18 Plant, Animal, and Microbe Invasive Species in the United States and World

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18.1 Introduction

Approximately 50,000 plant, animal, and microbe invasive species are present in the United States, and an estimated 500,000 plant, animal, and microbe invasive species have invaded other nations of the world. Immediately, it should be pointed out that the US and world agriculture depend on introduced food crops and livestock. Approximately 99% of all crops and livestock in all nations are intentionally introduced plants, animals, and microbes (Pimentel 2002). Worldwide, the value of agriculture (including beneficial non-indigenous species) is estimated to total $30 trillion per year. Other exotic species have been introduced for landscape restoration, biological pest control, sport, and food processing, also contributing significant benefits.

Unfortunately, some invasive species are causing major economic losses in the United States and worldwide in agriculture, forestry, fisheries, public health, and natural ecosystems. Documenting the full extent of the environmental and economic damages caused by exotic species, and the number of species extinctions is difficult because little is known about the estimated 750,000 species that exist in the US and the estimated 15 million that exist worldwide (McNeeley 1999). Only an estimated 2 million species have been described worldwide. In the US, an estimated 40% of those species forced to extinction can be accounted for by the impacts of invasive species (Pimentel et al. 2005). In some regions of the world, as many as 80% of endangered species have been threatened and forced to extinction due to the pressures of nonnative species (Armstrong 1995). In addition, many other species worldwide, even if they have not been forced to extinction or endangered status, are negatively affected by various alien species or ecosystem changes caused by alien species.

Calculating the negative economic impacts associated with the invasion of exotic species is difficult. For a few species, there are sufficient data to estimate
some impacts on agriculture, forestry, fisheries, public health, and the natural ecosystem in the US and worldwide. In this article, we estimate the magnitude of the economic benefits, and environmental and economic costs associated with a variety of invasive species that exist in the United States and elsewhere in the world.

18.2 Agricultural and Forestry Benefits from Introduced Species

The value of the US food system is more than $800 billion per year (USCB 2004–2005), and the value of the world food system is estimated at more than $30 trillion per year. According to the World Health Organization (Pimentel 2004a), the world’s food system is not providing adequate amounts of food for all people on earth, more than 3.7 billion of the current population of 6.5 billion being malnourished. In addition, food production per capita has been declining each year for the past 21 years (FAOSTAT 1960–2004). This assessment is based on cereal grains, since cereal grains provide about 80% of the world’s food. Clearly, more needs to be done to increase food production per capita, at the same time significantly reducing the rate of growth of the world population (Pimentel and Pimentel 2001).

18.3 Environmental Damages and Associated Control Costs

Most plant and vertebrate animal introductions in the US and world have been intentional, whereas most invertebrate animal and microbe introductions have been accidental. During the past 60 years, the total number of introductions of all species has nearly doubled in the world. The rate of introductions of exotic species has increased enormously because of high human population growth, rapid movement of people, and alteration of the environment everywhere in the world. In addition, significantly more goods and material are being exchanged among nations than ever before, creating greater opportunities for unintentional introductions (USCB 2004–2005). Some of the estimated 50,000 species of plants, animals, and microbes that have invaded the US, and 500,000 species of plants, animals, and microbes that have invaded the total world ecosystem provide significant benefits but also many types of damage to managed and natural ecosystems, as well as public health.
18.3.1 Plants

Most exotic plant species now established in the United States and elsewhere in the world were introduced for food, fiber, or ornamental purposes. An estimated 5,000 introduced plant species have escaped and now exist in US natural ecosystems (Morse et al. 1995), compared with a total of approximately 17,000 species of native plants (Morin 1995). In Florida, of the approximate 25,000 alien plant species (mostly introduced ornamental species), more than 900 have escaped and become established in neighboring natural ecosystems (Frank et al. 1997; Simberloff et al. 1997). More than 3,000 plant species have been introduced into California, and many of these have escaped into this natural ecosystem as well (Dowell and Krass 1992).

Worldwide, an estimated 30,000 species of exotic plants have been intentionally introduced as crops, and have escaped to become established in various natural ecosystems. Most of the non-indigenous plants that have escaped and become established have adapted well to the favorable living conditions characteristic of moist tropical regions in countries such as India, Brazil, and Australia.

Some of the invasive plants established in the US and world have displaced native plant species. In the United States, introduced plant species are spreading and invading approximately 700,000 ha of US natural ecosystems per year (Babbitt 1998). For instance, the European purple loosestrife (*Lythrum salicaria*), which was introduced in the early 19th century as an ornamental plant (Malecki et al. 1993), has been spreading at a rate of 115,000 ha per year, strongly altering the basic structure of the wetlands that it has invaded (Thompson et al. 1987). Stands of purple loosestrife have reduced the abundance of 44 native plant species, and endangered many wildlife species, including turtles and ducks (Gaudet and Keddy 1988). Loosestrife is present in 48 states, and about $45 million are spent each year for control of the weed (ATTRA 1997).

Many of these exotic species have become established in national parks. In the Great Smoky Mountains National Park, for example, 400 of the 1,500 vascular plant species are exotic, and 10 of these are currently displacing and threatening native plant species (Hiebert and Stubbendieck 1993). The problem of introduced plants is particularly serious in Hawaii, where 946 of the total of 1,690 plant species on the island are non-indigenous (Elredge and Miller 1997).

In some cases, one exotic plant species may competitively overcome an entire ecosystem. In California, the yellow starthistle (*Centaurea solstitialis*), for example, dominates more than 4 million ha of northern grassland in the state, resulting in the total loss of this once productive forage system (Campbell 1994). In addition, the European cheat grass (*Bromus tectorum*) is dramatically altering the vegetation and fauna of many natural ecosystems in the western US. Cheat grass is an annual that has invaded and spread throughout
the shrub-steppe habitat of the Great Basin in Idaho and Utah, predisposing
the altered habitat to fires (Kurdila 1995). Before the invasion of cheat grass,
fire burned once every 60 to 110 years, and shrubs in the region had a chance
to become reestablished. Currently, fires occur once every 3 to 5 years, and this
has led to a decrease in shrubs and other vegetation, and the occurrence of
monocultures of cheat grass on more than 5 million ha in Idaho and Utah.
The reason that the alteration of original vegetation is so significant is that all
the animals and microbes that were dependent on the original vegetation
have been reduced or totally eliminated.

Insufficient information exists concerning invasive plants in the United
States and other countries. This is true even in countries that are dominated
by invasive plants, such as the British Isles. For example, of the 27,515 total
plant species on the British Isles, only 1,515 species are considered native
(Crawley et al. 1996). More than 80% of alien plant species in the British Isles
are established in disturbed habitats (Clement and Foster 1994; Crawley et al.
1996).

One group of agriculturalists introduced 463 species of plants as potential
forage species in Australia (Lonsdale 1994). Only 21 species of this group of
463 plant species turned out to be beneficial, many others had little impact,
but several became serious pest weeds in Australia. In India, weeds are esti-
mated to cause a 30% loss in potential crop production each year (Singh
1996), amounting to about $ 90 billion in reduced crop yields. Assuming that
42% of the weeds in crops are alien (Nandpuri et al. 1986), the total cost asso-
ciated with the alien plants in India is about $ 37.8 billion per year.

18.3.2 Mammals

About 20 mammal species have been intentionally introduced into the United
States, including dogs, cats, horses, cattle, sheep, pigs, and goats (Layne 1997).
Several of these mammal species escaped into the wild, and have become
pests by preying on native animals, grazing on native vegetation, or intensify-
ing soil erosion. Goats (*Capra aegagrus hircus*), for instance, introduced on
San Clemente Island, California, have caused the extinction of 8 endemic
plant species and have endangered 8 others (Kurdila 1995).

Several small mammal species, especially rodents, have been introduced
into the United States. These include the European rat (*Rattus rattus*), the Asi-
atic rat (*Rattus norvegicus*), the house mouse (*Mus musculus*), and the Euro-
pean rabbit (*Oryctolagus cuniculus*; Layne 1997). Some of the introduced rats
and mice have become particularly abundant and destructive on farms. On
poultry farms, there is about 1 rat per 5 chickens (Smith 1984; D. Pimentel,
unpublished data). Using this ratio, it is estimated that the rat number is more
than 1.8 billion on farms in the US. Another 250 million rats are estimated to
be in homes and stores in cities and towns. If it is estimated that each rat
causes $15 in damages each year, then the damage per year would be about $30 billion.

Although the cost of the impact of invasive mammals is relatively high, the percentage of alien mammals introduced into the United States is relatively low, or 6%; in the United Kingdom, the percentage is relatively high, or 31% (Pimentel et al. 2001). The UK introduced mammals include those species recorded in the US, plus many others.

Australia is another nation that has a large number of alien mammals. In Australia, pigs native to Eurasia and North Africa were introduced and now number from 4 to 20 million (Emmerson and McCulloch 1994). Feral pigs cause soil erosion, damage agricultural crops, fences, native plants and animals, and are a threat to livestock and humans; they also spread various animal diseases, including tuberculosis, brucellosis, rabies, and foot-and-mouth disease (Lever 1994). The estimate of pig damage in Australia is more than $80 million per year (Emmerson and McCulloch 1994).

Rodents, including the European and Asiatic rats and the house mouse, have invaded all countries in the world. In addition, domestic dogs, cats, and European rabbits have been introduced into all nations of the world. In Australia, feral cats are a serious problem, killing native bird, mammal, marsupial, and amphibian populations. The estimate is that there are 3 million pet cats, and 18 million feral cats in Australia (Anon 1996). The cats are considered responsible for having exterminated 23 native Australian species of animals (Low 1999). Assuming that each bird has a minimum value of $30 in the US (Pimentel et al. 2000), then the total impact from cats in Australia is $540 million per year. In the US, it is estimated that cats kill an estimated 570 million birds per year, with an estimated damage of $17 billion (Pimentel et al. 2000).

18.3.3 Birds

Of the 1,000 species of birds in the United States, nearly 100 are exotic (Temple 1992). Approximately 5% of the introduced birds are beneficial, such as the chicken.

One of the bird pest species is the English sparrow (*Passer domesticus*), introduced in 1853 into the US for the control of canker worm and other pest caterpillars (Roots 1976). By 1900, English sparrows were reported to be a pest, consuming wheat, corn, and the buds of fruit trees (Laycock 1966). In addition, they harass native birds, including robins, Baltimore orioles, and the yellow-billed and black-billed cuckoos, and they displace bluebirds, wrens, purple martins, and cliff swallows (Long 1981). English sparrows are also associated with the spread of about 30 human and livestock diseases (Weber 1979).

One of the most serious bird pests is the common pigeon (*Columbia livia*), which has been introduced to all cities in the world (Robbins 1995). Pigeons
present a nuisance because they foul buildings, statues, cars, and sometimes people, and they feed on grains (Smith 1992). It is estimated that pigeons cause an estimated $1.1 billion in damages per year in the United States. They also serve as reservoirs and vectors of more than 50 human and livestock diseases, including parrot fever, ornithosis, histoplasmosis, and encephalitis (Long 1981).

Another serious bird pest in the US is the European starling (*Sturnus vulgaris*), a species that in some cases occurs at densities of more than one per hectare in agricultural regions (Moore 1980). They are capable of destroying as much as $2,000 worth of cherries ha$^{-1}$ in the spring (Feare 1980). They also destroy large quantities of grain crops (Feare 1980). The estimate is that they are responsible for damages amounting to $800 million per year (Pimentel et al. 2000).

Information on other bird species that have invaded other nations is not as abundant as one would expect. Of the other nations, the UK has some of the best data. Of the 542 species of birds in the UK, 47 are alien (Gooders 1982). Pigeons in the UK are as serious a problem as they are in the US. In the UK, pigeons are estimated to cause more than $270 million in damages each year (Alexander and Parsons 1986; Bevan and Bracewell 1986).

### 18.3.4 Amphibians and Reptiles

About 53 species of amphibian and reptile species have been introduced into the United States. These species invasions have all occurred in the warmer regions. For example, Florida is host to 30 species (Lafferty and Page 1997). The negative impacts of these invasive species have been enormous.

The brown tree snake (*Boiga irregularis*) is one of the worst. It was introduced into the US territory of Guam immediately after World War II, when military equipment was transferred to the island (Fritts and Rodda 1995). The snake population reached high densities of 100 snakes ha$^{-1}$, and dramatically reduced populations of native bird species, small mammals, and lizards. A total of 10 bird species and 9 lizard species were exterminated from Guam (Rodda et al. 1997). The brown tree snake also eats chickens, eggs, pet birds, and causes major problems to farmers. In some cases, the snake enters houses and bites small children in cribs and playpens (OTA 1993). Another costly impact is that the snake is causing power failures by damaging electric transformers. The estimate is that the brown tree snake causes more than $2$ million in damages per year on Guam. A major worry is that the snake will invade Hawaii, and cause major extinctions of birds, mammals, and amphibians on the island.

An estimated 700 species of reptiles and amphibians exist in Australia (Fox 1995). However, only two of these are exotic. One of the introduced species is the cane toad (*Bufo marinus*), introduced from South America for insect con-
trol in cane fields. However, it was soon reported to be a serious pest (Fox 1995). The cane toad is poisonous to dogs, cats, and other mammals (Sabath et al. 1981). In South Africa, there have been 13 species of reptiles and 11 species of amphibians introduced (Siegfried 1989). One of the invasive species is the red-eared slider (Chrysemys scripta elegans) that was introduced from North America. This invasive turtle has become a major threat to the 12 native turtle species (Boycott and Bourquin 1988).

18.3.5 Fishes

A total of 138 invasive fish species have been introduced into the United States (Courtenay et al. 1991; Courtenay 1997). Most of the invaders are found in the warmer regions such as Florida, which has at least 50 of these species (Courtenay 1997). Introduced fish species frequently alter the ecology of aquatic ecosystems. In the Great Lakes, for instance, nearly 50 invasive species are found, and these invaders are causing an estimated $5 billion in damages to the fisheries per year (Pimentel 2005). In addition, most of the alien fish species in South Africa are regarded as pests (Bruton and Van As 1985). In total, alien fish species are responsible for the reduction or local extinction of at least 11 species of fish in South Africa (Bruton and Van As 1985).

18.3.6 Arthropods

An estimated 4,500 arthropod species (more than 2,500 species in Hawaii alone, and more than 2,000 in continental US) have been introduced into the United States (OTA 1993). Approximately 95% of these introductions were accidental, the remainder being intentional for purposes of biological control and pollination. About 1,000 invasive species of insects and mites are crop pests in the US. Introduced insects account for 98% of the crop insect pests in Hawaii (Beardsley 1991). Approximately 40% of the insect and mite pests in crops in continental US are pests of agricultural crops. The major group of pests consists of native insects and mites that switched from feeding on native vegetation to feeding on crops (Pimentel et al. 2000). Pest insects are estimated to destroy $14 billion worth of crops per year. One ant species, the red imported fire ant, is alone causing $6 billion in damages and control costs (Linn 2005).

Of the 360 species of invasive species in US forests, about 30% are now serious pests in these forests (Liebold et al. 1995), causing about $7 billion in losses each year (Hall and Moody 1994). A new introduction, the Asian longhorn beetle, is threatening maple and ash trees in New York and Illinois (Hajek 2005).
Of the 80,000 species of insects, and 6,000 species of spiders and numerous other arthropod species that exist in South Africa, several invasive species are causing problems (South Africa 1998). One of the most serious invaders is the Argentine ant (*Linepithema humile*), which is destroying native vegetation, including endangered plants (Macdonald et al. 1986). This ant species is also negatively affecting native ants and other beneficial arthropod species. In addition, the Argentine ant is a serious pest in agriculture.

### 18.3.7 Mollusks

A total of about 88 species of mollusks have been introduced and established in United States aquatic ecosystems (OTA 1993). The two most serious pest species introduced are the zebra mussel, *Dreissena polymorpha*, and the Asian clam, *Corbicula fluminea* (see also Chaps. 5 and 15).

The zebra mussel was introduced from Europe, and probably gained entrance via ballast water released into the Great Lakes by ships traveling from Europe (Benson and Boydstun 1995). The mussel was first noted in Lake St. Clair, has spread into most of the Great Lakes and most aquatic ecosystems in the eastern United States, and is expected to invade most freshwater habitats throughout the nation. Large mussel populations (up to 700,000 m$^2$; Griffiths et al. 1991) reduce food and oxygen for the native fauna. Zebra mussels have been observed covering native mussel, clams, and snails, and threatening the survival of these and other species (Benson and Boydstun 1995; Keniry and Marsden 1995).

In addition to ecological effects on other aquatic organisms, the zebra mussel also invades and clogs water intake pipes in water infiltration and electric power plants. It is estimated that the mussels will cause $5$ billion in damages and associated control costs in the US. In the Great Lakes alone, they are reported to cause $1$ billion in damages and control costs (Pimentel 2005). Although the Asian clam grows and disperses less quickly than the zebra mussel, it also causes significant damage to native organisms and damage to water filtration plants and electric power plants. Costs associated with this animal are estimated to be more than $1$ billion per year (OTA 1993). In various US coastal bay regions, the introduced shipworm (*Teredo navalis*) is estimated to cause from $205$ million to $750$ million in damages per year (Cohen and Carlton 1995; D. and M. Pimentel, unpublished data).

Unfortunately, there are not data available on mollusk invaders in other nations. This is due to the general lack of knowledge concerning the ecology and systematics of mollusks in the world; they appear to be causing a relatively small amount of damage to aquatic ecosystems in other regions worldwide, and/or few biologists have investigated these organisms.
18.4 Livestock Pests

For a start, it should be pointed out that the majority of livestock worldwide are introduced species. For example, in the United States more than 99% of the livestock species are introduced (Pimentel 2004b). Microbial and other parasitic organisms have generally been introduced when the livestock species have been introduced. In addition, to the more than 100 species of pest microbes and other parasitic species that have already invaded the United States (Pimentel 2005), there are more than 60 additional microbes and other parasitic species that could easily invade the United States and become serious pests of US livestock (Pimentel 2005). A conservative estimate of the losses to US livestock from exotic microbes and other parasitic species is more than $9 billion per year.

Australia already has several species of alien diseases infecting and causing losses to livestock. In addition, there are an estimated 44 exotic diseases in other regions of the world that could infect Australian livestock, if they were introduced (Meischke and Geering 1985). At present, 3 alien insect and mite species already cause $228 million per year damage to the wool and sheep industry (Slater et al. 1996).

In India, there are more than 50 exotic species of disease and parasitic organisms that are causing major problems for the introduced livestock and native wildlife. Already present in India is the serious foot-and-mouth disease. Recently, it was reported that there were more than 50,000 cases of foot-and-mouth disease (Foot-and-Mouth Disease Leak 2004), treatment costs being about $20,000 per year.

South Africa also reports problems with introduced livestock pests. The exotic diseases include tuberculosis, brucellosis, East Coast fever, anthrax, and rinderpest. Estimates are that Brucellosis alone is causing livestock losses of more than $100 million per year (Coetzer et al. 1994). In Brazil and other Latin American countries, imported bovine tuberculosis has become a serious threat to the beef and dairy industry. These losses are estimated to be about $100 million per year (Cosivi et al. 1998).

18.5 Human Diseases

Various influenza virus types, originating mostly in the Far and Near East, have quickly spread to the United States and other nations in the past. Recent disease epidemics have been associated with SARS, and now there is the major threat of bird flu that is infecting some people in the Far and Near East. The current influenza strains are responsible for nearly 10% of all human deaths in the US (USCB 2004–2005). The costs of hospitalization for
a single outbreak of influenza, such as type A, can exceed $500 million per year.

One of the most notorious of all alien human disease is HIV/AIDS. The pathogen is reported to have originated in East Africa, probably from some species of monkey. The disease now occurs in all parts of the world. The costs of treatment of HIV/AIDS in the world today are estimated to be $100 billion per year. In addition to influenza and HIV/AIDS, there are numerous other diseases infecting humans in various parts of the world. These include syphilis, Lyme disease, and tuberculosis. These diseases are causing an estimated $20 billion in losses and damages per year.

New influenza strains in the UK are reported to cause from 3,000 to 4,000 deaths per year (Kim 2002). In total, both influenza and HIV/AIDS claim the lives of more than 4,000 people per year. The treatment costs are in excess of $1 billion per year. Influenza and tuberculosis in India are reported to cause more than 3 million deaths per year (Kim 2002). Several non-indigenous human diseases threaten people in South America. These diseases include HIV/AIDS, influenza, malaria, cholera, yellow fever, and dengue. More than 2 million people are infected per year, associated with more than $100 billion in damages and treatment costs per year.

18.6 The Situation Today and Projections for the Future

The number of invading species worldwide has been increasing rapidly, an estimated tenfold increase having been recorded in the past 100 years. Some countries with a rapidly increasing population, growing population movement, and increasing global trade, such as the United States, are suffering a greater problem from invaders than is the case for other nations. Approximately 500,000 species of plants, animals, and microbes have invaded the nations of the world, with about 50,000 in the US alone. It must be pointed out that, for all nations combined, about 5% of all these species were intentionally introduced as crops and livestock. Unfortunately, an estimated 10–20% of the introduced species are, or have become, pests and are causing major environmental problems. Although relatively few of these species become really serious pests, some species do inflict significant damage to natural and managed ecosystems, and cause serious public health problems. Various ecological factors help exotic species become abundant and emerge as serious ecological threats in their new habitat. These factors include exotic plant and animal species being introduced without their natural enemies (e.g., purple loosestrife); the existence of favorable predator–prey conditions in the new habitat (e.g., for house cats); the development of new associations between alien parasites and hosts (e.g., HIV/AIDS and humans); the occurrence of disturbed habitats that promote invasion by some species (e.g., crop
weeds); the occurrence of favorable, newly created artificial habitats for invasives (e.g., cheat grass); and the occurrence of species-specific traits promoting invasion by highly adaptable alien species (e.g., the water hyacinth and zebra mussel).

This investigation reports on various economic damages associated with invasive species in various nations of the world that total more than $1.4 trillion per year (Pimentel 2002). This amounts to about 5% of the world GNP (USCB 2004–2005). Unfortunately, precise economic costs associated with some of the most ecologically damaging species of invasives are not available. For example, cats and pigs have been responsible for the extinction of various animals, and perhaps some plants. For these invasive animals, however, only minimal cost impact data are available. In addition, it is impossible to assess the value attached to various species that have been forced to extinction. If economic values could be assigned to species forced to extinction, then in terms of losses in biodiversity, ecosystem services, and esthetics, the costs of destructive invasive species would be extremely high. The value of $1.4 trillion cited above already suggests that exotic species are extracting major environmental and economic tolls worldwide.

As mentioned above, 95–99% of all crop and livestock are introduced species. These alien crops (e.g., corn and rice) and livestock (e.g., cattle and poultry) are vital to maintaining world agriculture and the food system. The food system has an estimated value of $30 trillion worldwide. However, these benefits do not compensate for the enormous negative impacts of exotic pest species.

A real challenge lies in preventing further damage from invading exotic species to natural and managed ecosystems of the world. This is especially true in view of rapid population growth and increasing global trade. The United States has taken a few steps to protect and prevent the invasion of exotic species into the nation. Many governments of other nations have taken, and are taking, additional steps to combat non-indigenous species. Evidently, it is being increasingly recognized that investing a few million dollars to prevent future introduced species from invading a country, where they might cause billions of dollars worth of damage and control costs, is worthwhile.

Specific laws are needed in all nations to diminish or prevent invasive species introductions. All introductions of exotic species of plants, animals, and microbes – for whatever purpose – should be strictly regulated. In addition, governments should make efforts to inform the public concerning the serious environmental and economic threats that are associated with the invasion of exotic species.
Introducing a new species into a nation for the control of a plant, animal, or microbe pest invasive species is sometimes criticized as being a hazardous technology. In the past, where vertebrate species such as mammals, amphibians, birds, and fishes were introduced for biological control, several became pests themselves (Chaps. 2 and 23). For instance, the Indian mongoose, introduced for rat control in the West Indian Islands and Hawaiian Islands, and the English sparrow, introduced into the US for caterpillar control, have both turned out to be disasters. However, introductions of insect species, such as the vedalia beetle *Rodolia cardinalis* into the US, and of a virus species for the control of the European rabbit in Australia, have been notable successes. Controls of cacti in Australia, knapweed in the US, and the cassava mealy bug in Africa, all employing biocontrol insects, have also been successful.

The first response after detecting an invasive pest in a country should be to immediately travel to the country of origin of the pest, and attempt to introduce natural enemies of the pest. This is sometimes successful, but not always. There have been almost as many successful biological controls employing new associated biocontrol agents. In new associated biocontrol, the biological control agents are sought from a related species of the pest invasive in another country. The new association biocontrol agent offers an ecological advantage because the biocontrol agent has never interacted with the invasive pest species, and often this advantage makes the new biocontrol agent highly pathogenic to the invasive pest species. The advantage of biological controls is that they reduce the invasive pest species without the need for using pesticides in the new ecosystem, and with minimal or no damage to the new ecosystem (Hokkanen and Pimentel 1989). Details on the pros and cons of biological control are given in Chap. 23.

**References**

Alexander DJ, Parsons G (1986) Pathogenicity for chickens of avian paramyxovirus type I isolates obtained from pigeons in Great Britain 1983-1985. Avian Pathol 15:487–494  
Anon (1996) Menace of moggies. The Christchurch Press, Christchurch  
Armstrong S (1995) Rare plants protect Cape’s water supplies. New Scientist 11:8  
ATTRATA (1997) Purple loosestrife: public enemy #1 on federal lands. Interior Helper, Washington, DC  
Babbitt B (1998) Statement by Secretary of the Interior on invasive alien species. In: Proc National Weed Symp. Bureau of Land Management, Denver, CO  
Beardsley JW (1991) Introductions of arthropod pests into the Hawaiian Islands. Micronesica suppl 3:1–4  
Benson AJ, Boydstun CP (1995) Invasion of the zebra mussel into the United States. In: LaRoe ET, Farris GS, Puckett CE, Doran PD, Mac MJ (eds) Our living resources: a
report to the nation on the distribution, abundance, and health of U.S. plants, animals, and ecosystems. US Dept Interior, National Biological Service, Washington, DC, pp 445–446

Bevan BJ, Bracewell CD (1986) Chlamydiosis in birds in Great Britain. 2. Isolations of *Chlamydia psittaci* from birds sampled between 1976 and 1984. J Hygiene 96:453–458

Boycott RC, Bourquin O (1988) The South African tortoise book: a guide to South African tortoises, terrapins and turtles. South African Book Publishers, Johannesburg

Bruton MN, Van As J (1985) Faunal invasions of aquatic ecosystems in Southern Africa, with suggestions for their management. In: Macdonald AIW, Kruger FJ, Ferrar AA (eds) Proc National Synthesis Symp Ecology and Management of Biological Invasions in Southern Africa. Oxford University Press, Cape Town, pp 47–61

Campbell FT (1994) Killer pigs, vines, and fungi: alien species threaten native ecosystems. Endangered Species Tech Bull 19:3–5

Clement EJ, Foster MC (1994) Alien plants of the British Isles. Botanical Society of the British Isles, London

Coetzter JAW, Thomson GR, Tustin RC (1994) Infectious disease of livestock with special reference to Southern Africa. Oxford University Press, Cape Town

Cohen AN, Carlton JT (1995) Nonindigenous aquatic species in a United States estuary: a case study of the biological invasions of the San Francisco Bay and Delta. US Fish and Wildlife Service, Washington, DC

Cosivi O, Grange JM, Daborn C, Raviglione MC, Fujikura T, Cousins D, Robinson RA, Huchzermeyer HFAK, Kantor I, Meslin FX (1998) Zoonotic tuberculosis due to *Mycobacterium bovis* in developing countries. Emerg Infect Diseases 4:1–16

Courtenay WR (1997) Nonindigenous fishes. In: Simberloff D, Schmitz DC, Brown TC (eds) Strangers in paradise. Island Press, Washington, DC, pp 109–122

Courtenay WR, Jennings DP, Williams JD (1991) Appendix 2. Exotic fishes of the United States and Canada. In: Robins CR (ed) A list of common and scientific names of fishes from the United State and Delta. American Fisheries Society, Bethesda, MD, Spec Publ 20

Crawley MJ, Harvey PH, Purvis A (1996) Comparative ecology of the native and alien floras of the British Isles. Philos Trans R Soc Lond Biol Sci 351:1251–1259

Dowell RV, Krass CJ (1992) Exotic pests pose growing problem for California. California Agriculture 46:6–10

Eldredge LG, Miller SE (1997) Numbers of Hawaiian species: supplement 2, including a review of freshwater invertebrates. Bishop Mus Occas Pap 48:3–32

Emmerson G, McCulloch J (1994) Feral peril. Queensland’s introduced plants and animals. Queensland Parliamentary Library, Brisbane

FAOSTAT (1960–2004) Quarterly bulletin of statistics. FAO, Rome

Feare CJ (1980) The economics of starling damage. In: Wright EN, Inglis IR, Feare CJ (eds) Bird problems in agriculture. The British Crop Protection Council, Croydon

Foot-and-Mouth Disease Leak (2004) Foot-and-mouth disease leak at Plum Island BSL-3 Lab. GeneWatch 17(5/6):22 (www.gene-watch.org)

Fox MD (1995) Conserving biodiversity: impact and management of exotic organisms. In: Bradstock RA, Auld TD, Keith DA, Lunney RUT (eds) Conserving biodiversity: threats and solutions. Surrey Beatty, Chipping Norton, NSW, pp 177–183

Frank JH, McCoy ED, Hall HG, O’Meara F, Tschinkel WR (1997) Immigration and introduction of insects. In: Simberloff D, Schmitz DC, Brown TC (eds) Strangers in paradise. Island Press, Washington, DC, pp 75–100

Fritts TH, Rodda GH (1995) Invasions of the brown tree snake. In: LaRoe ET, Farris GS, Puckett CE, Doran PD, Mac MJ (eds) Our living resources. A report to the nation on the distribution, abundance, and health of US plants animals and ecosystems. US Dept Interior, National Biological Service, Washington, DC, pp 454–456
Gaudet CL, Keddy PA (1988) Predicting competitive ability from plant traits: a comparative approach. Nature 334:242–243
Gooders J (1982) Collins British birds. Harper Collins, London
Griffiths DW, Schloesser DW, Leach JH, Koalak WP (1991) Distribution and dispersal of the zebra mussel (Dreissena polymorpha) in the Great Lakes Region. Can J Fish Aquat Sci 48:1381–1388
Hall JP, Moody B (1994) Forest depletions caused by insects and diseases in Canada 1982-1987. Forest insect and disease survey information. Forest Insect and Disease Survey, Canadian Forest Service, Natural Resources, Ottawa, Rep ST-X-8
Hajek AE (2005) Asian longhorned beetle: ecology and control. In: Pimentel D (ed) Encyclopedia of pest management. Dekker, New York
Hiebert RD, Stubbendieck J (1993) Handbook for ranking exotic plants for management and control. US Dept Interior, National Park Service, Denver, CO
Hokkanen HMT, Pimentel D (1989) New associations in biological control: theory and practice. Can Entomol 121:828–840
Keniry T, Marsden JE (1995) Zebra mussels in southwestern Lake Michigan. In: LaRoe ET, Farris GS, Puckett CE, Doran PD, Mac MJ (eds) Our living resources: a report to the nation on the distribution, abundance, and health of US plants, animals, and ecosystems. US Dept Interior, National Biological Service, Washington, DC, pp 445–448
Kim Y (2002) World exotic diseases. In: Pimentel D (ed) Biological invasions: economic and environmental costs of alien plant, animal and microbe species. CRC Press, Boca Rotan, FL, pp 331–354
Kurdila J (1995) The introduction of exotic species into the United States: there goes the neighborhood. Environ Affairs 16:95–118
Lafferty KD, Page CJ (1997) Predation of the endangered tidewater goby, Eucyclogobius newberryi, by the introduced African clawed frog, Xenopus laevis, with notes on the frog’s parasites. Copeia 3:589–592
Laycock G (1966) The alien animals. Natural History Press, New York
Layne JN (1997) Nonindigenous species. In: Simberloff D, Smitz DC, Brown TC (eds) Strangers in paradise. Island Press, Washington, DC, pp 157–186
Lever C (1994) Naturalized animals: the ecology of successfully introduced species. Poyser Natural History, London
Liebold AM, MacDonald WL, Bergdahl D, Mastro VC (1995) Invasion by exotic forest pests: a threat to forest ecosystems. Forest Sci 41(2):1–49
Linn M (2005) Ant warfare: science fights fire with flies: natural enemy central to effort to limit spread of the insects. USA Today (Nation), 18 November 2005, p 3A
Long JL (1981) Introduced birds of the world: the worldwide history, distribution, and influence of birds introduced to new environments. Universe Books, New York
Lonsdale WM (1994) Inviting trouble: introduced pasture species in northern Australia. Austral J Ecol 19:345–354
Low T (1999) Feral future: the untold story of Australia’s exotic invaders. Viking Penguin Books, Melbourne
Macdonald IAW, Kruger FS, Ferrar AA (1986) Ecology and management of biological invasions in Southern Africa. Oxford University Press, Cape Town
Malecki RA, Blossey B, Hight SD, Schroeder D, Kok LT, Coulson JR (1993) Biological control of purple loosestrife. BioScience 43:680–686
McNeely JA (1999) Biodiversity: man is one among 15 million species. IUCN, Gland
Meischke HRC, Geering WA (1985) Exotic animal diseases. In: Gibbs A, Meischke R (eds) Pests and parasites as migrants. Cambridge University Press, Cambridge, pp 28–39
Moore NW (1980) How many wild birds should farmland support? In: Wright EN, Inglis IR, Feare CJ (eds) Bird problems in agriculture. The British Crop Protection Council, Croydon, pp 2–6

Morin N (1995) Vascular plants of the United States. In: LaRoe ET, Farris GS, Puckett CE, Doran PD, Mac MJ (eds) Our living resources: a report to the nation on the distribution, abundance, and health of US plants, animals, and ecosystems. US Dept Interior, National Biological Service, Washington, DC, pp 200–205

Morse LE, Cartes JT, Center L (1995) Native vascular plants. In: LaRoe ET, Farris GS, Puckett CE, Doran PD, Mac MJ (eds) Our living resources: a report to the nation on the distribution, abundance, and health of US plants, animals, and ecosystems. US Dept Interior, National Biological Service, Washington, DC, pp 205–209

Nandpuri KS, Singh B, Kolar JS, Kang MS, Chahal BS (1986) Field problems of important crops. Punjab Agricultural University, Ludhiana, India

OTA (1993) Harmful non-indigenous species in the United States. Office of Technology Assessment, United States Congress, Washington, DC

Pimentel D (2002) Biological invasions: economic and environmental costs of alien plant, animal, and microbe species. CRC Press, Boca Raton, FL

Pimentel D (2004a) Agriculture: changing genes to feed the world. Science 306:815

Pimentel D (2004b) Livestock production and energy use. In: Cleveland C (ed) Encyclopedia of energy. Elsevier, Amsterdam, pp 671–676

Pimentel D (2005) Aquatic nuisance species in the New York State Canal and Hudson River system and the Great Lakes Basin: an economic and environmental assessment. Environ Manage 35:692–701

Pimentel D, Pimentel M (2001) Agriculture, technology, and natural resources. In: Dorf R (ed) Technology, humans and society: toward a sustainable world. Academic Press, San Diego, pp 356–363

Pimentel D, Lach L, Zuniga R, Morrison D (2000) Environmental and economic costs of non-indigenous species in the United States. BioScience 50:53–65

Pimentel D, McNair S, Janecka J, Wightman J, Simmons C, O’Connell C, Wong E, Russel L, Zern J, Aquino T, Tsonomodo T (2001) Ecological and economic threat of alien plant, animal, and microbe invasions in the world. Agric Ecosyst Environ 84:1–20

Pimentel D, Zuniga R, Morrison D (2005) Update on the environmental and economic costs associated with alien-invasive species in the United States. Ecol Econ 52:273–288

Robbins CC (1995) Non-native birds. In: LaRoe ET, Farris GS, Puckett CE, Doran PD, Mac MJ (eds) Our living resources: a report to the nation on the distribution, abundance, and health of US plants, animals, and ecosystems. US Dept Interior, National Biological Service, Washington, DC, pp 437–440

Rodda GH, Fritts TH, Chiszar D (1997) The disappearance of Guam’s wildlife. BioScience 47:565–574

Roots C (1976) Animal invaders. Universe Books, New York

Sabath MD, Boughton WC, Eastal S (1981) Expansion of the range of the introduced toad Bufo marinus in Australia 1935-1974. Copeia 1981:676–680

Siegfried WR (1989) Preservation of species in Southern Africa nature reserves. In: Huntley BJ (ed) Biotic diversity in Southern Africa: concepts and conservation. Oxford University Press, Oxford, pp 186–201

Simberloff D, Smitz DC, Brown TC (1997) Strangers in paradise. Island Press, Washington, DC

Singh SP (1996) Biological control. In: Paroda RS, Chadha KL (eds) 50 years of crop science research in India. Indian Council of Agricultural Research, New Delhi, pp 88–116
Slater PD, Lewington D, Prathey JE (1996) An investigation into the effects of redlegged earth mite and Lucerne flea on the performance of subterranean clover in annual pasture in S. New South Wales. Plant Protect Quarant 11:6–8
Smith R (1984) Producers need not pay startling “rodent tax” losses. Feedstuffs 56(22):13–14
Smith RH (1992) Rodents and birds as invaders of stored-grain ecosystems. In: Jayas DS, White NDG, Muir WE (eds) Books in soils, plants, and the environment: stored-grain ecosystems. Dekker, New York, pp 289–323
South Africa (1998) South Africa government online (http://www.gov.za)
Temple SA (1992) Exotic birds, a growing problem with no easy solution. The Auk 109:395–397
Thompson DG, Stuckey RL, Thompson EB (1987) Spread, impact, and control of purple loosestrife (Lythrum salicaria) in North American wetland. US Fish and Wildlife Service, and Fish and Wildlife Research 2, Washington, DC
USCB (2004–2005) United States statistical abstracts. US Census Bureau, Washington, DC
Weber WJ (1979) Health hazards from pigeons, starlings and English sparrow: disease and parasites associated with pigeons, starlings, and English sparrows. Thomson Publications, Fresno, CA