow-billed cuckoos, and black-billed cuckoos, and displace native bluebirds, wrens, purple martins, and cliff swallows from their nesting sites (Laycock 1966; Roots 1976; Long 1981). They are also associated with the spread of about 29 human and livestock diseases (Weber 1979).

The single-most serious pest bird in the United States is the exotic common pigeon (*Columba livia*) that exists in most cities of the world, including those in the United States (Robbins 1995). Pigeons are considered a nuisance because they foul buildings, statues, cars, and sometimes people, and feed on grain (Long 1981; Smith, 1992). The control costs of pigeons are at least $9 per pigeon per year (Haag-Wackernagel 1995). Assuming 1 pigeon per ha in urban areas (Johnston and Janiga 1995) or approximately 0.5 pigeons per person, and using potential control costs as a surrogate for losses, pigeons cause an estimated $1.1 billion/yr in damages. These control costs do not include the environmental damages associated with pigeons, which serve as reservoirs and vectors for over 50 human and livestock diseases, including parrot fever, ornithosis, histoplasmosis, and encephalitis (Weber 1979; Long 1981).

Amphibians and Reptiles. Amphibians and reptiles introduced into the United States number about 53 species. All these non-indigenous species occur in relatively warm states -- Florida is now host to 30 species and Hawaii to 12 (McCoid and Kleberg 1995; Lafferty and Page 1997). The negative ecological impacts of several of these exotic species have been enormous .

The brown tree snake (*Boiga irregularis*) was accidentally introduced to the snake-free U.S. territory of Guam immediately after World War II, when military equipment was moved onto Guam (Fritts and Rodda 1995). Soon the snake population reached densities of 100 per ha, and dramatically reduced native bird, mammal, and lizard

populations. Of the 13 species of native forest birds originally found on Guam, only 3 still exist (Rodda et al. 1997); of the 12 native species of lizards, only 3 have survived (Rodda et al.1997). The snake eats chickens, eggs, and caged birds, causing major problems to small farmers and pet owners. It also crawls up trees and utility poles and has caused power outages on the island. One island-wide power outage caused by the snake cost the power utility more than $250,000 (Teodosio 1987). Local outages that affect businesses are estimated to cost from $2,000 to $10,000 per commercial customer (Coulehan 1987). With about 86 outages per year (BTSCP 1996), our estimate of the cost of snake-related power outages is conservatively $1 million/yr.

In addition, the brown tree snake is slightly venomous, and has caused public health problems, especially when it has bitten children. At one hospital emergency room, about 26 people per year are treated for snake bites (OTA 1993). Some bitten infants require hospitalization and intensive care, at an estimated total cost of $25,000 per year.

The total costs of endangered species recovery efforts, environmental planning related to snake containment on Guam and other programs directly stemming from the snake's invasion of Guam reach more than $1 million per year; in addition, up to $2 million per year is invested in research to control this serious pest. The brown tree snake has also invaded Hawaii but thus far has been exterminated. Hawaii's concern about the snake, though, has prompted the federal government to invest $1.6 million per year in brown tree snake control (Holt 1997-1998). The total cost associated with the snake is therefore more than $5.6 million/yr.

Fish. A total of 138 non-indigenous fish species has been introduced into the United States (Courtenay et al. 1991; Courtenay 1993, 1997). Most of these introduced fish have been established in states with mild climates, such as Florida (50 species) (Courtenay 1997) and California (56 species) (Dill and Cordone 1997). In Hawaii, 33 non-indigenous freshwater fish species have become established (Maciolek 1984). Forty-four native species of fish are threatened or endangered in the United States by non-indigenous fish species (Wilcove and Bean 1994). An additional 27 native fish species are also negatively affected by introductions (Wilcove and Bean 1994).

Introduced fish species frequently alter the ecology of aquatic ecosystems. For instance, the grass carp (Ctenopharyngodon idella) reduces natural aquatic vegetation, while the common carp (Cyprinus carpio) reduces water quality by increasing turbidity. These changes have caused the extinctions of some native fish species (Taylor et al. 1984).

Although some native fish species are reduced in numbers, are driven to extinction, or hybridized by non-indigenous fish species, alien fish do provide some economic benefits in the improvement of sport fishing. Sport fishing contributes $69 billion to the economy of the United States (Bjergo et al. 1995; USBC 1998). However, even taking into account these economic benefits, based on the more than 40 non-indigenous species that have negatively affected native fishes and other aquatic biota, a conservative

estimate puts the economic losses due to exotic fish at more than $1 billion annually.

Arthropods and Annelids. Approximately 4,500 arthropod species (2,582 species in Hawaii and more than 2,000 in the continental United States) have been introduced to the United States. Also, 11 earthworm species (Hendrix 1995), and nearly 100 aquatic invertebrate species have been introduced (OTA 1993). About 95% of these introductions were accidental, with many species gaining entrance via plants or through soil and water ballast from ships.

For example, the accidentally-introduced balsam woolly adelgid (*Adelges piceae*) inflicts severe damage in balsam-fir natural forest ecosystems (Jenkins 1998). According to Alsop and Laughlin (1991), this aphid is destroying the old-growth spruce-fir forest in many regions. Over the last two decades, it has spread throughout the southern Appalachians, where it has destroyed up to 95% of the fraser firs. Alsop and Laughlin (1991) report the loss of 2 native bird species and the invasion by 3 other bird species as a result of adelgid-mediated forest death.

Other introduced insect species have become pests of livestock and wildlife. For example, the red imported fire ant (Solenopsis invicta) kills poultry chicks, lizards, snakes, and ground nesting birds (Vinson 1994). A 34% decrease in swallow nesting success as well as a decline in the northern bobwhite quail populations was reported due to these ants (Allen et al. 1995). The estimated damage to livestock, wildlife, and public health caused by fire ants in Texas is estimated to be $300 million/yr. An additional $200 million is invested in control per year (Vinson 1992; TAES 1998). Assuming similar damages in other infested southern states -- such as Florida, Georgia, and Louisiana -- the fire ant damages total more than $1 billion/yr. Southern states are also affected by another insect, the Formosan termite (*Coptotermes formosanus*), which is reported to cause structural damages totalling approximately $1 billion/yr in Southern United States, especially in the New Orleans region (Corn et al. 1999).

The European green crab (*Carcinus maenas*) has been associated with the demise of the soft shell clam industry in New England and maritime provinces of Canada (Lafferty and Kuris 1996). It also destroys commercial shellfish beds and preys on large numbers of native oysters and crabs (Lafferty and Kuris 1996), with an annual estimated economic impact of $44 million/yr (Lafferty and Kuris 1996).

Mollusks. Eighty-eight species of mollusks have been both intentionally and accidentally introduced and established in U. S. aquatic ecosystems (OTA 1993). Two have become serious pests: the zebra mussel (*Dreissena polymorpha*) and the Asian clam (*Corbicula fluminea*).

The zebra mussel was first found in Lake St. Clair after gaining entrance via ballast water released in the Great Lakes from ships that had traveled from Europe (Benson and Boydstun 1995). It has spread into most of the aquatic ecosystems in the eastern United

States and is expected to invade most freshwater habitats throughout the nation in approximately 20 years (Benson and Boydstun 1995). Large mussel populations reduce food and oxygen for native fauna. In addition, zebra mussels have been observed completely covering native mussels, clams, and snails, thereby further threatening their survival (Benson and Boydstun 1995; Keniry and Marsden 1995). Mussel densities have reached 700,000/m^2 in some locations (Griffiths et al. 1991). Zebra mussels also invade and clog water intake pipes and water filtration and electric generating plants; it is estimated that they will cause $5 billion/yr in damages to these facilities and associated control costs by the year 2000 (Khalanski 1997).

Although the Asian clam grows and disperses less rapidly than the zebra mussel, it too is causing significant fouling problems and is threatening native species. Costs associated with its fouling damage are about $1 billion/yr (Isom 1986; OTA 1993).

Another pest mollusk is the introduced shipworm (*Teredo navalis*), which was first introduced into the San Francisco Bay. It has caused serious damage since the early 1990s. Currently, damages are estimated to be approximately $200 million/yr (Cohen and Carlton 1995).

CROP, PASTURE, AND FOREST LOSSES AND ASSOCIATED CONTROL COSTS

Many weeds, pest insects, and plant pathogens are biological invaders. These non-indigenous species cause several billion dollars worth of losses to crops, pastures, and forests annually in the United States. In addition, several billion dollars are spent on pest control.

Weeds. In crop systems, including forage crops, an estimated 500 introduced plant species have become weed pests; some of these, such as Johnson grass (*Sorghum halepense*) and Kudzu (*Pueraria lobata*), were actually introduced as crops and then became pests (Pimentel et al. 1989). Most of these weeds were accidentally introduced with crop seeds, from ship-ballast soil, or from various imported plant materials, among which were yellow rocket (*Barbarea vulgaris*) and Canada thistle (*Cirsium arvense*).

In U.S. agriculture, weeds cause an overall reduction of 12% in crop yields. In economic terms, this reduction represents about $33 billion in lost crop production annually, based on the crop potential value of all U.S. crops of more than $267 billion/yr (USBC 1998). Based on the survey that about 73% of the weed species are non-indigenous (Pimentel 1993), it follows that about $24 billion/yr of these crop losses are due to introduced weeds. However, non-indigenous weeds are often more serious pests than native weeds; this estimate of $24 billion/yr is conservative. In addition to direct losses, approximately $4 billion/yr in herbicides are applied to U.S. crops (Pimentel 1997), of which about $3 billion/yr is used for control of non-indigenous

weeds. Therefore, the total costs of introduced weeds to the U.S. economy is about $27 billion annually.

In pastures, 45% of weeds are non-indigenous species (Pimentel 1993). U.S. pastures provide about $10 billion in forage crops annually (USDA 1998), and the estimated losses due to weeds are approximately $2 billion (Pimentel 1991). Forage losses due to non-indigenous weeds are nearly $1 billion/yr.

Some introduced weeds are toxic to cattle and wild ungulates, such as leafy spurge (*Euphoria esula*) (Trammel and Butler 1995). In addition, several non-indigenous thistles have reduced native forage plant species in pastures, rangelands, and forests, thus reducing cattle grazing (Dewey 1991). According to Interior Secretary Bruce Babbitt (1998), ranchers spend about $5 billion each year to control invasive non-indigenous weeds in pastures and rangelands. Nevertheless, these weeds continue to spread.

Control of weed species in lawns, gardens, and golf courses is a significant proportion of the total management costs of about $36 billion/yr (USBC 1998). In fact, Templeton et al. (1998) estimated that each year about $1.3 billion of the $36 billion is spent just on residential weed, insect, and disease pest control each year. Because a large proportion of these weeds, such as dandelions (*Taraxacum officinale*) are exotics, we estimate that $500 million is spent on residential exotic weed control and an additional $1 billion is invested in non-indigenous weed control on golf courses.

Weed trees also have an economic impact, and from $3 to $6 million per year is being spent in efforts to control only the melaleuca tree in Florida.

Vertebrate Pests. Horses (*Equus caballus*) and burros (*Equus asinus*), deliberately released in the western United States, have attained wild populations of approximately 50,000 animals (Pogacnik 1995). These animals graze heavily on native vegetation, allowing non-indigenous annuals to displace native perennials (Rosentreter 1994). Burros inhabiting the northwestern United States also diminish the primary food sources of native bighorn sheep and seed-eating birds, thereby reducing the abundance of these native animals (Kurdila 1995). In general, the large populations of introduced wild horses and burros cost the nation an estimated $5 million/yr in forage losses (Pimentel et al. 1999).

Feral pigs (*Sus scrofa*), native to Eurasia and North Africa, have been introduced into some U.S. parks for hunting, including parks in the California coastal prairie and Hawaiian islands, where they have substantially changed the vegetation in these parks (Kotanen 1995). In Hawaii, more than 80% of the soil is bare in regions inhabited by pigs (Kurdila 1995). This disturbance allows annual plants to invade the overturned soil and intensifies soil erosion. Pig control per park in Hawaii (~1500 pigs/park) (Stone et al. 1992) costs about $150,000/yr . Assuming that the 3 parks in Hawaii have similar

pig control problems, the total is $450,000/yr (P. C., R. Zuniga, Cornell University, 1999).

Feral pigs have also become a serious problem in Florida, where their population has risen to more than 500,000 (Layne 1997); similarly, in Texas their number ranges from 1 to 1.5 million. In Florida, Texas, and elsewhere, pigs damage grain, peanut, soybean, cotton, hay, and various vegetable crops, and the environment (Rollins 1998). Pigs also transmit and are reservoirs for serious human and livestock diseases, including brucellosis, pseudobrucellosis, and trichinosis (Davis 1998).

Nationwide, there are an estimated 4 million feral pigs. Based on environmental and crop damages of about $200 per pig annually (one pig can cause up to $1000 of damages to crops in one night), and assuming that 4 million feral pigs inhabit the United States, the yearly damage amounts to about $800 million/yr. This estimate is conservative because pigs cause significant environmental damages and diseases that cannot be easily translated into dollar values.

Other animals that threaten crop production include birds. European starlings *(Sturnus vulgaris*) are serious pests and are estimated to occur at densities of more than 1 per ha in agricultural regions (Moore 1980). Starlings are capable of destroying as much as $2,000 worth of cherries per hectare (Feare 1980). In grain fields, starlings consume about $6/ha of grain (Feare 1980). Conservatively assuming $5/ha for all damages to many crops in the United States, the total loss due to starlings would be approximately $800 million/yr. In addition, these aggressive birds have displaced numerous native birds (Laycock 1966). Starlings have also been implicated in the transmission of 25 diseases, including parrot fever and other diseases of humans (Laycock 1966; Weber 1979).

Insect and Mite Pests. Approximately 500 non-indigenous insect and mite species are pests in crops in the United States. Hawaii has 5,246 identified native insect species, and an additional 2,582 introduced insect species (Howarth 1990; Frank and McCoy 1995a; Eldredge and Miller 1997). Introduced insects account for 98% of the crop pest insects in the state (Beardsley 1991). In addition to Florida's 11,500 native insect species, 949 introduced species have, mostly accidentally, invaded the state (42 species were intentionally introduced for biological control; Frank and McCoy 1995b). In California, the 600 introduced species are responsible for 67% of all crop losses (Dowell and Krass 1992).

Each year, pest insects destroy about 13% of potential crop production representing a value of about $33 billion in U.S. crops (USBC 1998). Considering that about 40% of the pests were introduced (Pimentel 1993), we estimate that introduced pests cause about $13 billion in crop losses each year. In addition, about $1.2 billion in pesticides are applied for all insect control each year (Pimentel 1997). The portion applied against introduced pest insects is approximately $500 million/yr. Therefore, the total cost for

introduced non-indigenous insect pests is approximately $13.5 billion/yr. In addition, based on the analysis of management costs of lawns, gardens, and golf courses, we estimate the control costs of pest insects and mites in lawns, gardens, and golf courses to be at least $1.5 billion/yr.

In addition to crops, about 360 non-indigenous insect species have become established in American forests (Liebold et al. 1995), of which approximately 30% of these are now serious pests. Insects cause the loss of approximately 9% of forest products, amounting to a cost of $7 billion per year (Hall and Moody 1994; USBC 1998). Because 30% of the pests are non-indigenous, annual losses attributed to non-indigenous species is about $2.1 billion per year.

The gypsy moth (*Lymantria dispar*), intentionally introduced into Massachusetts in the 1800s for possible silk production, has developed into a major pest of U.S. forest and ornamental trees, especially oaks (Campbell and Schlarbaum 1994). The U.S. Forest Service currently spends about $11 million annually on gypsy moth control (Campbell and Schlarbaum 1994).

Plant Pathogens. There are an estimated 50,000 parasitic and non-parasite diseases of plants in the United States, most of which are caused by fungae species (USDA 1960). In addition more than 1300 species of viruses are plant pests in the United States (USDA 1960). Many of these microbes are non-native and were introduced inadvertently with seeds and other parts of host plants and have become major crop pests in the United States (Pimentel 1993). Including the introduced plant pathogens plus other soil microbes, we estimate conservatively that more than 20,000 species of microbes have invaded the United States.

U.S. crop losses to all plant pathogens total approximately $33 billion per year (Pimentel 1997; USBC 1998). Approximately 65% (Pimentel 1993), or an estimated $21 billion per year of losses are attributable to non-indigenous plant pathogens. In addition, $0.72 billion is spent in total annually for fungicides (Pimentel 1997), with approximately $0.5 billion/yr for only the control of non-indigenous plant pathogen. This brings the costs of damage and control of non-indigenous plant pathogens to about $21.5 billion/yr. In addition, based on the earlier discussion of pests in lawns, gardens, and golf courses, we estimate the control costs of plant pathogens in lawns, gardens, and golf courses to be at least $2 billion/yr.

In forests, more than 20 non-indigenous species of plant pathogens attack woody plants (Liebold et al. 1995). Two of the most serious plant pathogens are the chestnut blight fungus (*Cryphonectria parasitica*) and Dutch elm disease (*Ophiostoma ulmi*). Before the accidental introduction of chestnut blight, approximately 25% of eastern U.S. deciduous forest consisted of American chestnut trees (Campbell 1994). Now chestnut trees have all but disappeared. Removal of elm trees devastated by *O. ulmi* costs about $100 million/yr (Campbell and Schlarbaum 1994).

In addition, plant pathogens of forest plants cause the loss of approximately 9%, or $7 billion, of forest products each year (Hall and Moody 1994; USBC 1998). The proportion of introduced plant pathogens in forests is similar to that of introduced insects (about 30%), thus, approximately $2.1 billion in forest products are lost each year to non-indigenous plant pathogens in the United States.

LIVESTOCK PESTS

Similar to crops, exotic microbes (e.g., calf diarrhea rotavirus) and parasites (e.g., face flies, *Musca autumnalis*) were introduced along with livestock brought into the United States (Drummond et al., 1981; Morgan, 1981). In addition to the hundreds of pest microbes and parasites that have already been introduced, more than 60 microbes and parasites could invade and become serious pests to U.S. livestock (USAHA 1984). A conservative estimate of the losses to U.S. livestock from exotic microbes and parasites was reported to be approximately $3 billion/yr in 1980 (Drummond et al. 1981; Morgan 1981). Current livestock losses to pests are estimated to be approximately $9 billion/year.

HUMAN DISEASES

The non-indigenous diseases now having the greatest impact on humans are Acquired Immune Deficiency Syndrome (AIDS), syphilis, and influenza (Newton-John 1985; Pimentel et al. 1999). In 1993, there were 103,533 cases of AIDS with 37,267 deaths (CDC 1996). The total U.S. health care cost for the treatment of AIDS averages about $6 billion per year (USPHS 1994).

New influenza strains originating in the Far East spread quickly to the United States. Influenza causes 540 deaths in the United States each year (USBC 1998). Costs of hospitalizations for a single outbreak of influenza, like type A, can exceed $300 million/yr (Chapman et al., 1992).

In addition, each year there are approximately 53,000 cases of syphilis in the United States; to treat only newborn children infected with syphilis costs $18.4 million/yr (Bateman et al. 1997).

In total, AIDS and influenza take the lives of more than 40,000 people each year in the United States, and treatment costs for these diseases total approximately $6.5 billion/yr. The costs of treating other exotic diseases pushes this total much higher. An increasing threat of exotic diseases exists because of rapid transportation, encroachment of civilization into new ecosystems, and growing environmental degradation.

THE NON-INDIGENOUS SPECIES THREAT

With more than 50,000 non-indigenous species in the United States, the fraction that is harmful does not have to be large to inflict significant damage to natural and managed ecosystems and cause public health problems. A suite of ecological factors may cause non-indigenous species to become abundant and persistent. These include the lack of controlling natural enemies (e.g., purple loosestrife and imported fire ant); the development of new associations between alien parasite and host (e.g., AIDS virus in humans and gypsy moth in U.S. oaks); effective predators in a new ecosystem (e.g., brown tree snake and feral cats); artificial and/or disturbed habitats that provide favorable invasive ecosystems for the aliens (e.g., weeds in crop and lawn habitats); and invasion by some highly adaptable and successful species (e.g., water hyacinth and zebra mussel).

Our study reveals that economic damages associated with non-indigenous species effects and their control amount to approximately $138 billion/yr. The Office of Technology Assessment (OTA 1993) reported average costs of $1.1 billion/yr ($97 billion over 85 years) for 79 species. The reason for our higher estimate is that we included more than 10 times the number of species in our assessment and found higher costs reported in the literature than OTA (1993) for some of the same species. For example, for the zebra mussel, OTA reported damages and control costs of slightly more that $300, 000 per year; we used an estimate of $5 billion/yr (Khalanski 1997).

Although we reported total economic damages and associated control costs to be $138 billion/yr, precise economic costs associated with some of the most ecologically damaging exotic species are not available. The brown tree snake, for example, has been responsible for the extinction of dozens of bird and lizard species on Guam. Yet for this snake, only minimal cost data are known. In other cases, such as the zebra mussel and feral pigs, only combined damage and control cost data are available. The damage and control costs are considered low when compared with the extensive environmental damages these species cause. If we had been able to assign monetary values to species extinctions and losses in biodiversity, ecosystem services, and aesthetics, the costs of destructive non-indigenous species would undoubtedly be several times higher than $138 billion/yr. Yet even this understated economic loss indicates that non-indigenous species are exacting a significant toll.

We recognize that nearly all of our crop and livestock species are non-indigenous and have proven essential to the viability the U.S. agriculture and economy. However, the fact that certain non-indigenous crops (e.g., corn and wheat) are vital to agriculture and the U.S. food system does not diminish the enormous negative impacts of other non-indigenous species (e.g, zebra mussel and exotic weeds).

The true challenge lies not in determining the precise costs of the impacts of exotic

species, but in preventing further damage to natural and managed ecosystems caused by non-indigenous species. Formulation of sound prevention policies needs to take into account the means through which non-indigenous species gain access to and become established in the United States. Since the modes of invasion vary widely, a variety of preventative strategies will be needed. For example, public education, sanitation, and effective screening and searches at airports, seaports, and other ports of entry will help reduce the chances for biological invaders becoming established in the United States.

Fortunately, the problem is gaining the attention of policy makers. On February 2, 1999, President Clinton issued an Executive Order allocating $28 million to combat alien species invasions and creating an Interagency Invasive Species Council to produce a plan within 18 months to mobilize the federal government to defend again non-indigenous species invasions. In addition, a Federal Interagency Weed Committee has been formed to help combat non-indigenous plant species invasions (FIWC 1999). The objective of this interagency committee is education, formation of partnerships among concerned groups, and stimulation of research on the biological invader problem. Secretary Bruce Babbitt (1999) has also established an Invasive Weed Awareness Coalition to combat the invasion and spread of non-native plants, such as knapweed (*Centaurea spp.*) and St. Johnswort (*Hypericum perforatum*).

While these policies and practices may help prevent accidental and intentional introduction of potentially harmful exotic species, we have a long way to go before the resources devoted to the problem are in proportion to the risks. We hope that this environmental and economic assessment will advance the argument that investments made now to prevent future introductions will be returned many times over in the preservation of natural ecosystems, diminished losses to agriculture and forestry, and lessened threats to public health.

Table 1. Estimated annual costs associated with some non-indigenous species introduction in the United States (see text for details and sources) (x millions of dollars).

Category	Non-Indigenous Species	Losses and Damages	Control Costs	Total
PLANTS	**25,000**			
Purple loosestrife		---	---	$45
Aquatic weeds		$10	$100	110
Mealeuca tree		NA	3-6	3
Crop weeds		24,000	3,000	27,000
Weeds in pastures		1,000	5,000	6,000
Weeds in lawns, gardens, golf courses		NA	1,500	1,500
MAMMALS	**20**			
Wild horses and burros		5	NA	5

Feral Pigs		800	0.5	800.5
Mongooses		50	NA	50
Rats		19,000	NA	19,000
Cats		14,000	NA	14,000
Dogs		250	NA	250
BIRDS	**97**			
Pigeons		1,100	NA	1,100
Starlings		800	NA	800
REPTILES & AMPHIBIANS	**53**			
Brown tree snake		1	4.6	5.6
FISH	**138**	**1,000**	**NA**	**1,000**
ARTHROPODS	**4,500**			
Imported fire ant		600	400	1,000
Formosan termite		1,000	NA	1,000
Green crab		44	NA	44
Gypsy moth		NA	11	11
Crop pests		13,000	500	13,500
Pests in lawns, gardens, golf courses		NA	1,500	1,500
Forest pests		2,100	NA	2,100
MOLLUSKS	**88**			
Zebra mussel		---	---	5,000
Asian clam		1,000	NA	1,000
Shipworm		205	NA	205
MICROBES	**20,000**			
Crop plant pathogens		21,000	500	21,500
Plant pathogens in lawns, gardens, golf courses		NA	2,000	2,000
Forest plant pathogens		2,100	NA	2,100
Dutch elm disease		NA	100	100
LIVESTOCK DISEASES		**9,000**	**NA**	**9,000**
HUMAN DISEASES		**NA**	**6,500**	**6,500**
TOTAL				**$138,229.1**

ACKNOWLEDGMENTS

We thank the following people for reading an earlier draft of this article and for their many helpful suggestions: D. Bear, Council on Environmental Quality, Executive Office of the President, Washington , DC; J.W. Beardsley, University of Hawaii; A.J. Benson, U.S. Geological Survey, Gainesville, FL; B. Blossey, Cornell University; C.R. Bomar, University of Wisconsin, Stout; F.T. Campbell, Western Ancient Forest Campaign, Springield, VA; R. Chasen, Editor, *BioScience*; P. Cloues, Geologic Resources Division, Natural Resource Program Center, Lakewood, Colorado; W.R. Courtenay, Florida Atlantic University; R.H. Cowie, Bishop Museum, Honolulu, HI; D. Decker, Cornell University; R.V. Dowell, California Department of Food and Agriculture; T. Dudley, University of Califonia, Berkeley; H. Fraleigh, Colorado State University; H. Frank, University of Florida; T. Fritts, U.S. Geological Survey, Washington, DC; E. Groshoz, University of New Hampshire; J. Jenkins, Forest Service, USDA, Radnor, PA; J.N. Layne, Archbold Biological Station, Lake Placid, FL; J. Lockwood, University of Tennessee; J.D. Madsen, U.S. Army Crops of Engineers, Vicksburg, MS; R.A. Malecki, N.Y. Cooperative Fish & Wildlife Research Unit, Ithaca, NY; E.L. Mills, Cornell University; S.F. Nates, University of Southwestern Louisiana; H.S. Neufeld, Appalachian State University; P.J. O'Connor, Colorado State University; B.E. Olson, Montana State University; E.F. Pauley, Coastal Carolina University; M. Pimentel, Cornell University; S. Pimm, University of Tennessee; W.J. Poly, Southern Illinois University; G. Roberts, University of Hawaii; G.S. Rodrigues, Empresa Brasilerira de Pesquisa Agropecuaria, Brazil; M. Sagoff, Institute for Philosophy and Public Policy, University of Maryland, College Park; B. Salter, Maryland Department of Natural Resources; D.L. Scarnecchia, University of Idaho; D. Simberloff, University of Tennessee; J.N. Stuart, University of New Mexico;S.B. Vinson, Texas A & M University; L.A. Wainger, University of Maryland; J.K. Wetterer, Collumbia University; and C.E. Williams, Clarion University of Pennsylvannia.

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