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SCIENCE DIRECT

Ecological Economics xx (2004) xxx–xxx

ECOLOGICAL ECONOMICS

www.elsevier.com/locate/ecolecon

Update on the environmental and economic costs associated with alien-invasive species in the United States

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Abstract

Invading alien species in the United States cause major environmental damages and losses adding up to almost $120 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 alien-invasive species.

Keywords: Environmental and economic cost; Threatened or endangered species; Alien-invasive species

1. Introduction

In the history of the United States, approximately 50,000 alien-invasive (nonnative) 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, 2001). Other exotic species have been used for landscape restoration, biological pest control, sport, pets, and food processing. Some nonindigenous 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 ca used 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 of which half have not 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 or predation by nonindigenous species (Wilcove et al., 1998). In other regions of the world, as many as 80% of the endangered species are threatened and at risk due to the pressures of nonnative species (Armstrong, 1995). Many other species not listed are also

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doi:10.1016/j.ecolecon.2004.10.002

Table 1
Estimated annual costs associated with some alien species introduction in the United States (see text for details and sources) (×millions of dollars)

Category	Nonindigenous species	Losses and damages	Control costs	Total
Total				
PLANTS	25,000			
Purple loosestrife		–	–	45
Aquatic weeds		10	100	110
Mealeuca tree		NA	3–6	3–6
Crop weeds		24,000	3000	27,000
Weeds in pastures		1000	5000	6000
Weeds in lawns, gardens, golf courses		NA	1500	1500
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		17,000	NA	17,000
Dogs		620	NA	620
BIRDS	97			
Pigeons		1100	NA	1100
Starlings		800	NA	800
REPTILES and AMPHIBIANS	53			
Brown tree snake		1	11	12
FISH	138	5400	NA	5400
ARTHROPODS	4500			
Imported fire ant		600	400	1000
Formosan termite		1000	NA	1000
Green crab		44	NA	44
Gypsy moth		NA	11	11
Crop pests		13,900	500	14,400
Pests in lawns, gardens, golf courses		NA	1500	1500
Forest pests		2100	NA	2100
MOLLUSKS	88			
Zebra mussel		–	–	1000
Asian clam		1000	NA	1000
Shipworm		205	NA	205
MICROBES	20,000			
Crop plant pathogens		21,000	500	21,500
Plant pathogens in lawns, gardens, golf courses		NA	2000	2000
Forest plant pathogens		2100	NA	2100
Dutch elm disease		NA	100	100
LIVESTOCK DISEASES		14,000	NA	14,000
HUMAN DISEASES		NA	7500	7500
TOTAL				$120,105

negatively affected by alien species and/or ecosystem changes caused by alien species. Estimating the economic impacts associated with nonindigenous 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, as much as possible, we assess the magnitude of the environmental impacts and economic costs associated with the diverse alien species that have become established within the United States. Although translocated species can also have significant impacts, this assessment is limited to alien species that did not originate within the United States or its territories.

2. 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 risk 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, 2001).

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

2.1. Plants

Most alien plants now established in the United States were introduced for food, fiber, and/or ornamental purposes. An estimated 5000 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 (Dowell and Krass, 1992).

Most of the 5000 alien plants established in U.S. natural ecosystems have displaced several native plant species (Morse et al., 1995). Alien weeds are spreading and invading approximately 700,000 ha/year 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/year 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, like the bog turtle 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. national parks (Hiebert and Stubbendieck, 1993). In Great Smoky Mountains National Park, 400 of approximately 1500 vascular plant species are exotic, and 10 of these are currently displacing and threatening other species in the park (Hiebert and Stubbendieck, 1993).

Hawaii has a total of 2690 plant species, 946 of which are alien species (Eldredge and Miller, 1997). About 800 native species are endangered and more than 200 endemic species are believed to be extinct because of alien species (Vitousek, 1988).

Sometimes, one nonindigenous plant species competitively overruns an entire ecosystem. For example, in California, yellow star thistle (*Centaurea solstitalis*) now dominates up to 8 million ha of California grassland, resulting in the total loss of this once productive grassland (Campbell, 1994; DeLong, 2002).

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, 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). Some animals dependent on the shrubs and other original vegetation have been reduced or eliminated.

An estimated 138 alien 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/year 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 in the Hudson River basin of New York number 53 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). Despite this large expenditure, hydrilla infestations in just 2 Florida lakes have prevented their recreational use, causing $10 million annually in losses (Center et al., 1997). In the United States, a total of $100 million is invested annually in alien species aquatic weed control (OTA, 1993).

2.2. 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 eight endemic plant species as well as the endangerment of eight 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*), European rabbit (*Oryctolagus cuniculus*), as well as the domestic cat (*Felis cattus*), and dog (*Canis familiaris*; Layne, 1997).

Some introduced rodents have become serious pests on farms, in industries, and in homes (Layne, 1997). On farms, rats and mice are particularly abundant and destructive. On poultry farms, there is approximately 1 rat per 5 chickens (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, 2001). 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 1 rat per person in the United States (Wachtel and McNeely, 1985), there are an estimated 250 million rats in U.S. urban and suburban areas (USBC, 2001).

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/year, 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).

The Indian mongoose (*Herpestes auropunctatus*) was first introduced into Jamaica in 1872 for biological control of rats in sugarcane (Pimentel, 1955). It was subsequently introduced to Puerto Rico, other West Indian Islands, and Hawaii. The mongoose controlled the Asiatic rat but not the European rat, and preyed heavily on native ground nesting birds (Pimentel, 1955; Vilella and Zwank, 1993). It also preyed on beneficial native amphibians and reptiles, causing a minimum of 7 to 12 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, 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 (Pimentel, unpublished data; and P.C., David Foote, Hawaii Volcanoes National Park, 1998).

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). Assuming 8 birds killed per feral cat/year (McKay, 1996), then 240 million birds are killed per year in the nation. Each adult bird is 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 \$17 billion/year. This cost does not include the number of birds killed by pet or urban cats, a figure reported to be similar to the number killed by feral cats (McKay, 1996); nor does the cost include the many small mammals, amphibians, and reptiles that are killed by feral and pet cats (Dunn and Tessaglia, 1994).

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 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.

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/year, and the indirect costs, such as lost work, increase the total costs of dog bites to $250 million/year (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).

2.3. Birds

About 97 of the 1000 birds in the United States are exotic (Temple, 1992). Of the 97 introduced bird species, only 5% are considered beneficial, while most (56%) are pests (Temple, 1992). However, several species, including chickens and pigeons, were introduced into the United States for agricultural purposes.

In Hawaii, 35 of 69 alien birds introduced between 1850 and 1984 are still extant on the islands (Moulton and Pimm, 1983; Pimm, 1991). The common myna (*Acridotheres tristis*), introduced into Hawaii, helped control pest cutworms and armyworms in sugarcane (Kurdila, 1995). However, it became the major disperser of seeds of the introduced pest-weed, *Lantana camara*. To cope with the weed problem, Hawaii resorted to the introduction of insects as biocontrol agents (Kurdila, 1995).

The English or house sparrow (*Passer domesticus*) was introduced into the United States intentionally in 1853 to control the canker worm (Laycock, 1966; Roots, 1976). By 1900, the birds were considered 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 robins, Baltimore orioles, yellow-billed cuckoos, and black-billed cuckoos, and displace native bluebirds, wrens, purple martins, and cliff swallows (Laycock, 1966; Roots, 1976; Long, 1981). They are also associated with the spread of about 29 diseases of human and livestock (Weber, 1979).

The exotic common pigeon (*Columba livia*) 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 there is 1 pigeon per ha in urban areas (Johnston and Janiga, 1995) or approximately 0.5 pigeons per person in the urban areas, and using potential control costs as a surrogate for losses, pigeons cause an estimated $1.1 billion/year in damages. These damage costs do not include the environmental damages associated with their serving as reservoirs and vectors for over 50 diseases, including parrot fever, ornithosis, histoplasmosis, and encephalitis (Weber, 1979; Long, 1981).

2.4. Amphibians and reptiles

Amphibians and reptiles introduced into the United States number about 53 species. All these alien species occur in states where it seldom freezes; Florida is now host to 30 species and Hawaii to 12 (McCoid and Kleberg, 1995; Lafferty and Page, 1997). The negative ecological impacts of a few of these exotic species have been enormous.

The brown tree snake (*Boiga irregularis*) was accidentally introduced to snake-free 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 species still exist (Rodda et al., 1997); of the 12 native species of lizards, only 3 retain the possibility of surviving (Rodda et al., 1997). The snake eats chickens, eggs, and caged birds, which causes major problems to small farmers and pet owners. This snake crawls up trees and utility poles, causing power outages on the island. One island-wide power outage caused by the snake cost the power utility more than $6 million per year. Local outages that affect business are estimated to cost from $2000 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/year.

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 snakebites (OTA, 1993). Some bitten infants require hospitalization and intensive care; this is estimated to cost $25,000 per year (P.C., T. Fritts, U.S. Geological Survey, 1998). 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 constitute costs in excess of an additional $1 million per year; in addition, up to $2 million per year is invested in research and control of this serious pest (1998 federal budget, P.C., T. Fritts, U.S. Geological Survey, 1998). Hawaii's concern about the snake 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 more than $12 million/year.

2.5. Fish

A total of 138 alien 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, like Florida (50 species; Courtenay, 1997) and California (56 species; Dill and Cordone, 1997). In Hawaii, 33 alien freshwater fish species have become established (Maciolek, 1984). Forty-four native species of fish are threatened or endangered by alien-invasive fish (Wilcove and Bean, 1994). An additional 27 native species of 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 forced to extinction, or hybridized by alien fish species, alien fish do provide some benefits in the improvement of sport fishing. Sport fishing contributes $69 billion to the economy of the United States (Bjergo et al., 1995; USBC, 2001). However, based on the more than 40 alien invasive species that have negatively affected native fishes and other aquatic biota, and considering the fact that sports fishing is valued at $69 billion/y (USBC, 2001), the conservative economic losses due to exotic fish is $5.4 billion annually (Pimentel, unpublished data).

2.6. Arthropods

Approximately 4500 arthropod species (2582 species in Hawaii and more than 2000 in the continental United States) have been introduced. Also, 11 earthworm species (Hendrix, 1995), and nearly 100 aquatic invertebrate species have been introduced (OTA, 1993). More than 95% of these introductions were accidental, with many species gaining entrance via plants or through soil and water ballast from ships.

The 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 about a 20-year period, it has spread throughout the southern Appalachians and has destroyed up to 95% of the fraser firs (P.C., H.S. Neufeld, Appalachian State University, 1998). Alsop and Laughlin (1991) report the loss of two native bird species and the invasion by three other 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/year. Two people were killed by fire ants in Mississippi in 2002.

An additional $200 million is invested in control per year (Vinson, 1992; TAES, 1998). Assuming equal damages in other infested southern states, the fire ant damages total approximately $1 billion per year. The Formosan termite, (*Coptotermes formosanus*), is reported to cause structural damages of approximately $1 billion/year in Southern United States, especially in 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 Nova Scotia (Lafferty and Kuris, 1996). It also destroys commercial shellfish beds and preys on large numbers of native oysters and crabs (Lafferty and Kuris, 1996). The annual estimated economic impact of the green crab is $44 million/year (Lafferty and Kuris, 1996).

2.7. Mollusks

Eighty-eight species of mollusks have been introduced and established in the U.S. aquatic ecosystems (OTA, 1993). Three of the most serious pests are the zebra mussel (*Dreissena polymorpha*), Asian clam (*Corbicula fluminea*), and quagga mussels (*Dreissena bugensis*).

The European 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 over from Europe (Benson and Boydstun, 1995). The zebra mussel has spread into most of the aquatic ecosystems in the eastern United States and is expected to invade most freshwater habitats throughout the nation (Benson and Boydstun, 1995). Another related mussel species, the quagga mussel, is spreading rapidly and in some cases displacing zebra mussels (C.A. Stepien, PC, Cleveland State University, 2003).

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 been recorded as high as 700,000/m^2 (Griffiths et al., 1991). Zebra and quagga mussels also invade and clog water intake pipes, water filtration, and electric generating plants; it is estimated that they cause $1 billion/year in damages and associated control costs per year (Army, 2002).

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 damage are about $1 billion/year (Isom, 1986; OTA, 1993).

The introduced shipworm (*Teredo navalis*) in the San Francisco Bay has also caused serious damage since the early 1990s. Currently, damages are estimated to be about $205 million/year (Cohen and Carlton, 1995).

3. Crop, pasture, and forest losses and associated control costs

Many weeds, pest insects, and plant pathogens are biological invaders causing several billion dollars in losses to crops, pastures, and forests annually in the United States. In addition, several billion dollars are spent on pest control.

3.1. Weeds

In crop systems, including forage crops, an estimated 500 introduced plant species have become weed pests; many of these 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 them were yellow rocket (*Barbarea vulgaris*) and Canada thistle (*Cirsium arvense*).

In U.S. agriculture, weeds cause a reduction of 12% in crop yields. In economic terms, this 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/year (USBC, 2001). Based on the estimate that about 73% of the weeds are alien (Pimentel, 1993), it follows that about $24 billion of these crop losses are due to introduced weeds. Note, alien invasive weeds are more serious pests than native weeds; thus, this is likely to be a conservative estimate. In addition, approximately $4 billion in herbicides are applied to U.S. crops (Pimentel, 1997), of which about $3 billion is used for control of alien invasive weeds. Therefore, the total costs of introduced weeds to the U.S. economy is about $27 billion annually.

In pastures, 45% of weeds are alien 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). Since about 45% of the weeds are alien invasives (Pimentel, 1993), the forage losses due to these nonindigenous weeds are nearly $1 billion/year.

Some introduced weeds are toxic to cattle and wild ungulates, like leafy spurge (*Euphoria esula*; Trammel and Butler, 1995). In addition, several alien thistles have replaced desirable native 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 alien weeds in pastures and rangelands, yet these weeds continue to spread.

Management of weed species in lawns, gardens, and golf courses is a significant proportion of their total management costs of about $36 billion/year (USBC, 2001). In addition, Templeton et al. (1998) estimated that about $1.3 billion of the $36 billion is spent just on residential weed, insect, and disease pest control each year. Because large proportions of these weeds are exotics, we estimate that $500 million is spent on residential exotic weed control and an additional $1 billion is invested in alien invasive weed control on golf courses.

Weed trees also have an economic impact. $3 to $6 million per year is being spent in efforts to control only the melaleuca tree in Florida (P.C. Curtis J. Richardson, Duke University, 1998).

3.2. Vertebrate pests

Horses (*Equus caballus*) and burros (*Equus asinus*) released in western United States have attained wild populations of approximately 50,000 animals (Pogacnik, 1995). These animals graze heavily on native vegetation, allowing alien invasive annuals to displace native perennials (Rosentreter, 1994). Furthermore, burros inhabiting the northwestern United States 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/year 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 the California coastal prairie and Hawaii, and 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/year. Assuming that the three parks in Hawaii have similar pig control problems, the total is $450,000/year (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 (P.C., J.P. Bach, Texas A and M University, 1999). 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 diseases of humans and livestock, like 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 (one pig can cause up to $1000 of damages in one night; P.C., J.P. Bach, Texas A and M University, 1999), and assuming 4 million feral pigs inhabit the United States, the yearly cost is about $800 million/year. This estimate is conservative because pigs cause significant environmental damages and diseases that cannot be easily translated into dollar values.

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 approximately $2000/ha worth of cherries (Feare, 1980). In grain fields, starlings consume about $6/ha of grain (Feare, 1980). Conservatively, assuming $5/ha for all damages to agriculture crop production in the United States, the total loss due to starlings would be approximately $800 million/year. 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).

3.3. Insect and mite pests

Approximately 500 alien insect and mite species are pests in crops. Hawaii has 5246 identified native insect species, and an additional 2582 introduced insect species (Howarth, 1990; Frank and McCoy, 1995a; Eldredge and Miller, 1997). Introduced insects account for 98% of the pest insects in the state (Beardsley, 1991). In addition to Florida's 11,500 native insect species, 949 introduced species have invaded the state (42 species were 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, 2001). Considering that about 40% of the pests were introduced (Pimentel, 1993), we estimate that these 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/year. Therefore, the total cost for introduced invasive insect pests is approximately $13.5 billion/year. In addition, based on the earlier discussion 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/year.

About 360 alien insect species have become established in American forests (Liebold et al., 1995). 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, 2001. Because 30% of the pests are alien pests, annual losses attributed to alien invasive species is about $2.1 billion per year.

The gypsy moth (*Lymantria dispar*), intentionally introduced into Massachusetts in the 1800s, has developed into a major pest of U.S. forests 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).

3.4. Plant pathogens

There are an estimated 50,000 parasitic and non-parasitic diseases of plants in the United States and most of these are fungi species (USDA, 1960). In addition, there are more than 1300 species of viruses that are plant pests in the United States (USDA, 1960). Many of these microbes 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 microbes, we estimate 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, 2001). Approximately 65% (Pimentel, 1993), or an estimated $21 billion per year of losses are attributable to alien plant pathogens. In addition, $0.72 billion is spent annually for fungicides (Pimentel, 1997), with approximately $0.5 billion for the control of alien plant pathogen. This brings the costs of damage and control of alien invasive plant pathogens to about $21.5 billion/year. 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/year.

In forests, more than 20 alien 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 introduction of chestnut blight, approximately 25% of eastern U.S. deciduous forest consisted of American chestnut trees (Campbell, 1994). Elm tree removal costs about $100 million/year (Campbell and Schlarbaum, 1994).

Approximately 9%, or $7 billion, of forest products are lost each year due to plant pathogens (Hall and Moody, 1994; USBC, 2001). Assuming that the proportion of introduced plant pathogens in forests is similar to that of introduced insects (about 30%), approximately $2.1 billion in forest products are lost each year to alien-invasive plant pathogens in the United States.

4. Livestock pests

Similar to crops, exotic microbes (e.g., calf-diarrhea-rotavirus) and parasites (e.g., face flies, *Musca autumnalis*) were introduced when livestock were brought to the United States (Drummond et al., 1981; Morgan, 1981). In addition to the hundreds of microbes and parasites that have already been introduced and are pests, there are more than 60 microbes and parasites that 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 approximately \$9 billion/year in 2001 (personal conversation, Kelsey Hart, College of Veterinary Medicine, Cornell University, 2001).

A recently introduced disease in U.S. livestock is the Mad Cow disease. Currently the Mad cow disease could cause at least \$5 billion in damages and control costs. The threat of this devastating disease could destabilize the livestock industry, worth \$50 billion/year in Washington State alone.

5. Human diseases

The alien diseases now having the greatest impact 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 health care cost for the treatment of AIDS averages about \$6 billion per year (USPHS, 1994).

New influenza strains, originating in the Far East, quickly spread to the United States. These are reported to cause 5% to 6% of all deaths in 121 U.S. cities (Kent et al., 1992). Costs of hospitalizations for a single outbreak of influenza, like type A, can exceed \$300 million per year (Chapman et al., 1992). In addition, each year there are approximately 53,000 cases of syphilis; to treat only new born children infected with syphilis costs the nation \$18.4 million/year (Bateman et al., 1997).

In total, AIDS, influenza, and syphilis take the lives of more than 40,000 people each year in the United States, and treatment costs for these diseases plus syphilis total approximately \$6.5 billion/year and does not include the other exotic diseases. In addition, West Nile virus is a new invading disease of humans, birds, horses and other animals. Approximately 4200 humans were infected last year, with 284 deaths (CDC, 2003). The estimated public health costs are \$631 million per year (Table 1). An increasing threat of exotic diseases exists because of rapid transportation, encroachment of civilization into new ecosystems, and growing environmental degradation.

6. Conclusion

With more than 50,000 alien invasive 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. There is a suite of ecological factors that may cause alien invasive 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 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 alien species (e.g., water hyacinth and zebra and quagga mussel).

Our study reveals that economic damages associated with alien invasive species effects and their control amount to approximately \$120 billion/year. The Office of Technology Assessment (OTA, 1993) reported costs of \$1.1 billion/year (\$97 billion averaged 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 \$1 billion/year (Army, 2002).

Although we reported specific total economic damages and associated control costs, 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. These are considered low when compared with the extensive environmental damages these species cause, and do not include indirect costs. If we had been able to assign monetary values to species extinctions and losses in biodiversity, ecosystem services, and aesthetics, the costs of destructive alien invasive species would undoubtedly be several times higher than $120 billion/year. Yet, even this understated economic loss indicates that alien invasive species are exacting a significant toll.

We recognize that nearly all our crop and livestock species are alien and have proven essential to the viability our agriculture and economy. Although certain alien crops (e.g., corn and wheat) are vital to agriculture and the U.S. food system, this does not diminish the enormous negative impacts of other nonindigenous species (e.g., mussels 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. Formulation of sound prevention policies needs to take into account the means through which alien species gain access to and become established in the United States. Since the invasions vary widely, we should expect that a variety of strategies would be needed for prevention programs. For example, public education, sanitation, and effective prevention programs 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 policymakers. On February 2, 1999, President Clinton issued an Executive Order allocating $28 million and creating an Interagency Invasive Species Council to produce a plan within 18 months to mobilize the federal government to defend against alien species invasions. In addition, a Federal Interagency Weed Committee has been formed to help combat nonindigenous 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.

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.

In our view, investments to prevent or reduce the introduction of potentially harmful exotic species should be focused on educating the public and inspectors at airports and seaports concerning the threat of alien-invasive plants, animals, and microbes to the U.S. environment and economy.

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 and 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; W. Roberts, Rainbow Beach, Australia; 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; G.S. Rodrigues, Empresa Brasilerira de Pesquisa Agropecuaria, Brazil; J.N. Stuart, University of New Mexico;S.B. Vinson, Texas A and 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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