ERADICATION AND CONTROL OF INVASIVE SPECIES

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Summary

Biologists are issuing dire warnings in response to the threat from nonindigenous species (NIS). According to the "tens rule," one introduced species in 10 appears in the wild, one in 10 of these become established, and one in 10 of established NIS becomes an invasive species. Invasive species have dramatic effects on native populations, species, communities, and ecosystems, and provoke heavy economic costs. As claimed by invasion biologists, any intervention towards NIS requires (a) preventing the introduction of NIS; (b) when prevention is not possible, fast detection of NIS; (c) assessing the overall "danger" of the NIS; and, (d) when NIS have been proven to be "dangerous," choosing one management option along a gradient of possible interventions. As far as (d) is concerned, questions are addressed to understand the best measure to undertake, as well as to predict the cons and pros of any program of intervention and the potential of its success. All these questions can be answered only when the adopted strategy has been passed through a thorough process of "situationalization." Conflicts of interest between the public and researchers/managers are expected, conflict resolution being an integral component of invasive species management.

The difference between eradication and control is only one of grade; these two strategies are part of a gradient of interventions and both share the purpose of annulling or (if not feasible) mitigating the impact exerted by invasive species. The methods used are practically the same: (a) mechanical removal of invasive species from an area; (b) construction of barriers to prevent their spread; (c) reduction of their population size by using biological means; or (d) by using biocides; or (e) by having recourse to autocidal approaches; and (f) habitat management. Eradication, that is the removal of every potentially reproducing individual of a species from an area where this behaves as

invasive or the reduction of its population density below sustainable levels, is the best management option, since it removes the need for further control and ongoing financial and environmental costs. However, eradication is likely to be successful only in the earliest stages of an invasion, or in "island" systems of manageable size. Before starting any eradication program, managers should be fully aware that (a) adequate funds and commitment exist to complete the eradication, (b) monitoring of the population size is feasible, and (c) eradication will be followed by the restoration or management of the community or ecosystem resulting from the removal of a "keystone" target species.

Apart from a few cases, a disproportionate amount of money has been spent on the intervention by itself, compared to what was spent on the studies of both the biology and ecology of the target species and the efficacy of the treatment. To the contrary, every intervention should be viewed as an ecological experiment, future and ongoing programs providing excellent research opportunities for ecologists to study the roles of species in communities, the impact of NIS, and the behavior and population dynamics of exotics for which eradication is being considered. This knowledge should be the necessary baseline in the design of new and more appropriate strategies that, through a constant interchange of opinions and an integration of experience between scientists and managers, would lead to their situationalization, with the development of a four-level protocol of intervention aiming at defining the danger of NIS in terms of impacts on agricultural productivity and environmental damage, determining objectives and performance indicators, identifying and evaluating management options, and implementing, monitoring, and evaluating the management program.

1. Invaders and Monsters

“Man did not weave the web of life,
he is merely a strand in it. Whatever
he does to the web, he does to himself.”
—Chief Seattle 1852

After Elton’s prediction of "huge changes in the natural populations balance of the world," several researchers maintain that humanity's continued role in biological introductions may cause irreversible changes to Earth's biota in a relatively short time. At present, 100–10 000 species per year have been estimated to be either unintentionally or purposively introduced into non-native countries by humans. Although undertaken to solve some local problems, intentional introductions may ultimately lead to the Frankenstein Effect; that is, attempts to improve nature may turn out to be a monster. If we believe to "tens rule," one introduced species in 10 appears in the wild, one in 10 of these become established, and one in 10 of established nonindigenous species (NIS) becomes an invader. And invasive species have dramatic effects on native populations, species, communities, and ecosystems. They also provoke heavy economic costs, due to the effects directly and indirectly exerted on the invaded habitats (e.g., in the American Great Lakes, US$3.1 billion are spent every 10 years to clear blocked intake pipes by the invasive bivalve *Dreissena polymorpha*). In addition, under a long-term perspective, economic resources are required to help affected ecosystems return to their “underlying element of organization and constancy.”

In response to the threat from introduced species, biologists are issuing dire warnings. Popular science writers, environmentalists, and several ecologists have vilified NIS, defining them "malignancies in the environment." Edward O. Wilson speaks of introduced species as "the stealth destroyers of the American environment." NIS were seen part of the "Evil Quartet" by Diamond, as main agents of recent extinctions. It has been claimed that NIS "are likely to rise progressively to the most widespread and dominant proportion of terrestrial biota." Many biologists define the introduction of NIS as biological pollution, components of global environmental changes—perhaps even more significant than global warming, causes of the Macdonaldization of the biosphere or of a global McEcosystems.

One exemplification of the dramatic effects of NIS on the invaded habitat and of their monstrous nature has been provided by Shrader-Frechette in the paradigmatic case of *Melaleuca quinquenervia*. "When this thirsty, fast-growing tree was first imported from Australia to drink up the swamps of south Florida, nurserymen of the 1930s could not grow enough to satisfy demand. Foresters seeded the Everglades with melaleuca dumped from airplanes. Less than a century later this NIS has invaded more than 600 000 ha of Florida wetland, and it threatens to destroy the Everglades. Its impenetrable stands displace virtually all other vegetation, and its dense root mat oozes substances poisonous to other plants. Its airborne secretions are poisonous to humans and cause severe respiratory and skin irritation. Conservationists have tried to burn it out, but it is fire adapted and spreads by burning. Its inner bark is a wet, insulating sponge, while its outer bark is dry, and its leaves are laced with a flammable oil. Although it sucks up water four times as fast as the native sawgrass, it burns with explosive force. Several days after a devastating fire, the tree sprouts new growth and rains millions of seeds onto burn land. They germinate in only three days, and seedlings may reach six feet in their first year."

2. A History of Introductions: Australia and New Zealand

The development of ocean-going ships in the 15th century initiated several centuries of exploration and colonization in all parts of the world by the major European countries. Traditionally, explorers and their immediate successors, who in the Southern Hemisphere were whalers and sealers, deliberately released rabbits and goats on oceanic islands to provide a food source for shipwrecked mariners, and, unintentionally, often introduced rodents and pet animals, such as cats and dogs. The last countries to be colonized were those most distant from Europe: Australia in 1788, and New Zealand in 1840.

The colonizers from Britain found two different but alien environments, populated by Polynesians in New Zealand and by primitive hunter-gatherers, the Australian Aborigines, in Australia, each living in country dominated by trees, shrubs, grasses, animals, and birds of types unknown anywhere else in the world. The early settlers brought their domestic animals and plants with them, initially to produce food for their sustenance. Once settlement had been firmly established, they arranged for other animals and plants with which they were familiar to be brought out, so that they could establish at least a domestic environment in which they would feel more comfortable. With increasing affluence, the more prosperous colonists wished to introduce field sports such as fox hunting, rabbit shoots, and deer hunting. Deer were imported into Sydney in 1803, and deer, partridges, and hares into Tasmania by 1830. Rabbits were introduced with other domestic animals in 1788, but they did not become common until the importation of wild rabbits from England in 1859. To further foster such introductions, Acclimatization Societies were established in Australia and New Zealand, and in both countries these societies enjoyed widespread support, especially from the more prosperous colonists.

Acclimatization Societies were also founded in several European countries, stimulated by curiosity about exotic species and the possibility of the commercial exploitation of new plants and animals. The first Acclimatization Society in the world was set up in Paris in 1854, subscribers including no less than 14 crowned heads and almost all of the nobility of Europe. A similar society was set up in London in October 1860, stimulated by a letter to the Times by Edward Wilson of Melbourne. Many European wild animals, including rabbits, foxes, and deer, and several plants, including prickly pear, were already established in Australia when the Acclimatization Society of Victoria was established in 1862, with Wilson as president. Similar societies were set up in New South Wales, Queensland, and South Australia soon afterwards, and they organized a wide range of importations.

In New Zealand, legislative acts were passed by the Colonial Parliament in 1861 “to encourage the importation of these animals and birds, not native to New Zealand, which would contribute to the pleasure and profit of the inhabitants, when they became acclimatized and spread over the country in sufficient numbers." In 1867, provision was made for the registration of Acclimatization Societies at the Colonial Secretary’s office, and, by the early years of the 20th century, 48 species of mammals and 30 species of birds had been introduced into New Zealand. One prominent reason for these introductions was their value for sport, at least for 45% of the mammals introduced.

By far, the largest part of species introduced under the patronage of the Acclimatization Societies were garden plants. Some spread outside of gardens and several have become major pests in forests and farmlands, for example the shrubs *Lantana* (from South America) in Queensland and *Pyracantha* (from Europe) in parts of New South Wales. The same happened in Europe, with some species of *Eucalyptus* (from Australia), and in South Africa with *Acacia* and *Hakea* (from Australia).

Freed from the pressure of competitors, predators, and disease, in Australia and New Zealand, respectively, 16 and 25 mammals introduced by these Societies are at present invasive species, such as rabbits, foxes, rats, mice, cats, goats, pigs, and horses, as well as in some areas red deer and camels in Australia; and opossums (from Australia) and rabbits, rats, red deer, cats, goats, pigs, stoats, and weasels (mainly from England) in New Zealand. Of all of these, in the 1860s the European rabbit was by far the most important invasive species in both Australia and New Zealand. In southern Australia, rabbits encountered a favorable climate, a country with few effective native predators, and an ecological niche occupied by a variety of small marsupials, none of which could match the reproductive capacity or the aggressive behavior of the rabbit. In New Zealand, there were no predators and their only ecological competitors were flightless birds.

3. Towards a Management of Biological Invasions: The Rise of a New Discipline

Since Elton's (1958) pioneer *The Ecology of Invasions by Animals and Plants*, nearly 40 years of latency were necessary to stimulate the rise of invasion biology as a scientific discipline. Williamson's *Biological Invasions*, published in 1996, represented the manifesto of the new discipline; this book took the credit of catalyzing the explosive development of researches having broad scopes. Invasion biologists ranged in their objectives from the discussion of theories and concepts to the proposal of practical recommendations in matter of management strategies.

In 2001, epistemological and conceptual reasons were set forth by Shrader-Frechette to argue that invasion biology has not yet formulated a comprehensive, predictive "theory of invasibility" that might guide ecological decision-making regarding NIS. Above all, no firm, empirical generalizations were provided to reveal when a colonizer might be likely to take over a new environment, and when it might succeed in doing so. Invasion theory, Shrader-Frechette claims, is full of rules of thumb such as "nonindigenous species are likely to become invasive and out-compete natives, as evidenced by the degree to which NIS are implicated as a major cause of extinctions," or "all things being equal, NIS will be successful colonizers if they have high dispersal rates, or large native ranges, or a broad diet." Because these statements do not have precise predictive power, it is impossible to use them to guide reliable public policy. To the contrary, the latter objective can be fulfilled when, in addition to a top-down account of ecological explanation, a bottom-up approach is followed to obtain detailed natural-history information and to formulate precise and clear empirical generalizations.

Notwithstanding the correctness of at least part of this criticism and the recognition that the interest of invasion biologists was mainly concentrated on theoretical issues, since its rise, invasion biology has been ready both to suggest strategies to manage invasive species and to provide cost/benefit analyses for their application.

Thus, as recurrently claimed by invasion biologists, any intervention towards NIS requires acting as follows:

- prevent the introduction of NIS;
- when prevention is not possible, detect NIS quickly;
- assess (a) their rate of invasiveness and (b) their impact on native populations, species, communities, and ecosystems, that is, their overall "danger"; and
- when NIS have been proved to be "dangerous," behave by choosing one management option along a gradient of possible interventions that comprises their eradication or control.

First, it is imperative to prevent further spread of NIS. This endeavor includes many different actions, ranging from legislation to cooperation among authorities and coordination of their actions to the re-establishment of native species and habitats and the increase of public knowledge and awareness. The importance of prevention is well expressed in President Clinton's mandate (February 1999) to the Congress of the United States for the development of an Invasive Species Management Plan in the USA, emphasizing in the Executive Order 13112 the severity of the economic, human health, and ecological threats posed by NIS. The plan reviewed the anthropogenic vectors of species and recommended measures to minimize future introductions.

The first line of defense against invading species is detection. In the USA, the federal government maintains inspection services at ports of entry throughout the states. In California, there are border stations on all major highways entering the state. Workers have a list of various undesirable species that they look for or they confiscate certain plant material, fruit, or anything that might be infested. Certainly these procedures discourage the public from trying to bring potentially infested material into the state, but the question is, “What percentage of the material is caught at the borders or the ports of entry and is this costly exercise economically justified?” Detection of invaders by using pheromones or chemical attractants is a rapidly developing field in applied entomology. Early detection, although important, perhaps could also lead to many more eradication programs for some species that could never become established. In the case of insects, there is an increasing tendency to initiate an eradication program based on the trapping of adults alone; however, it is important in many cases that a second life stage (eggs, larvae, or pupae) is found before initiating a program that may not be necessary.

Although prevention and detection are crucial steps to halting the spread of NIS at its beginning, the main objective of this essay is to discuss those measures adopted to manage NIS, with constant reference to the problems encountered in assessing their dangers. Questions are addressed to understand the best measure to undertake, as well as simultaneously to predict the pros and cons of any program of intervention and the potential of its success. All these questions can be correctly answered only when an in-depth knowledge of the ecological and human context has been achieved, that is when the adopted strategy has been passed through a thorough process of "situationalization" (Section 5.1).

4. When is an Organism "Dangerous"?

4.1. Definition of Pests: An Anthropocentric View

The word pest is derived from the Latin *pestis*, which means plague, and usually refers to a troublesome or destructive animal. Pest plants, plants that grow where they are not wanted, are usually called weeds, whereas destructive microorganisms and fungi are generally called parasites.

At its conceiving, the idea that an organism is a pest was anthropocentric; a living thing was regarded as a pest if it was of trouble to humans. This idea dates from the agricultural revolution, when animals that were not dangerous, such as locusts, caterpillars, rats, and mice, were viewed as pests because of their numbers and their interference with crops and stored food. Only during recent decades, with the increase in environmental awareness, has the definition of pests been enlarged to include microorganisms, fungi, plants, and animals that threaten ecological equilibria and biodiversity.

Nevertheless, at this writing, the definitions of which particular organisms are pests or weeds depend on the interest of the observer and still appear human-centered. With the development of agriculture some 10 000 years ago, humankind's major pest became, and remain, animals that feed on or otherwise damage our crops: vertebrates such as rabbits, rats, mice, and large herbivores, and invertebrates such as insects and helminths. Many insects are defined as pests because they carry viruses or protozoa that cause infectious diseases to humans, domestic animals, and plants, as well as insects that are persistent and annoying, like mosquitoes and flies. The major weeds are plant species that compete with pasture or garden plants, or foreign plants that spread into native woodlands or savanna.

The way in which perceptions of a pest change with changing circumstances, referring to indigenous species and NIS, is well illustrated by a study of the occupation by Europeans of the Bega district, on the south coast of New South Wales. Now a dairying district, the area was occupied by a few hundred Aboriginals before the European settlement began in the 1830s. The new settlers used river flats for grazing cattle and sheep for meat and wool production; then the forests were cleared and cattle numbers were greatly increased. Initially, native animals such as opossums, bandicoots, and various macropods were viewed as the most important pests, and between 1880 and 1898 bounties were paid for their scalps. European hares, introduced into Australia in 1859, reached the Bega district in the 1880s and in the early 20th century they briefly peaked at "super-plague" levels. Rabbits were first seen in the district around 1900 and by 1910 they had reached super-plague levels, replacing hares as the major vertebrate pest. Here, pests are judged in function of the damages produced to humans, and never related to the damages produced to the ecosystems.

4.2. Not all Pests are Nonindigenous Species: The Red Deer and the Grey Seal

Many of the most serious pest problems have followed the human introduction of NIS, but every country has indigenous species that are at some time regarded as pests or weeds.

One case is the red deer. In recent years, throughout the Northern Hemisphere deer have been increasing in numbers. Red deer on open moorland in Scotland, for example, have doubled their numbers to 300,000 in the past 20 years. At a density of 15 deer per square kilometer, browsing deer begin to damage the Sitka spruce, the most important tree in commercial plantations. Red deer damage spruce in two ways: they either strip the bark or browse the leaves. Researchers found that less than 1% of the trees they monitored had been stripped of bark, and many of these trees were poor specimens. When they looked at damage caused by browsing, they discovered that deer preferred smaller trees of ~40–55 cm; at ~80 cm, Sitka spruce is safe from deer; although no one knows why, because deer can browse much higher. Deer do most damage during a three-week period as the buds burst. At that time, spruce is an important source of food. Trees need protection until they are past the critical height.

A second case is the grey seal (*Halichoerus grypus*). Because of overhunting, by 1900, seals were so few in the seas around Britain that in 1914 the government passed the Grey Seals Act to protect them. This worked so well that by the late 1950s the fishing industry wanted controls to keep the population of seals down. At the same time, there was an increase in infestations of parasitic cod worm in fish. Although the worm does not become a parasite in humans, it spoils the look of fish so that it cannot be sold for human consumption. Grey seals are an intermediate host for the parasite and many fishermen blame the seals for the increased parasitism of cod. In recent years, the number of seals has continued to increase, but infestations of cod worm have leveled off. Another reason for complaints of fishermen against the grey seal is that each seal eats ~5 kg of fish a day. A population of nearly 100 000 grey seals can eat almost 200 000 tons a year. Many people argue that this is a direct loss to the fishing industry. But seals usually eat species of fish that are commercially unimportant. In the North Sea, for example, sand eels form 60% of a grey seal's diet. Thus, killing seals does not necessarily mean that more fish will be available to the fisheries.

Because the word "pest" (as well as "weed") is ambiguous in its definition and has still a strong anthropocentric connotation, and because our interest here is mostly directed to the damages that species inflict on native populations, species, communities, and ecosystems more than to human activities, hereafter we will avoid this term and simply refer to invasive species (and mostly to NIS).

4.3. How Do We Assess the Impact of Invasive Species?

A surprising amount of disagreement has often been observed among invasion biologists over the magnitude of impact caused by even the most celebrated invasions. For example, it is an undisputed fact that the invasion of the chestnut blight fungus (*Cryphonectria parasitica*) decimated populations of its hosts over millions of hectares. However, ecologists disagree over whether or not that invasion had a biologically significant impact on the deciduous forest of eastern North America, as a whole.

Despite the considerable attention several invasive species receive, the paucity of data on impacts leaves us largely ignorant about the ecological changes they have brought about. Considering, for example, that ~5000 plant species are naturalized in the USA, of which at least 10% are seriously invasive, quantitative evidence for potential changes in ecosystem processes and species diversity is missing for most of these species. Most of the available information involves more easily obtainable data on ecosystem processes. Information is provided on changes of fire regimes (*Bromus tectorum*), alterations of biogeochemical cycling (*Tamarix* sp.), alterations of geomorphological processes (*Ammophila arenaria*), changes in hydrological cycles (*Melaleuca quinquenervia*), prevention of recruitment or reproduction of native species (*Lonicera japonica*, *Casuarina equisetifolia*), hybridization with native species (*Spartina alterniflora*), and concerns over human health effects. Quantitative data on these species' impacts on biotic communities are totally missing and, when provided, still anecdotal.

This inability to agree on the impact of historical invasions and the scarce data available on the impact of extensively studied species reflect the lack of any common framework for quantifying or comparing the overall impacts of invasive species. This dilemma represents more than an esoteric academic issue, because there is an urgency to rank invasive species in order to prioritize management efforts. Thus, shared questions, use of standardized methods, and communal efforts in building up a catalogue of data are required to coordinate and improve both control and research efforts for existing

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Biographical Sketches

Claudia Angiolini was born in Gallarate (Italy) in 1974. She graduated in Biological Sciences at the University of Varese in 2000 with a thesis about the ecology of two species of lizards in a heathland to the south of Malpensa airport. She started apprenticeship (six mouths) with Dr. Gherardi and Dr. Corti at the University of Florence in 2001. Now she is working to take a specialization in the Department of Animal Biology and Genetics, University of Florence.

Dr Francesca Gherardi teaches Zoology, Conservation Biology, and Applied Ethology at the University of Florence (Italy). She received her PhD in Animal Biology in 1987 and is currently a permanent researcher at the Department of Animal Biology and Genetics "Leo Pardi". Dr Gherardi is actively involved as a referee for more than 30 international journals. She is associate editor of the *Journal of Crustacean Biology* (USA), Ethology, Ecology, and Evaluation (Italy), and Biological Invasions (The Netherlands). She has been also editor of Crayfish in Europe as Alien Species. How to Make the Best of a

Bad Situation? (A. A. Balkema, Rotterdam, 1999) and of Biological Invasions in Inland Waters (Springer, The Netherlands, 2007). Dr Gherardi has coordinated six international workshops and held more than 100 presentations at international and national meetings and conventions. She directed or participated in scientific in scientific expeditions abroad, in particular in: East Africa (Somalia and Kenya), South Africa, Indian Ocean, Israel, USA, Western Australia, and Europe. In Italy, she worked at the Stazione Zoologica "A. Dohrn" in Naples. She has been the President of the International Association of Astacology (2004-2006) and a member of five other societies, including the American Association for the Advancement of Science and the Crustacean Society. She worked as summer Fellow at the MBL at Woods Hole in 2003-04 and as Visiting Scholar at the Columbia University in the City of New York in 2006-07. Dr Gherardi is the author or co-author of more than 140 scientific articles published in peer reviewed international journals, more than half devoted to problems of biodiversity conservation; she is also the author of eight reports commissioned by public administrations. She has participated in six EU projects, and in projects funded by NATO and by the Australian Nature Heritage. Dr Gherardi is currently a partner of the EU project "Environmental impacts of invasive alien species in aquaculture (IMPASSE)" and acts as supervisor for projects funded by the Ministry of University, the Ministry of Agriculture, and local administrations.