Biological Invasions as Global Environmental Change

Our mobile society is redistributing the species on the earth at a pace that challenges ecosystems, threatens human health and strains economies

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The human species is noteworthy for its ability to forge into new environments and drastically alter them. No other species in the earth's history has spread throughout every continent and explored every remote island. We recognize some of the environmental consequences of the expansion and movement of the human population—chemical pollution, ravaged landscapes and the subsequent effects on natural ecosystems—but we fail to fully appreciate the extent to which we manipulate the distribution of life on the earth. In the course of our global travels, we don't merely bring the material trappings of our cultures, we also carry other species with us, frequently with a benevolent purpose in mind, but often unwittingly and without any particular intent. Unfortunately, the redistribution of the earth's species is proving to be ecologically and economically damaging, and the costs will continue to worsen.

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One recent and notorious example is the Eurasian zebra mussel. Like many other aquatic organisms, the zebra mussel entered North America in the ballast water of ships. And, like many other introduced species, it spread rapidly once it arrived, covering the bottoms of rivers and lakes and venturing into the waterworks of municipalities and industries. According to a 1993 report from the Office of Technology Assessment, the cost of clearing blocked intake pipes will reach about $3.1 billion over a 10-year period. The economic consequences are enormous, but the ecological consequences may dwarf them: Zebra mussels reduce natural algae populations and biological productivity and increase the concentrations of nutrients in entire ecosystems. They continue to spread into rivers, lakes and canals throughout North America.

We suggest that biological invasions by notorious species such as the zebra mussel and by its many less-famous counterparts have become so widespread as to constitute a significant component of global environmental change. This point is not widely appreciated, even by the global-change research community and by those who work to control biological invasions. (See Elton 1958 for one important exception.) In part, this lack of appreciation reflects the natural limitations of an individual's spatial perception. Individuals can observe biological invasions almost anywhere, but it is much more difficult for an indi-

Figure 1. Biological invasions can be deceptively beautiful, as exemplified by these purple loosestrife (*Lythrum salicaria*) that flourish

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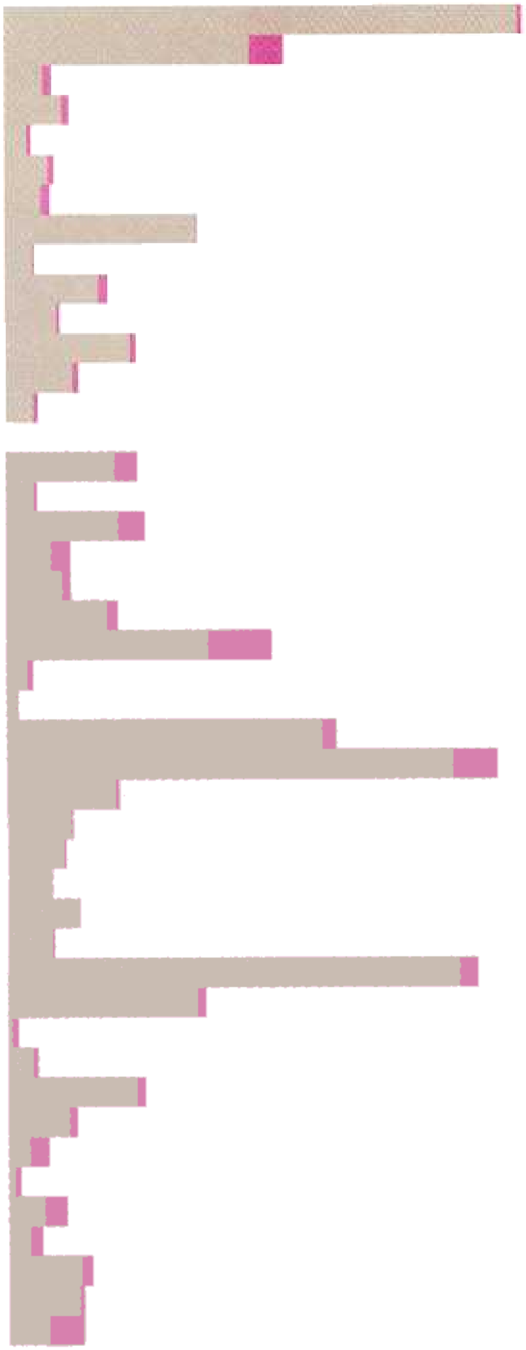
in a Minnesota marsh. Since its introduction to North America the purple loosestrife has spread throughout the northeastern and midwestern United States, where it has become the dominant plant in many wetland areas. It is estimated that from 5 to 25 percent of the vascular plants in the United States reserves are non-native species.



region	number of native species	number of non-native species	percentage of non-native species
Mediterranean	23,000	250	[a]1.1
Europe	[b]11,000	[c]1,568	12.5
Germany	1,718	429	[d]20.0
Germany	2,572	339	[c]11.6
Finland	1,006	221	[d]18.0
Poland	1,958	293	[d]13.0
Britain (+Ireland)	1,623	442	[c]21.4
Turkey	8,575	79	[c]0.9
Turkey	1,245	86	[e]6.5
France	[c]4,200	[e]438	9.4
Czech Republic	2,288	194	[c]7.8
Italy	5,599	294	[c]5.0
Switzerland	3,030	280	[c]8.5
Denmark	1,250	239	[c]16.1
USA	--	[f]2,000	--
California	4,844	1,025	[d]17.5
Alaska	1,229	144	[d]10.5
Florida	4,994	1,210	[d]19.5
New England	1,995	877	[d]30.5
Great Plains	2,495	394	[d]13.6
Texas	4,498	492	[d]9.9
Canada	9,028	2,840	[c]23.9
Newfoundland	906	292	[c]24.4
Greenland	427	86	[d]16.8
Mexico	14,140	639	[d]4.3
Australia	15-20,000	15-2,000	[j]10.0
Uganda	4,848	152	[e]3.0
Egypt	2,815	86	[e]3.0
Rwanda	2,500	93	[e]3.6
Tanzania	1,940	19	[e]1.0
Namibia	3,159	60	[e]1.9
Senegal	1,980	120	[e]5.7
South Africa	20,263	824	[e]3.9
South Africa	8,500	379	[g]4.3
Bermuda	165	303	[d]64.7
Bahamas	1,104	246	[d]18.2
Cuba	5,790	376	[d]6.1
Puerto Rico	2,741	356	[d]11.5
Hawaii	956	861	[h]47.4
Cook Islands	284	273	[i]49.0
Fiji	1,628	1,000	[i]38.1
French Polynesia	959	560	[i]36.9
New Caledonia	3,250	500	[i]13.3
Solomon Islands	3,172	200	[i]5.9
New Zealand	1,790	1,570	[i]46.7

Figure 2. Non-native species of vascular plants have invaded many parts of the globe. The total number (*bar length*) of native (*tan*) and non-native (*red*) species in a region varies from about 500 in Bermuda to more than 23,000 in the countries bordering the Mediterranean Sea. The percentage of non-native species in a particular region tends to be greater on island habitats, but many species have invaded the continents as well. Sources: a - Quezal, Burbero, Bonini and Loisel 1990; b - Heywood 1985, estimate of native species; c - Weber (in preparation); d - Rejmanek and Randall 1994; e - Rejmanek (unpublished); f - U.S. Congress, Office of Technology Assessment 1993; g - Kruger, Breytenbach, Macdonald and Richardson 1989; h - Wagner, Herbst and Sohmer 1990; i - Given 1992; j - Heywood 1989.

vidual to perceive that the invasions are almost everywhere. In part, it may also reflect a narrow view of global environmental change, one that emphasizes climatic change to the exclusion of other, equally significant components of human-caused global change.

There are several components to global change that are widely recognized as being caused by the explosive growth of industry and agriculture in the past two centuries. These include the increasing concentration of carbon dioxide in the atmosphere, alterations to the global biogeochemical cycle of nitrogen and other elements, the production and release of persistent organic compounds such as the chlorofluorocarbons, widespread changes in land use and land cover, and the hunting and harvesting of natural animal populations. To this list we add

Figure 3. Invasive saltcedar (tamarisk) trees have displaced the native flora in many southwestern river courses in the United States. The species is believed to increase soil salinity and to lower the water table.

another component—the introduction of non-native species to habitats and ecosystems that were previously isolated from each other. To varying degrees each of these components plays a role in enhancing the greenhouse effect or reducing the earth's biological diversity (through the extinction of genetically distinct populations or species).

Invasions Are Everywhere

Until recently the worst effects of biological invasions were largely considered to be restricted to oceanic islands. But it is becoming increasingly apparent that non-native species are also abundant on the continents. Attaching a number to the magnitude of these continental invasions is not always an easy task, however. Two different investigators may cite disparate numbers of introduced species for a particular region. This may be due to differences in the definition of "introduced species," the geographic boundaries used for the assessment or the year in which the study took place. Even so, the results of different studies almost always suggest that the scale of the continental invasions is much larger than is widely supposed.

Consider the extent of the invasions on the basis of some countries where reasonable data exist. Australia, Canada and the United States each harbor more than 1,500 species of invasive non-native plants. (California and Florida lead the continental U.S., each with close to 1,000 invasive introduced species of plants.) Flora of many European countries have several hundred introduced species, and South Africa alone supports nearly 800 species of non-native plant invaders.

As a proportion of the total flora and fauna in a particular country, the non-native species may comprise anywhere from a few percent to more than 20 percent of the total number. Remote islands tend to have a relatively greater proportion of non-native species, often as much as 50 percent of the total number.

Another general tendency is that the total numbers of invading introduced species are greater for plants than for animals. This is partly because the introduction of animal species (with the exception of insects) typically requires a greater degree of purposeful human intervention. This is especially true for birds and fishes. Nonetheless, isolated islands often have more non-native species of fish than native fishes. Even many continental areas, such as California, Europe and Brazil, have relatively large numbers of non-native fish species. Similarly, non-native birds have established wild populations in many parts of the world. Here again, the proportion of non-native species tends to be greater on islands than on the continents. Nevertheless, non-native avian species can be quite abundant on the continents—consider the widespread and abundant European house sparrow and the European starling in North America.

Parks as Canaries

One way to assess the extent of the biological invasions in a particular region is to take a closer look at parks and biological preserves. These habitats generally represent the least disturbed areas of land in a country. A former director of the U.S. National Park Service championed the concept that the park lands are an environmental analogue of miners' canaries—relatively pristine sites where the extent of large-scale environmental changes might be evaluated.

region	breeding birds		freshwater fish	
	native species	non-native species	native species	non-native species
Europe	[k]514	[l]27	--	[a]74
California			[b]76	[c]42
Alaska			55	[d]1
Canada			177	[e]9
Mexico			275	[e]26
Australia	--	[l]32	145	[e]22
South Africa	[m]900	[l]14	107	[e]20
Peru			--	[f]12
Brazil	1,635	[n]2	517	[g]76
Bermuda	--	[l]6		
Bahamas	[o]288	[l]4		
Cuba	--	[l]3	--	[f]10
Puerto Rico	105	[p]31	3	[h]32
Hawaii	57	[l]38	6	[i]19
New Zealand	155	[q]36	27	[j]30
Japan	[r]248	[l]4	--	[f]13

Figure 4. Numbers of native and non-native species of breeding birds and freshwater fish are shown here for selected regions of the world. (Sources: a - Holcik 1991; b - McGinnis 1984; c - Courtenay, Hensley, Taylor and McCann 1984; d - Moyle 1986; e - Macdonald, Kruger and Ferrar 1986; f - Welcomme 1981; g - Nomura 1984; h - Erdman 1984; i - Stone and Stone 1989; j - McDowall 1984; k - Jonsson 1993; l - Long 1981; m - Roberts 1985; n - Sick 1993; o - Paterson 1972; p - Raffaele 1989; q - Kinsky 1980; r - Higuchi, Minton and Katsura 1995.)

An examination of floristic lists reveals that anywhere from 5 to 25 percent of the vascular plants in the United States reserves are non-native species. For the most part the introduced species pose little or no threat to native species or ecosystems. There are some important exceptions, however. Fire-promoting grasses (such as cheatgrass) have invaded several semi-arid areas, tamarisk is prevalent in many riparian habitats of the Southwest, *Melaleuca* is rampant in the wetlands of the Florida Everglades, and purple loosestrife dominates waterways in the Northeast and Midwest. Plant invasions also threaten native biota in Hawaiian reserves, where the percentage of non-native species may be as much as 50 to 70 percent of the flora.

There are some serious threats to U.S. parks from animal invasions as well, especially ungulates. Feral pigs may be the single most damaging introduction in the national parks and reserves of the United States. The effects of the pigs on otherwise undisturbed areas are severe and pervasive in the Great Smoky Mountains National Park and in Haleakala and Hawaii Volcanoes National Parks. In Hawaii the pigs make a significant contribution to the dispersal of invading plants. Other harmful invaders include feral goats in Hawaii (now largely removed), feral burros in the Grand Canyon and other southwestern parks and mountain goats in Olympic National Park.

The consequences of invasion by several fish species into the aquatic and wetland ecosystems on the continental U.S. are as severe as many island invasions. In the streams of Sequoia-Kings Canyon National Park, for example, intentionally introduced brook trout and brown trout have displaced the native rainbow trout. In other parks, the introduction of brook trout and rainbow trout in waters that were originally barren of fish has greatly reduced the numbers of native invertebrates and amphibians. In the Great Smoky Mountains National Park the introduction of rainbow trout threatens the existence of native brook trout populations. Even the relatively pristine waters of Glacier National Park have been largely compromised by the introduction of fish in this century.

The introduction of non-native insects and microorganisms has also worked havoc on the forests of the U.S. parks and reserves. The white pine blister rust and the balsam woolly adelgid, which were costly to commercial forestry for many years, are now devastating the parks. Both were brought to the United States nearly 100 years ago on nursery stock from Europe. White pine blister rust attacks five-needled pines and is now killing sugar pines in the forests of Yosemite and Sequoia-Kings Canyon National Parks. Whitebark pine trees are also being hit hard throughout their entire range—fewer than 10 trees in 100,000 are rust resistant. Since the seeds of the whitebark pine are an important source of food for the grizzly bear and other animals, the decline of the tree may have severe consequences for the wildlife in Glacier, Yellowstone and Grand Teton National Parks. The balsam woolly adelgid attacks true firs of the genus *Abies*, causing death within 2 to 7 years by chemical damage and by feeding on the plant's vascular tissue. This small cottony insect is particularly damaging to the Fraser fir, which is found only in the southern Appalachian Mountains (primarily within the high elevations of the Great Smoky Mountains National Park). Since 1963 the adelgid has killed nearly every adult (cone-bearing) fir tree in the park.

Consequences of Invasions

Many invasions are reflections of other changes rather than agents of change themselves. For example, invading plants that only occupy roadsides thrive in these circumscribed habitats. These plants cannot be regarded as serious threats to native biological diversity except where ecological restoration is attempted. Moreover, some introduced species are beneficial to humanity—it would be impossible to support the present population of the United States entirely on native plants and animals. However, many invading species degrade human health and wealth, whereas others affect the structure of ecosystems or the maintenance of native biological diversity. We shall discuss an example of each of these to illustrate some of the consequences of recent invasions. For every example we discuss here, there are many others that are equally well documented and at least as harmful.

Newly introduced species can act as vectors of disease. A recent example of an introduced disease vector is the Asian tiger mosquito, larvae of which were brought into the United States in used automobile tires that were imported for retreading and resale. Two earlier introductions of the tiger mosquito in shipments of military tires had failed to become established. With the recent growth of commercial tire imports, however, the importation of mosquitoes has also increased. (In 1986, 6.8 of every 10,000 tires were infested with mosquito larvae.) The Asian tiger mosquito first became established in the United States in the 1980s, and by 1992 the mosquito had spread throughout 25 states. In its natural range, the mosqui-

Figure 5. Zebra mussels clog the municipal and commercial waterworks in the Great Lakes region. Since their introduction to North America in the late 1980s, the zebra mussels have spread throughout the waters in the Great Lakes. Here a water jet is used to clear zebra mussels from the walls of a pump room in a Detroit power station.

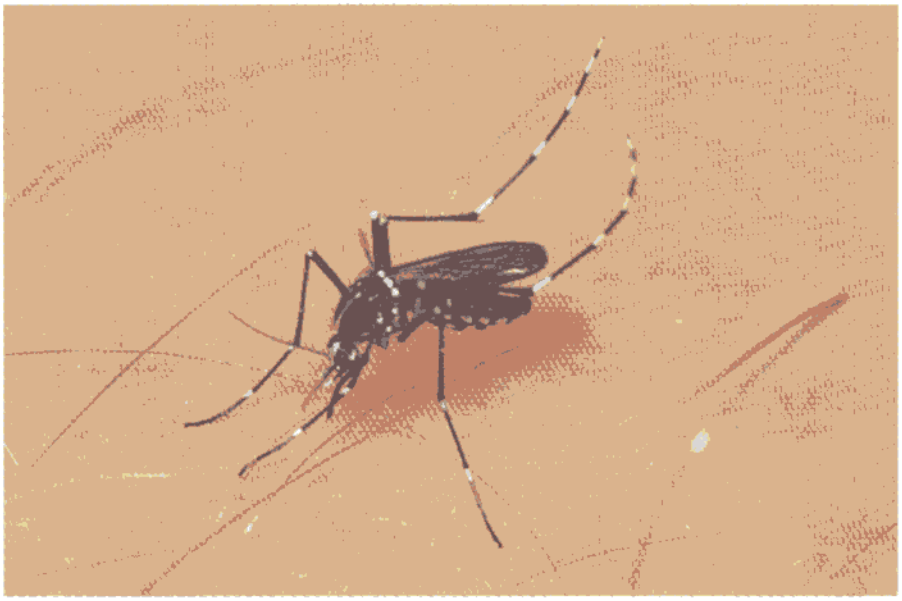
to is a vector of dengue fever and other human arboviruses. In the United States the mosquito can feed on most mammals and birds and is a vector for eastern equine encephalitis, an often fatal viral infection of people as well as horses (Craig 1993).

Biological invasions can be expensive. Non-native species can affect crops, rangelands and commercial forests, costing millions of dollars annually in lost yields and expensive efforts to control the invasions. Biological invasions can also be especially costly to developing economies, which typically have smaller margins for dealing with additional costs.

One prime example is the golden apple snail (*Pomacea canaliculata*) in Asian rice ecosystems. The snail was originally brought from South America to Taiwan to provide a supplemental source of protein and to increase the export income of small rice farms. Its benefits proved to be illusory. The local people find the snail distasteful—a recipe calling for "washing in a vinegar solution repeatedly to remove mucus and slime" may explain why. Moreover, the snail export market was closed because of health concerns. At the same time, both the environmental and economic costs of importing the golden apple snail have been very high. Snail populations grow rapidly, consuming young rice plants as they spread throughout irrigation canals. Despite the outcome of snail introduction in Taiwan, the entrepreneurs who originally imported the snail simply exported it to other countries. As of today the snail has spread throughout most of the Far East and southeastern Asia.

The life history of the snail invasion in the Philippines can be traced in the titles of publications over the span of a few years. A 1986 article, "Golden Kuhol propagation good source of income," promises economic opportunity, whereas a 1988 report, "The distribution and control of the introduced golden snail in the Philippines," hints at the need for restraint, and a 1989 article, "The golden apple snail: A serious pest of lowland rice in the Philippines," documents the costly turn of events. Rosamond Naylor of Stanford University has recently evaluated the economic costs of the snail invasion in the Philippines. In 1990, the total cost to farmers was between \$27.8 million and \$45.3 million, including the costs of picking the rice by hand, replanting destroyed crops and controlling the snail with molluscides and the loss of crop yields. This amounted to 25 to 40 percent of what the Philippines spent on rice imports in 1990. It represents just one year's damage in one of many infested countries.

Invaders alter ecosystem processes. Invaders don't simply consume or compete with native species—they can change the rules of existence for all species by altering ecosystem processes such as primary productivity, decomposition, hydrology, geomorphology, nutrient cycling or natural disturbance regimes. Invaders that affect each of these processes are known. One dramatic example is the invasion of the nitrogen-fixing tree *Myrica faya* into Hawaii Volcanoes National Park. Because the seeds of this tree are dispersed by a variety of birds, the tree can easily spread to new sites created by volcanic eruptions. The consequences for the native plant life are



David T. Roberts/Photo Researchers, Inc.

Figure 6. Asian tiger mosquito entered the United States by way of imported automobile tires in the 1980s. By 1992 the species had spread throughout 25 states. Here a mosquito rests on a human arm.

profound. Usually the growth of native plants in young volcanic sites is limited by the poor availability of nitrogen in the soil. With the introduction of *Myrica*, however, there may be a rapid, fourfold increase in the amount of biologically available nitrogen added to the soil. This alters the plants and soil organisms that can thrive in the newly formed volcanic habitats. As it happens the species that do well in these altered habitats are non-native organisms. In essence, an invasion by one species changes the composition and the dynamics of an entire ecosystem.

Invasions reduce biological diversity. The eastern deciduous forests of North America are a diverse ecosystem that appear to be as resistant to biological invasions as any. Although these forests were cleared extensively in the 1800s, they have recovered substantially in this century. The scientific community has put a great deal of effort into understanding various assaults on these forests, including the effects of climatic change, the increased concentrations of atmospheric CO_2, acid rain and oxidant air pollution. However, by far the greatest perturbations in this century have involved repeated waves of invading pests and diseases (Sinclair, Lyon and Johnson 1987). Some pests, such as the gypsy moth, consume a variety of species, and their full effects on forest diversity are not yet known. Other more specialized pathogens in the eastern forest have virtually eliminated the once dominant American chestnut and the American elm. Other species that are declining because of newly introduced insects and diseases include the American beech, mountain ash, butternut, eastern hemlock, flowering dogwood and sugar maple (Langdon and Johnson 1992, Campbell and Schlarbaum 1994). We predict that the invasion of non-native species will continue to be the greatest threat to the diversity of these forests in the foreseeable future.

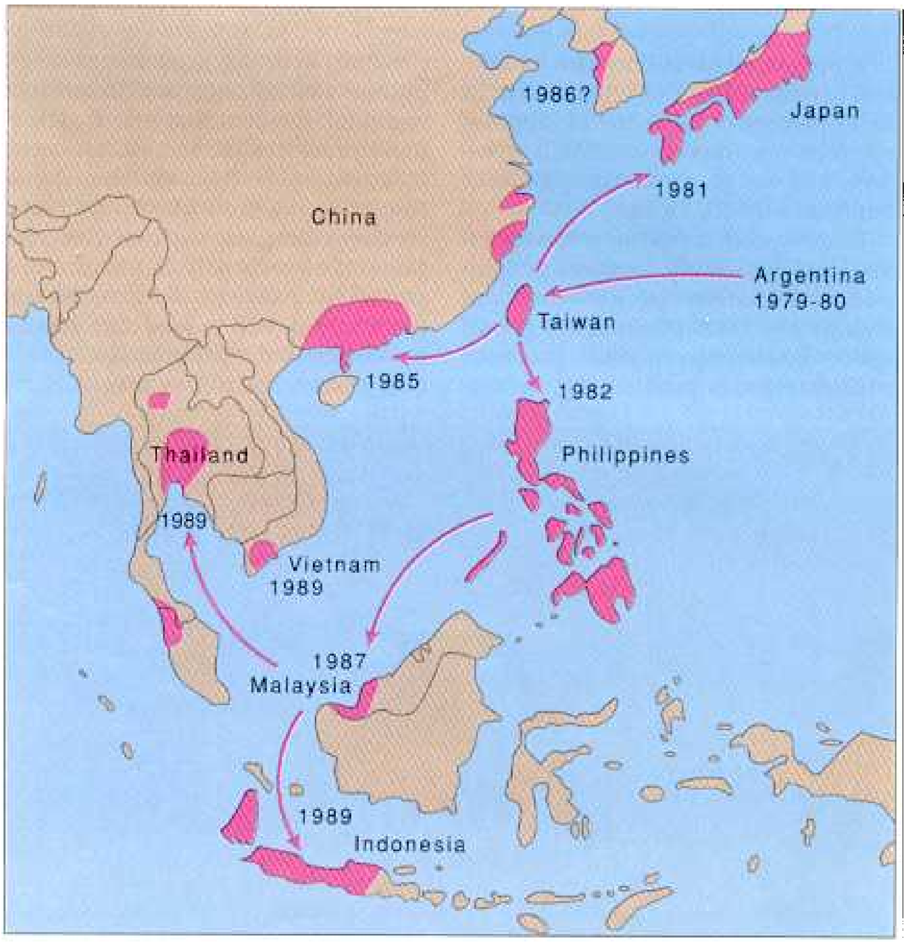


Figure 7. Invasive spread of the golden apple snail (*red*) threatens the rice crops of several countries in Southeast Asia. The snail was initially introduced to Taiwan from Argentina in 1980 as a potential source of protein. Within 10 years it had spread north to the Korean peninsula and south to Indonesia. Ironically, the snail not only consumes a significant proportion of the annual rice crop, it has failed to be a palatable source of protein in the Asian diet. The snail has proved to be a costly experiment in the redistribution of a species. (Adapted from R. L. Naylor, in press.)

Global Changes Interact

The recognition that biological invasions are a component of global change leads one to ask how the movement of species might interact with other changes taking place on a worldwide scale. It seems likely that each component of change interacts with others to varying degrees. We are far from understanding the dynamic among all of these components, but the ultimate consequences may go beyond simple additive effects. Here we introduce some examples of how two of these components might interact with changes in the distribution of plants and animals.

Changes in land use can promote invasions. The human species is now the premier agent of ecological disturbance on the planet. We have not merely increased the frequency and intensity of disturbances; we have also created landscapes that are unlike anything in the evolutionary history of many species. The alteration of natural disturbance regimes often promotes the invasion of species that would otherwise not be found in a region.

Consider the interaction between land use and the invasion of fire-promoting grasses. Many grasses from Eurasia and Africa have spread throughout the arid and semiarid ecosystems of the Americas, Australia and Oceania, where they increase the frequency and the intensity of fires. They also threaten tropical dry forests, and they are a major impediment to the restoration and reforestation of cleared lands (D'Antonio and Vitousek 1992).

Initial disturbances such as land clearing (often with fire) allow the invasion of these grasses. The invading grasses not only provide more fuel for the fire; they also create a microclimate that favors an increase in the frequency of fires. In turn, fires select against many native species and further promote the spread of fire-adapted grasses. The result is a positive-feedback system that perpetuates low-diversity shrublands and savanna.

External disturbances are not always required to set the cycle in motion. In some cases the invasion of grass alone can increase the probability of fire by increasing the load of fuel in an area. (This happened, for example, in Hawaiian woodlands.) It is also possible that the ready availability of forage grasses that withstand grazing and drought conditions can promote land-use change. In Mexico the conversion of millions of hectares of the Sonoran woodland desert to monocultures of African buffel grass has occurred in less than a decade. Similarly the dry and mesic forests of Central and South America have been replaced by grazing-tolerant (and fire-responsive) African pasture grasses (Parsons 1972).

Perhaps the most dramatic and well-documented example of a cyclic relationship between an introduced grass and the increased incidence of fire is the invasion of European cheatgrass into North America. This annual species invaded shrub and steppe habitat in the Great Basin, which was previously dominated by native shrubs and perennial grasses. After the invasion of cheatgrass the frequency of fires has increased from about once every 80 years to every 4 years or so. Almost 5 million hectares of land in Idaho and Utah are now nearly monospecific stands of cheatgrass (Whisenant 1990).

The suppression of natural disturbances by human activity can also promote the invasion of non-native species. This is especially true in aquatic ecosystems, where reproduction is often synchronized with natural disturbance cycles. The damming and impoundment of most of the rivers in the United States is correlated with the invasion of non-native species into rivers, streambanks and floodplains. It is also associated with the rapid conversion of species-rich riparian forests to species-poor stands of non-native species. For example, prior to the construction of the large network of dams that control the Colorado River, its floodplain forests were dominated by native cottonwood and willow. With the construction of dams, the groundwater tables have dropped and the intermittent floods that scoured the river banks have ceased. As a result the cottonwoods and the willows have been largely replaced by introduced saltcedar (tamarisk).

The fragmentation of natural habitats with the encroachment of farm lands and urban development has also encouraged the spread of non-native species. Urban forests and parks represent an increasing percentage of our remaining near-natural habitat and are often prime areas for newly introduced plants and animals. This is partly because the international traffic in cities is often the route by which a non-native species is introduced to a country. Having established themselves in these environments, the non-native species can then spread into less-urban habitats. The gypsy moth first became established in an urban forest and subsequently spread throughout the eastern United States, where it is now a major forest pest (Liebold, MacDonald, Bergdahl and Mastio 1995). Outbreaks of non-native fungal pathogens are also more common in fragmented forests close to urban areas.

Invasions promote extinction. The extinction of genetically distinct populations may be the least reversible of all global changes, and there is clear evidence that biological invasions contribute substantially to an increasing rate of extinction. As of 1991, 44 species of fishes in the continental United States were threatened or endangered by the introduction of non-native fishes. Of the 40 fish species known to have gone extinct since 1890, 27 were negatively affected by the introduction of non-native fishes (Wilcove and Bean 1994).

Although the native species on islands and in aquatic ecosystems have historically suffered the most from the introduction of non-native species (witness the rapid extirpation of the entire native forest-bird population on Guam due to the introduced brown tree snake), the potential for invasion-driven extinctions on the continents is substantial. One way to estimate the potential for extinction on the continents is to appreciate the relationship between species diversity and habitat area. For example, on many islands and isolated habitats the number of avian species present is linearly related to the logarithm of the land area that supports them (Preston 1960). If this relationship is extrapolated to include the total area of land on the earth, the projected number of avian species is substantially less than the actual number. The difference comes about because isolated habitats can support entirely different groups of birds. If these

Figure 8. Eggs of the golden apple snail (*pink*) cluster on rice plants in Southeast Asia.

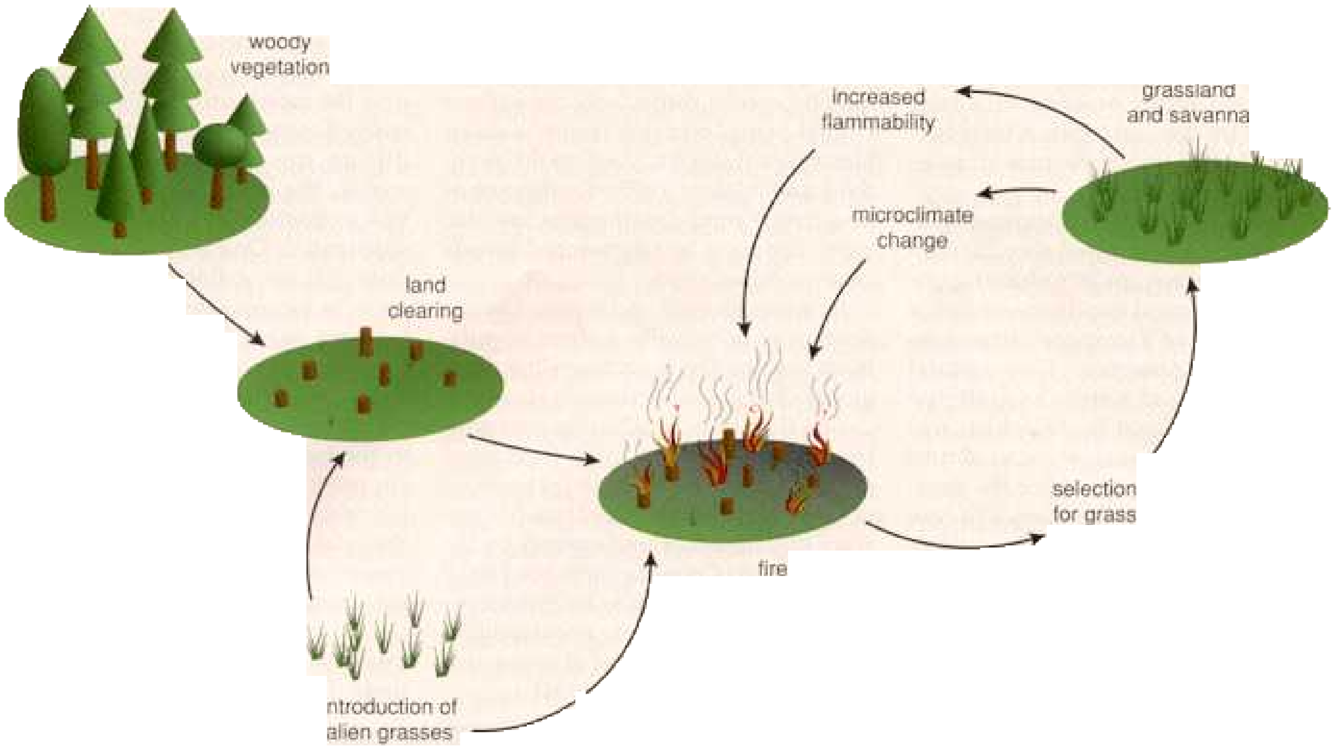


Figure 9. Grass invasions can initiate and maintain a grass-fire feedback system that prevents the regeneration of native woody species over large areas of the planet. The cycle can begin after the purposeful land clearing or after "natural" invasions of woodland or shrubland by introduced grasses. (Adapted from D'Antonio and Vitousek 1992.)

isolated areas were to be brought into contact with each other, some species would eventually be lost through competition, predation or disease. Regional distinctiveness begets global diversity.

One of us (Westbrooks) and colleagues applied this approach to calculate the potential for extinctions resulting from biological invasions. Based on known species–area relationships and the number of mammalian species present on each continent, they calculated that a single supercontinent comprising all the land area on the earth would support about 2,000 mammalian species. In fact the earth supports about 4,200 species of mammals. This analysis implies that the complete breakdown of biogeographic barriers might result in the eventual extinction of more than half of the earth's mammalian species.

We think that estimating the potential for extinction with species-area relationships is as valid as estimates that are based on the loss and fragmentation of habitats (Wilson 1992). This approach is also supported by paleobiological evidence. About 3 million years ago North and South America became connected by the Isthmus of Panama, which allowed a massive exchange of plants and animals across the two continents. The result was asymmetrical: Although some South American mammals (notably the opossum) crossed the isthmus, many more North American mammals spread into the Southern Hemisphere. The invasion of the North American mammals was associated with a significant increase in the extinction rate for the native mammals of South America (Marshall, Webb, Sepkowski and Raup 1982).

What Can Be Done?

In our attempts to convince others of the significance of biological invasions we have run into two major obstacles. First, there is a belief that invasions represent a natural process that has always been a part of evolutionary history. The second is a feeling that the ease of travel and the continued expansion of the global economy will make it impossible to prevent invasions.

It is of course true that invasions (like extinctions) have always been with us. What differs now is the increased *rate* of the invasions, which is so large as to represent a difference in kind rather than degree. For example, until recently all of the insects on the Hawaiian Islands arose from a successful colonization by one group or another every 50,000 years or so. Recently, however, about 15 to 20 insect species become established on the islands every year (Beardsley 1979). Similarly, in eastern North America, there is only one known instance in the postglacial past (within about 10,000 years) in which a species of tree (the eastern hemlock) declined over much of its range in a way that is consistent with an attack by a pathogen (Davis 1981). Yet several species of American trees have been devastated by introduced pathogens in the past century alone. Both examples suggest that recent invasions are very different from those of the past.

It is true that stemming the tide of biological invasions poses a huge challenge to the ingenuity of humankind. But it is not hopeless. A large part of the task is simply convincing our colleagues, students and the public at large that it is a problem worthy of our best efforts. A greater awareness of the issues increases the likelihood that citizens will respond in a positive way. In some respects this is already being achieved at a local level in California, Hawaii and Florida. Here the prevention of biological invasions is becoming popular as county councils consider the creation of emergency funds for the control of invasive species to assure the protection of biodiversity, the local lifestyles and the tourist industry. Ultimately, reducing the extent of biological invasions may prove to be as rewarding as reducing the rate of fossil-fuel consumption—while being less of a threat to economic growth and lifestyles.

The legal framework concerning the control and quarantine of plants and animals also needs improvement. Existing laws and policies such as the Federal Noxious Weed Act of 1974, the Nonindigenous Aquatic Nuisance Prevention and Control Act of 1990 and the Lacey Act can be enforced and strengthened. Given a reasonable amount of public support, intelligent new approaches can be devised. Moreover, concerned and informed citizens can participate personally by recognizing incipient invaders and preventing them from spreading. The concept of thinking globally and acting locally applies well to stopping biological invasions. No other form of global change offers educated and dedicated individuals such an opportunity to make a lasting difference.

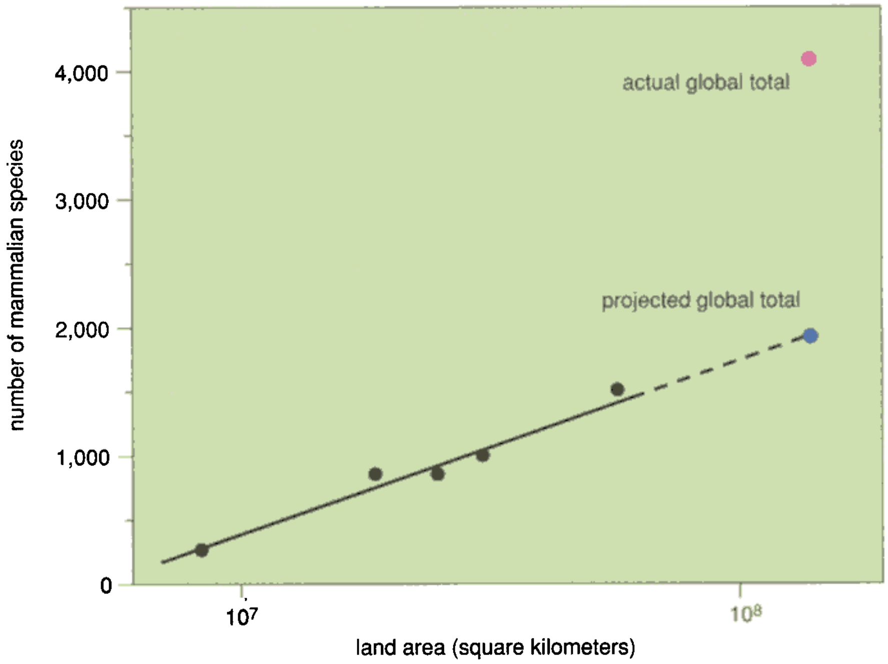


Figure 10. Number of mammalian species in a given area of land is dependent on the isolation of these species from each other. If the earth's land masses were united into a single supercontinent, the total area of land (more than 10^8 square kilometers) is projected to support about 2,000 species of mammals (*blue dot*). However, there are about 4,200 mammalian species on earth (*red dot*). The authors suggest that the current geographic isolation of the earth's species promotes and maintains biological diversity. By transporting other species across natural geographic boundaries, human beings threaten to reduce the diversity of life on the earth. The projected total number of mammalian species is based on surveys (*black dots*) showing a linear relationship between the number of species in a region and the logarithm of the area of land in the region. (Adapted from work by A. Launer of the Center for Conservation Biology, Stanford University.)

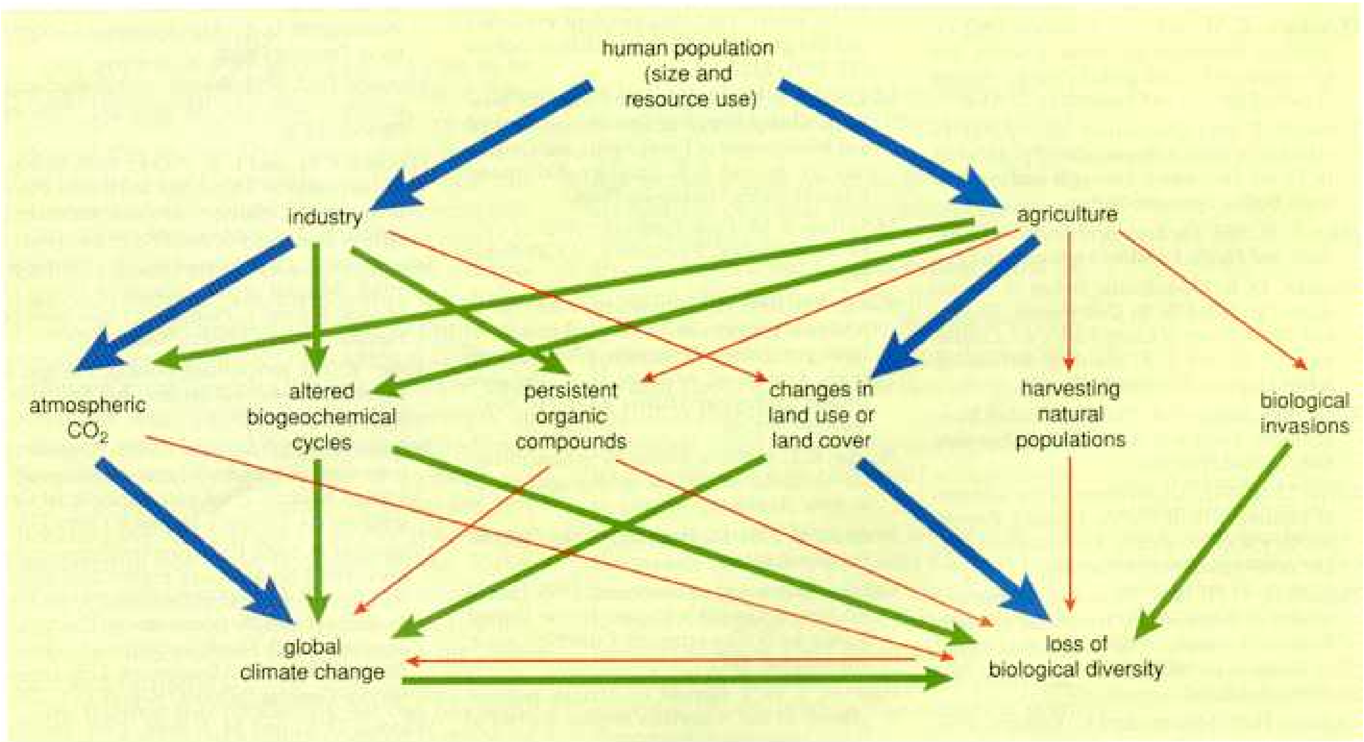


Figure 11. The growth of industry and agriculture in the past 200 years has promoted at least six identifiable components (*middle row*) of global environmental change. To varying degrees these components alter the earth's climate and reduce the planet's biological diversity. A general notion of the magnitude of these effects (*arrow thicknesses*) can be estimated, but the interrelationships and the synergistic effects of all six components have yet to be fully appreciated. (After Vitousek 1994.)

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