Western North American Naturalist 61(3), © 2001, pp. 308–315

BIOLOGICAL INVASIONS—HOW ARE THEY AFFECTING US, AND WHAT CAN WE DO ABOUT THEM?

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ABSTRACT.—Nonindigenous species affect native ecosystems, communities, and populations in myriad ways, from plants (and a few animals) that overgrow entire communities, to plants and animals that hybridize individual native species to a sort of genetic extinction. Further, nonindigenous species sometimes interact to worsen each other's impact. These impacts are commonly seen in national parks throughout the United States. The key policy change required to alleviate this threat is a shift from blacklists of prohibited species and a presumption of harmlessness to combinations of white and blacklists and a presumption that any species may be damaging. This new guiding philosophy must be inculcated at international and national levels, which will not be easy during a period when free trade is seen as an unmitigated blessing. Within the United States, enhanced cooperation and coordination will be required among all parties (i.e., federal, state, and local agencies as well as private entities) charged with managing invasions. Internationally, the key forum is the World Trade Organization. Various management tools available to combat nonindigenous species have produced some striking successes, but new research could improve their effectiveness and reliability. There is a particular need for research on ecosystem management to control introduced species. In the face of the increasingly publicized onslaught of invaders, there is a widespread tendency to view increased biotic homogenization as inevitable. However, advances in both policy and technology could greatly slow this process and perhaps (in concert with restoration measures) even reverse it. The necessary pressure and resources to effect these changes must come from an increasingly alarmed and vocal public.

Key words: biological control, blacklist, ecosystem management, eradication, Executive Order 13112, introduced species, invasion, nonindigenous species, white list, World Trade Organization.

Biological invasions are now the 2nd leading cause (after habitat destruction) of species endangerment and extinction in the United States and worldwide. In the United States, for example, about 42% of all species listed under the Endangered Species Act are threatened in part or wholly by nonindigenous species (Wilcove et al. 1998). However, most introduced species are not invasive. Although no one can yet say what fraction of introduced species become problematic in any region, it is surely no more than a few percent; the great majority of introduced species probably do not even survive, and, of those that do, only a few invade natural ecosystems (Williamson 1996). But these few can have enormous impacts.

In addition to causing massive ecological problems, nonindigenous species impose huge economic costs not only on nature but on agriculture, silviculture, industry, and public health; and this is the real reason for the sudden surge of new activities to try to deal with them. After all, Charles Elton (1958) pointed out most of the ecological problems caused by invasions in his book, *The Ecology of Invasions by Animals and Plants,* but he did not discuss the costs, and not many people cared, not even ecologists. Recently, a preliminary report (Pimentel et al. 2000) estimates the cost of nonindigenous species in the United States alone to be over $130 billion annually, and finally everyone is eager to do something about them.

First, I will outline the kinds of problems associated with introduced species. Then I will discuss why this crisis is occurring. Finally, I will recommend means of dealing with invasive introduced species.

KINDS OF IMPACTS

All major impacts of introduced species can be exemplified by problems found in United States national parks, although some are more dramatic in other settings. The most significant problems, in terms of ecological damage, are usually caused by plant species that overgrow entire communities, replacing native, dominant plants and often most species of

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plants and animals associated with them. For example, the Australian paperbark tree (*Melaleuca quinquenervia*), Brazilian pepper (*Schinus terebinthifolius*), and Australian pines (*Casuarina* spp.) together cover approximately 650,000 ha in south Florida (Schmitz et al. 1997), including many thousands of hectares in Everglades National Park (Doren and Jones 1997).

Overgrowth and replacement of the original community is not restricted to terrestrial systems. Water hyacinth (*Eichhornia crassipes*) in Lake Victoria (McKinley 1996) and many other freshwater sites, as well as the tropical alga *Caulerpa taxifolia*, which has invaded 9 of 10 marine reserves of the northwest Mediterranean Sea (Meinesz 1999), have had similar impacts on aquatic systems. The latter species has just been found in a lagoon near San Diego (Anonymous 2000). Occasionally, an animal species can overgrow an area with devastating effects on the entire native community, as has zebra mussel (*Dreissena polymorpha*), which has invaded many freshwater systems in North America (Johnson and Padilla 1996).

Of course, an introduced species that removes a dominant plant species can have enormous impacts on the entire native community. The Asian chestnut blight fungus (*Cryphonectria parasitica*) arrived in New York on nursery stock in the late 19th century, spread over 100 million ha of the eastern United States in less than 50 years, and killed almost all mature chestnuts (*Castanea dentata;* von Broembsen 1989). Because chestnut had been a dominant tree (comprising more than one-quarter of all canopy trees in many places, including parts of Great Smoky Mountains National Park), the impacts on the native community must have been enormous. There are occasional claims that the chestnut blight invasion shows how a dominant species can be replaced with little real impact on the ecosystem (e.g., Williamson 1996). Such statements rest on ignorance; few data exist from before this invasion that allow one to assess its full impact. Where evidence exists, it suggests major changes. For example, several lepidopterans that were host-specific to chestnut became extinct (Opler 1979).

Chestnut blight is just one of many invasions that have successively removed dominant plant species from Great Smoky Mountains National Park. The European balsam woolly adelgid (*Adelges piceae*) has more recently destroyed nearly all Fraser fir trees (*Abies fraseri*), a formerly dominant species in upper elevations of the park (Campbell and Schlarbaum 1994). Additionally, dogwood anthracnose (*Discula destructiva*) is eliminating dogwoods (*Cornus florida;* Campbell and Schlarbaum 1994), while beech scale (*Cryptococcus fagisuga;* also from Europe) is spreading beechbark disease, a European fungus (*Nectria coccinea faginata*) that arrived in Nova Scotia in 1890, reached the park by 1993, and is now ravaging beeches (*Fagus grandifolia;* Simmons 1999a). The Asian hemlock woolly adelgid (*Adelges tsugae*), a huge threat to forests dominated by hemlock (*Tsuga canadensis*) in the Northeast, is nearing the park after infesting 80% of hemlocks in Shenandoah National Park (Simmons 1999b).

In addition to ecosystemic effects, many introduced species affect particular native species or groups of them. Introduced species can eat natives, for example. The brown tree snake (*Boiga irregularis*) has eliminated virtually all forest birds of Guam after invading from the Admiralty Islands (Rodda et al. 1992), while the Nile perch (*Lates niloticus*) has extinguished over 100 species of native cichlid fishes in Lake Victoria (Goldschmidt 1996). Introduced herbivores can also eat natives to extinction: goats brought to St. Helena in 1513 quickly eliminated about half the native plant species, all of which were endemic (Groombridge 1992). Pathogens can heavily impact particular native species. The introduction of Asian songbirds to the Hawaiian Islands brought avian pox and avian malaria, facilitating the decline of native forest bird species (van Riper et al. 1986). Introduced species can also compete for resources with native species. For example, in Great Britain the North American gray squirrel (*Sciurus carolinensis*) is replacing the native red squirrel (*S. vulgaris*) by foraging more efficiently (Williamson 1996). Introduced species can directly affect native ones by attacking them, rather than indirectly by depleting their resources. This is how the South American red imported fire ant (*Solenopsis invicta*), which has spread throughout the southeastern United States and has now reached California, is replacing several native ant species (Tschinkel 1993). Allelopathy is a plant analog of aggression. Thus, for example, the African crystalline ice plant (*Mesembryanthemum crystallinum*) accumulates salt, which remains in the soil when the plant decomposes and thereby eliminates native plants (Vivrette and Muller 1977). Nonindigenous species also threaten the existence of native species, at least as distinct genetic entities, by mating with them. For example, both the New Zealand Gray Duck (*Anas superciliosa superciliosa*) and the Hawaiian Duck (*A. wyvilliana*) are threatened by hybridization and introgression with the introduced North American Mallard (*A. platyrhynchos;* references in Rhymer and Simberloff [1996]). Even when there is little or no gene flow, a species can be imperiled simply by loss of productive mating opportunities. The introduced brook trout (*Salvelinus fontinalis*) threatens native bull trout (*S. confluentus*) in this way in the western United States (Leary et al. 1993); hybrid individuals rarely backcross to either parental species.

Sometimes the actions of one introduced species worsen the impact of others (Simberloff and Von Holle 1999). For example, the zebra mussel, by its prodigious water filtration, increases water clarity and thus aids the invasion of several introduced macrophytes, such as Eurasian watermilfoil (*Myriophyllum spicatum*). The increased growth of the macrophytes, in turn, aids the mussel by providing settling substrate (MacIsaac 1996). In other instances, highly coevolved species (that alone would be innocuous) produce, in concert, a damaging invasion, as witness the sudden spread of exotic fig trees (*Ficus* spp.) from Miami into Everglades National Park after the arrival of obligatory fig wasp (Hymenoptera: Agaonidae) pollinators (Kauffman et al. 1991).

WHAT TO DO—POLICY

In an era when free trade is almost a religion and amounts of travel and cargo are rapidly increasing, it will be difficult to attempt to introduce impediments and barriers to movement of species. However, one of the most important policy arenas is the World Trade Organization (WTO). The WTO Agreement on the Application of Sanitary and Phytosanitary Measures states that all new trade items, trade routes, or transportation methods are acceptable until they are proven to be too risky. This is called the “presumption of admissibility.” The International Plant Protection Convention was revised to be in accord with the WTO Agreement in 1997.

The guiding philosophy of the WTO is that of a blacklist law. Anything may be imported unless it is on a blacklist of prohibited species. However, blacklist laws have never worked well to control introduced species (Simberloff 2000). It is difficult to get a species on a blacklist unless it has already caused damage, and by then it is usually too late because the great majority of established introductions are irrevocable. The WTO Appellate Body recently ruled against the Australian government in a salmon import case along these lines (Low 1999). The Appellate Body demands formal risk assessments and explicitly rejected scientific uncertainty about a risk as an adequate basis to preclude entry. However, risk assessments for introduced species are in their infancy, and there are several aspects of biology (such as evolution and autonomous dispersal) that make it extremely difficult to predict the trajectory of invasions (Simberloff and Alexander 1998). In other words, as a party to the WTO, if the United States wanted to adopt a broad ban such as, “no untreated wood or wood products unless the party proposing the import demonstrates no risk,” they could be turned down on the grounds that this is protectionism. An appeal would have to be based on a risk assessment that presently cannot be done well and may always have a huge margin of error. It is worth noting that wooden packing material is believed to be responsible for the recent arrival of the Asian long-horned beetle (*Anoplophora glabripennis*) in New York and Chicago.

What is needed is a change in philosophy, away from innocent until proven guilty. The WTO must recognize that the very nature of introduced species makes current risk assessments unreliable documents, that introductions are generally irrevocable once they are established, and that the harm some species can cause is not only staggering in economic terms but incalculable in ecological ones. The United States, of course, has enormous influence on the WTO, but the leadership will have to come from the top—the President and the federal trade representative. What is really needed is a combination of a white list law (Ruesink et al. 1995) and a blacklist law; certain products and species are so inherently dangerous that they should be prohibited under any circumstances, while others (the vast majority) must all be subjected to detailed expert examination before they are put on an approved white list. That is, a precautionary principle is needed for introduced species.

The Convention on Biodiversity, held in Rio de Janeiro in 1992, specifically called for preventing introduction of species (article 8h): each contracting party shall "as far as possible and as appropriate . . . prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats or species." The United States, unfortunately, has not yet ratified the Convention, but ca 180 nations have, and this United States shortcoming will probably be remedied some day. Another problem is that article 8h has never really been made an action item for the Conference of Parties to the Convention (Glowka and de Klemm 1996); but this is simply a matter of building international interest in the problem. An extremely promising development is the growth of the Global Invasive Species Program (GISP), a component of an international program on the science of biodiversity (DIVERSITAS). GISP is coordinated by the Scientific Committee on Problems of the Environment in conjunction with the International Union for the Conservation of Nature, the United Nations Environment Program, and Commonwealth Agricultural Bureau International. In the last 3 years, GISP has sponsored an increasing number of workshops on many aspects of the introduced species problem, with emphasis on practical matters such as exclusion and management (Mooney 1999). This degree of high-level international activity may help to shift the direction of the WTO and other multilateral organizations.

Within the United States, many of the same problems arise as one finds on the international scene. For example, it is quite difficult for states to exclude a species they think might be a risk (e.g., bait or game fish, biocontrol agents), as the U.S. Supreme Court has usually called such exclusion an infringement of interstate commerce and therefore unconstitutional. However, a species from one part of the United States, even a native, can be extremely damaging in other parts of the United States where it is nonindigenous. East coast cordgrass (*Spartina alterniflora*) is a huge problem on California and Washington beaches (Daehler and Strong 1996). On ecological grounds, it is illogical for a nation as large as the United States to act as if a species native to one region is native to all.

At the federal level, Executive Order 13112 of 3 February 1999 on introduced species is a promising start at bringing about major changes in the way the United States deals with invaders. Currently, we operate largely by federal blacklists, such as the Federal Noxious Weed List. Species not on a blacklist (the vast majority of all species) are generally permitted entry into the United States. The primary agency in the United States charged with governing import of species, the United States Department of Agriculture Animal and Plant Health Inspection Service, currently operates without clear guidance on what should be quarantined, and it has recently relaxed controls on immigration of woody plants. The aforementioned executive order, sections 2.2 and 2.3, enjoins all federal agencies to prevent the introduction of invasive species and not to authorize or carry out actions that it believes are likely to cause or promote the introduction of invasive species, unless it has determined that the benefits of such actions clearly outweigh the potential harm. It will be interesting to see how these injunctions affect the overall flow of living organisms into the United States.

Executive Order 13112 also sets up an Invasive Species Council of the federal agencies. This council took a long time to initiate work, but by July 2000 it had established its expert advisory committee and produced a draft of a comprehensive management plan. The council has the prestige and scope to do much that is needed. The executive order is explicit only about federal activities, demanding a report from the council on what they are and how to improve them within 18 months. It has only inspirational language with respect to the states, municipalities, and private property owners, who are every bit as crucial in this battle. However, the council could be instrumental in generating the necessary coordination.

Both exclusion and management of introduced species could be greatly improved by increased cooperation between various entities managing nonindigenous species. On the management side, there is insufficient overall prioritization, and many agencies lack sufficient tools even to predict which invaders are likely to be problems. The National Park Service has a ranking system for plants (Hiebert and Stubbendieck 1993), while the Nature Conservancy has another one (Randall et al. 1996), the State of Washington uses yet a 3rd (S. Reichard personal communication), which one of the largest horticulture firms in this country claims to use voluntarily (Klinkenborg 1999), and the Australian government uses yet another one (Pheloung 1995). For animals, there really are no comparable tools. There is little retrospective research on how any of these tools for plants is working. Until some order is brought to this area and the scope is expanded, there will be no consensus on what to worry about and what to ignore.

Much more cooperation is also needed. For instance, we cannot have a situation that occurred in July 1999 (Barnard 1999). The Oregon Department of Agriculture had been trying for years to control Scotch broom (*Cytisus scoparius*), a weed that infests over 6 million ha in western Oregon. They had tried backhoes, root wrenches, and herbicides with little success. Finally, they found what they considered a promising biological control: European beetle (*Bruchidius villosus*) that eats seeds of Scotch broom. By 1999 they had reared enough individuals for a field test. At 1 of 12 sites, they released 250 beetles. A few days later a road crew of the Bureau of Land Management ripped out the entire Scotch broom patch and killed all the beetles. This case is emblematic; in the information age, there can surely be better organization and cooperation. There has to be more readily accessible and comprehensive data on which species are where, what they are doing, and which agencies are doing what where (Ricciardi et al. 2000). Information on successful and unsuccessful management techniques should be much more widely disseminated.

The biggest improvement of all, from both national and international standpoints, must come from increased public pressure. The battle against invaders can be won. All techniques in use can be improved, and coordination will enhance success. The key is for the public to pressure policymakers to ensure creation of an improved legal and operational framework.

WHAT TO DO—MANAGEMENT

Both in the United States and worldwide, many invaders have been eradicated completely (Simberloff 1997, 2000). Most had inhabited only small areas (e.g., Asian wild rice [*Oryza rufipogon*] in a 0.1-ha area of Everglades National Park), but several were well established over wide ranges. For example, the African malaria mosquito (*Anopheles gambiae*) was eradicated from over 30,000 km^2 in northeastern Brazil (Davis and Garcia 1989). The probability of successful eradication is enhanced if a species is detected early in the invasion and eradication efforts begin quickly. However, such efficiency requires either great luck or a good monitoring program and a rapid response mechanism. Other factors conducive to successful eradication include a thorough understanding of the biology of the target organism, sufficient resources to carry the project to completion, and the regulatory power to enforce cooperation in such matters as quarantines.

If eradication fails or is not attempted, there are 4 basic control approaches, and for the first 3 there have been some striking successes, as well as crushing failures (Simberloff et al. 1997, Simberloff 2000). First, mechanical means as simple as hand-picking and as complicated as elaborate machinery can control certain species at acceptably low densities. Volunteer labor has frequently been used in such efforts, as has convict labor. Second, chemical means (i.e., herbicides, rodenticides, insecticides, etc.) are sometimes effective, although they are often controversial. Some early-generation pesticides had substantial nontarget impacts, including human health effects, and these problems have left a legacy of chemophobia in some circles (Williams 1997). Even though many current chemical controls have few if any nontarget impacts, there are other disadvantages. First, many are expensive, particularly if they are to be used routinely over large natural areas. Second, species evolve resistance to them, which both increases the cost and means that no chemical can be used in perpetuity.

The 3rd approach, biological control, is often seen as a green alternative to chemical control. In some instances it has worked superbly (e.g., the control of South American alligatorweed [*Alternanthera phyloxeroides*] in Florida by the flea-beetle *Agasicles hygrophila* [Center et al. 1997]), with the pest kept in check at a relatively constant low density in homeostatic fashion by its natural enemy. However, biological control has recently come under critical scrutiny. First, it usually does not work; that is, the target pest is usually not substantially reduced. However, about 3 times as many introduced biological control agents establish populations as effect substantial control (data in Williamson [1996]). Second, in some instances, biological control agents have attacked nontarget species, and they have even driven some to extinction (Simberloff and Stiling 1996, and references therein).

Finally, management of an entire ecosystem can sometimes create conditions inimical to introduced species but suitable for the natives. Consider the forests of the southeastern United States dominated by longleaf pine (*Pinus palustris*). These forests formerly extended over 28 million ha. Less than 600 ha of old growth remains, but there are substantial amounts of 2nd growth with varying degrees of similarity to the original forests. Longleaf pine forests are classical fire disclimaxes (Hermann 1993); they are maintained by cool, growing-season fires, usually every 2–5 years, and the longleaf pine itself, groundcover plants (often dominated by wiregrass [*Aristida* spp.]), and all other inhabitants are adapted to thrive in such a fire regime. It is striking that, when a natural fire regime is maintained, this community is barely invaded, even though the Southeast has more than its share of nonindigenous species. The red imported fire ant, though wreaking havoc in much of the Southeast (Tschinkel 1993), does not get into intact longleaf pine forest except along roads (McInnes 1994); a native fire ant (*S. geminata*) persists here, though the invader replaces it in other habitats. Similarly, the plant community notably lacks invaders. In the largest old-growth longleaf pine forest (80-ha Wade Tract in south Georgia), there are few introduced plants, though these are worrisome because nearby areas are increasingly converted to suburban housing with exotic landscaping. The groundcover of the Wade Tract has almost 400 species of native plants. There are about 11 nonindigenous plant species (S. Hermann personal communication), and almost all individuals are within 2 m of human disturbance, especially the old trails that dissect the fragment. There are approximately 22 other nonindigenous plants within 200 m of the Wade Tract, but they have not invaded. The apparent resistance to invasion probably has to do with the frequent fires that destroy the exotics except on the trails, which rarely burn. If a fire-adapted nonindigenous species such as Asian cogon grass (*Imperata cylindrica*) were to colonize this region, the Wade Tract might be invaded. However, to date, it seems as if the prescribed burns, more or less mimicking the natural fire regime, have controlled invasive species in this forest.

Ecosystem management, though adopted by virtually all federal agencies as the operative means of managing natural resources, has largely been a catch-phrase rather than a group of well-defined and tested techniques (Simberloff 1998). Whether longleaf pine forests are unusual in that a particular management tool (routine growing season fires) tends to maintain an entire ecosystem remains to be seen. There may be other communities that can be kept largely intact in the face of potential invaders by managing entire ecosystems.

Because it is the newest approach, ecosystem management is most in need of enhanced research. But all of the approaches—eradication plus mechanical, chemical, and biological control—could be greatly enhanced by substantial research. First, much management literature is very gray. Some management techniques are transmitted only verbally. Thus, wheels are probably continually reinvented, even some that failed to work the first time. Again, in an age of information transfer, this should not happen. As introduced species databases are improved and become increasingly user-friendly and compatible with one another (Simberloff 1999), it is important that management techniques and attempts be part of the easily accessible record. Second, much basic research is required on all management techniques. As I stated at the outset, all are characterized by some successes and some failures, and there is little doubt that percentages of the former can be increased by well-designed, traditional research.

CONCLUSIONS

An aura of hopelessness sometimes surrounds the issue of introduced species, as if an increasing flood of invaders is inevitable and our potential arsenal to limit their entry and impact is meagre (Quammen 1998). Although the battle to manage this problem adequately will be long and difficult, there are 2 reasons not to surrender. First, if the public gives up, many habitats will surely progressively drown in a sea of exotics, and much of the Earth, national parks included, will indeed become a "planet of weeds" (Quammen 1998). Second, many things can be done to improve the response to this assault. On the policy front, a shift from a blacklist philosophy to a combination of white lists and blacklists would drastically reduce the number of nonindigenous species that would actually invade any nation, and perhaps even parts of large nations. Coordination and cooperation on many fronts seem logistically feasible, if sufficient resources are devoted to this problem. Areas in which coordination would greatly improve the current situation are monitoring, risk assessments and prioritization procedures, rapid response teams, reporting of attempted management procedures, and availability of basic biological data on introduced species.

Further, various procedures already used for management could all be greatly improved. With increased monitoring, an appropriate rapid response mechanism, and technological improvements in methods of attack, a major increase could be achieved in the rate at which nonindigenous species are eradicated before they are widespread or even established. For established pests, although ecosystem management is probably most in need of substantial research as a tool to exclude exotics, the more traditional methods—mechanical, chemical, and biological control—could all be enhanced in terms of both efficacy in eliminating the target pests and minimization of nontarget impacts. In light of the striking successes that each of these methods (and combinations of them) has already achieved, with a relatively small research effort compared to that in, say, public health or pollution control, there is reason for optimism that major technological advances in all of them could make vast strides toward bringing the introduced species problem under control.

What will be required to achieve these improvements in policy and technology? Public pressure! As the public increasingly recognizes the terrible cost imposed by nonindigenous species, they will demand more effective action to do something about this problem. And when the public demands action, they will get it.

ACKNOWLEDGMENTS

Brian W. Smith and an anonymous referee made numerous suggestions that helped clarify the manuscript.

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Received 15 March 2000
Accepted 15 August 2000