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 ten appears in the wild, one in ten of these become established, and one in ten 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 proved 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) decreasing 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 purposely 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 ten appears in the wild, one in ten of these become established, and one in ten 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 fifteenth 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, they 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 fourteen 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 twentieth 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 to both suggest strategies to manage invasive species and 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) be 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 understanding the best measure to undertake, as well as simultaneously predicting 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 has 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 the carry viruses or protoza 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 twentieth 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 process. 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’ impact 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
invaders, and to elaborate a general framework for predicting the impacts of future introductions.

From this perspective, at least five questions need to be addressed that are both important within an applied issue and fascinating from the scientific point of view. a) Do impacts on single populations adequately predict the response of community measures of diversity? That is, are there useful bioindicators for invasion impact? b) Do impacts assessed via simple composite measures such as species richness capture the more complex picture of community change that can be obtained by multivariate methods? c) How closely correlated are impacts on population characteristics with impacts on ecosystem functions? Do changes in the community drive changes in ecosystem function, or vice versa? d) Are invaders with large effect those that have large ranges, or that spread rapidly, or that develop the greatest abundance or collective biomass? How closely correlated are ecological impacts as traditionally measured? How well do ecological impacts correlate with economic impacts? e) To what extent does the quantitative measure of the impact of an invasive species depend on the community or ecosystem in which it is measured? On what level can we generalize across systems? How often does the impact of an invader depend on the presence of other NIS (the "Invasional Meltdown Hypothesis")?

4.4. Conflicts in Invasive Species Management

The attitude demonstrated towards purple loosestrife (*Lythrum salicaria*) highlights a variety of conflicts in invasive species management. This species, introduced to North America around 1800, slowly spread through the Northeast, became a valuable ornamental, and was widely distributed by beekeepers and horticulturists; now it occurs in all lower 48 states of the USA and was declared noxious in at least 15 states, which prohibit sale and growth.

Its detrimental impacts on wetland flora and fauna are manifold and this species is listed as one of the "dirty dozen" invasive species by the Nature Conservancy. Specialized marsh birds (Black Terns, Least Bittern, American Bittern, Long-billed Marsh Wren), of special management concern to the U.S. Fish and Wildlife Service because of declining populations, do not nest in purple loosestrife. In addition, encroachment by *L. salicaria* is suspected to reduce the available habitat and recruitment of a number of duck species, Canada Goose, and Sandhill Cranes. Furthermore, negative impacts are suspected for two rare plant species, as well as for the bog turtle, muskrat, and mink, as the result of loss of favorable habitats due to the purple loosestrife invasion. Experiments confirm field observations of local extinction of cattails for the latter competition with *L. salicaria*. Possibly, the success of *L. salicaria* depends on the increase in leaf area, resulting in increased evapotranspiration rates in mixed stands during early stages of its invasion of a cattail stand, drier conditions thus favoring the invasive species. Indications that such a situation can be reversed come from observations during the successful control of purple loosestrife by leaf beetles in a wetland in upstate New York. As *L. salicaria* was suppressed, the remaining cattails increased in height and density, the site became flooded again and muskrats returned. In addition, as a result of the replacement of cattails by purple loosestrife, changes in
decomposition rates and sediment chemistry occur which may have important impacts to the invaded system or to wetlands downstream.

As opposed to these observations and experiments that support an intervention to control this species, initiatives against *L. salicaria* have been strongly criticized by public opinion and the media, claiming a lack of robust evidence demonstrating the negative ecological impacts of this species and its use by native species. In fact, a number of generalist bird and insect species were found on purple loosestrife, leopard frogs may breed in flooded *L. salicaria*, and white-tailed deer and muskrats occasionally feed on its shoot tips. Ninety-four different indigenous insect species (excluding nectar feeders) are reported to feed on this species.

Conflicts of interest between the public on one side and researchers/managers on the other are thus to be expected; conflict resolution should be an integral component of invasive species management, should be based on factual—and not anecdotal—evidence, but however requires taking into account the main objections raised towards the battle against NIS. The potential risks associated with any intervention against invasive species will be discussed in Section 5.3. Objections can be of an economic, ecological, aesthetic, and ethical nature.

Referring to the invasive plants in US, most were intentionally introduced for their aesthetic value and sale as garden ornamentals. The Soil Conservation Service (now the Natural Resource Conservation Service, NRCS) has introduced and distributed species such as kudzu (*Peria lobata*) to prevent soil erosion and multiflora rose (*Rosa multiflora*) as windbreaks. More esoteric uses involve reeds in musical instruments made from *Arundo donax*, antidepressant effects of *Hypericum perforatum*, or garlic mustard leaves as salad ingredient. Although the latter uses may represent a true (albeit small) economic value, they usually are of minor importance and alternatives are available. More persistent have been claims by beekeepers to safeguard prolific honey producers such as saltcedar or purple loosestrife. Other arguments involve the potential value of introduced plants for game species, native insects or birds and their use as food by indigenous herbivores.

The economic reasoning in favor of invasive species is more stringent when these are considered as food or recreational resources by some sectors of society (e.g., pigs in Hawaii, Himalayan tahr in New Zealand, guava in Mauritius). In such circumstances, management options may include harvesting for a sustained yield in certain areas. For hunted wildlife, this will involve reducing and holding the population below its carrying capacity and can result in benefits to native species that are able to coexist with moderate densities of the invasive species.

Finally, it is not surprising that efforts to manage invasives, especially when target species were vertebrates, have been the subject for confrontations with advocates of animal rights; even the legendary eradication of coypu from East Anglia, as described in Section 6.3, faced such objections. Several management actions are often seen to be not feasible, too expensive, and perceived to have horrendous nontarget impacts. On the other hand, if we look at the opposing attitude of puristic conservationists to always fight against nonindigenous, foreign species whatever they are, because some species
are long-established members of equilibrate communities, the suggestion is raised to give them an unlimited "permit of residence" and to protect them.

5. A Gradient of Interventions to Manage Invasive Species

5.1. Eradication and Control: Two Opposing Strategies of Managing Invasive Species?

The specific literature on the management of invasive species underlines that the proponents of eradication and those proposing control sharply diverge in their philosophical attitude. Literally, to eradicate a species means to tear it out by its roots; its more widespread definition 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.” In applied entomology, eradication has a number of different meanings, the most realistic being: “the destruction of every individual of a species from an area surrounded by naturally occurring or human-made barriers sufficiently effective to prevent reinvasion of the area except through the intervention of humans.” Control is viewed as distinct from eradication in that it seems likely to be a perpetual activity and hence its aims are judged differently. Thus, on one hand, the idea of totally eliminating a noxious species from an invaded area has had great appeal to the invader-control profession: the apparent simplicity of removing the problem completely and not having to worry about the future seems a panacea, while perpetual half-hearted and ill-focused control efforts are likely to be a waste of time and resources. On the other hand, some managers consider this feeling totally unrealistic and sometimes dangerous.

Within the framework of invasion biology, our belief is that 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 amnulling or (if that isn't feasible) decreasing the impact exerted by invasive species on native populations, species, communities, and ecosystems. In both cases, the need is felt to scientifically evaluate the situations for which the intervention is biologically feasible, as well as acceptable under ecological, economical, political, and ethical viewpoints (what we call "situationalization"). The methods used to contrast invasive species are practically the same and both necessitate respecting the same criteria in order to avoid undesirable damages to nontarget organisms.

Both require an estimate of the area where the program has to be carried out, whether over thousands of hectares or restricted to localized sites. Large-scale projects have greater potential for nontarget impacts and, consequently, tend to be more costly and controversial, while programs to be developed in urban areas usually elicit protests by residents. A preliminary evaluation of costs and benefits of programs are in both cases necessary, and an evaluation must be done of their potential success. Some of the unanticipated costs might include expenses for public meetings required to alleviate the fears of the residents of the interested areas, and for public-relations campaigns to convince taxpayers of the need for increased taxation to support expensive programs. Also, lawsuits following property damage might incur additional costs. Benefits are
often hard to estimate if the potential impact of invaders is difficult to predict and if the
time to reintroduction is impossible to anticipate.

One main difficulty encountered, particularly within control strategies, is to establish
the threshold density of the invader at which the benefit of control equals its costs. Actually, the relationship between invasive-species density and impact is often not
known, as shown in Section 4.3, and even if attempts are made to establish it, it may be
highly complex. For example, invasive-species impact may vary with seasonal
conditions, or it may be that only a small proportion of the population is causing the
impact. The other difficulty is that damage has usually not been quantified, which
makes it difficult to determine the extent of control required. For these reasons, it would
be more reasonable that control targets should not be set in terms of number of
individuals of the invasive species to be removed, or area treated, but instead in terms of
measurable response in the native species or ecosystems which the control aims to
benefit.

5.2. A Classification of the Methods Used Against Invasive Species

Several and diversified methods have been used through the years within programs of
eradication and control of invasive species. We can tentatively classify these,
distinguishing the initiatives as follows: mechanical removal of invasive species from
an area; construction of "barriers" to prevent their spread; reduction of their population
size by using biological means; or by using biocides; or by having recourse to autocidal
approaches; and habitat management.

5.2.1. Mechanical Removal

Rather than attempting to eliminate the whole species, the mechanical removal of an
invasive species over an area can decrease long-term control in that area. The initial
program can be expensive and requires the cooperation of land owners and/or agencies.
In the USA, trapping a nuisance population of the crayfish *Orconectes rusticus*
suppressed the population in the area under concern, but subsequent control of
recolonization was not feasible. One success of this technique is exemplified in the case
of the sabellid polychaete worm, *Terebrasabella heterouncinata*. The sabellid worm
was accidentally imported into California with South African abalone in the 1980s, and
by 1995 it had become established at Cayucos, California. The worms encrust abalone
and other native gastropods. In this case, an army of volunteers removed 1.6 million
large (>10 mm) parasitized gastropods from the infested area. Little negative
environmental impact resulted after this program, because the pelagic larvae of the
native gastropods ensured the rapid recolonization of the area. No new infections of
sentinel snails were observed over two years of observation following the removal
program and further spread of the worms from the mariculture facility was prevented by
screening the outflow and eliminating the dumping of shell debris into the intertidal
area.
5.2.2. Constructing Barriers

The spread of an invasive species may be decreased or prevented by constructing and maintaining a barrier zone. Animals that can be noxious to humans and human activities are often kept out of the areas of interest by fencing (if they are large), by netting (if they are small), and by screening (in the case of insects). On a larger scale, "barrier fences" have been erected to prevent the movement of vertebrate invaders from one region to another. In the late nineteenth and in early twentieth centuries, long "rabbit-proof" fences were erected between and within several Australian states in an endeavor to stop the migration of rabbits from one part of Australia to another. They failed with rabbits, but the same or similar fences are still in use in some parts of Australia to control the movement of dingoes (the Australian wild dogs). Other barriers are national or international laws that have been formulated to prevent the spread of invasive species by declaring them officially noxious, and making it illegal to sell, keep, or cultivate them. Where such legislation is impossible to institute and enforce, the listing of undesirable species, education about the threats which they pose, and voluntary withdrawal from sale by nurseries and pet shops (for example) can reduce the risk of spread. Notwithstanding, at least in the case of crayfish, no matter that legislation is in a place: illegal introductions are very difficult to halt, often being made by anglers or those with an interest in harvesting crayfish for profit. For example, in Britain “no-go” areas have been legally established against the three commonest nonindigenous crayfish (Pacifastacus leniusculus, Astacus leptodactylus, and Astacus astacus), but these are still diffusing throughout the country.

5.2.3. Biological Control

Biological control (or biocontrol) is a collective term that includes a wide range of interventions aimed at reducing the population density of invasive species. It is characterized by the use of biotic agents that are the natural enemies of the invader. Risks lie in that these enemies are not always specific to the organism that has to be controlled and may attack useful organisms, thus the intervention would result in "fighting fire with fire"; there are numerous example of mistakes, including the introduction of the Indian Myna (Acridotheres tristis) for the control of army worms in Hawaii, the Indian mongoose (Herpestes auropunctatus) for rats in Puerto Rico and Hawaii, the giant toad (Bufo marinus) for ground insects in sugarcane plantations in Queensland. Provided its specificity for the invader, the advantages of biological control are several: it is the only method practicable in national parks, rangelands, and forests; the control organisms are usually self-perpetuating; the land-tenure arrangements pose no problems and societal patterns are unaffected; and the benefit/cost ratio is usually high compared with other methods. Although a sharp distinction between the three categories as follows may be often difficult, natural enemies of invaders can be classified into parasites (or parasitoids in the case of insect invaders), predators, and pathogens.

A classic model of a parasite used against invasive species is Cactoblastis cactorum, which, in Australia, was released for the control of prickly pear. Predators have been used from time immemorial to control small vertebrates, not necessarily invaders but animals that are generally noxious to humans (dogs against wolves and other large
carnivores, cats against rats and mice). Pathogens, such as microbes, can control population numbers in invaders as lethal agents, as agents that reduce fertility, and as vectors for immunocontraception; *Salmonella spp.* was used for the control of rodents; myxoma virus and rabbit haemorrhagic disease virus for the control of rabbits; swine-specific viruses such as hog cholera virus for the control of feral pigs.

A further biological method is the use of microbial insecticides, such as that produced from the bacterium *Bacillus thuringensis* (Bt). This microorganism occurs naturally in the soil and on the surface of leaves. At sporulation, the bacterium forms a toxic protein crystal, which can be used as an insecticide. The toxin produced by one strain, Btk, is specific to Lepidoptera; the gene for the Bt toxin has been genetically engineered into several major crops, including maize and cotton.

It is difficult to get an estimate of the percentage of successes out of the number of attempts at releasing natural enemies. In part this is due to poor record keeping, but it is also due to inadequate sampling and evaluation procedures. This is often a result of the length of time necessary for the establishment and buildup of the natural enemies. By 1971, biological control had been attempted against 223 species of insects and some degree of success had been recorded for over half of these species. In the Coccoidea (scale, mealybugs, etc.), there has been some degree of success with 50 of 64 species attempted (78% successful). With all the other insect groups, some degree of success has been attained with 70 of 159 species (44% successful).

The history of biological control against the cottony cushion scale, *Icerya purchasi*, in California is considered the milestone for biological controls. Its native range was thought to be Australia and was believed to have been introduced near Menlo Park, California, around 1868. By 1887, the scale was threatening the California citrus industry. At the recommendation of the Division of Entomology in the U.S. government, a search for the natural enemies of the cottony cushion scale in its native home was conducted. From Australia, first some parasitic flies, *Cryptochetum iceryae*, and later the coccinellid, *Rodolia* (*Vedalia*) *cardinalis*, were imported into California. By the end of 1889, many growers were reporting that the beetles had literally cleaned their trees of the scale. The cost of this success was about US$1500. Since the California experience, *Rodolia cardinalis* has been used successfully in 25 other countries, where complete control has been achieved, and in four countries, where there has been a substantial degree of control.

### 5.2.4. Biocides

Biocides is a general term (synonymous with pesticides) that covers all the chemicals used to control invader and noxious organisms, including insecticides when used for the control of insects, herbicides when used for the control of plants and, for vertebrates, rodenticides (for rats and mice) or just poisons (for large animals, such as foxes and rabbits).

The origins of chemicals date back to the dawn of agriculture, when it became essential to preserve stored grains between seasons. Sulfur was used by the Sumerians about 2500 BC; in China, chalk, wood ash, and botanical products were used for the treatment
of stored grain from about 1200 BC, and arsenic was used as an insecticide in the second century BC. After centuries of use as elements of traditional folklore, the insecticidal properties of certain botanical products such as pyrethrum, nicotine, and derris were recognized from about the sixteenth century. The early twentieth century saw the standardization of petroleum oils and botanical products and the beginnings of the investigation of the relationships between chemical structure and biological activity. The explosive development of chemical insecticides dates about 1940, when the insecticidal properties of DDT (1,1,1-dichlorodiphenyltrichloroethane) and BHC (benzene hexachloride) were discovered. A large number of different chemicals were tested for their insecticidal properties and many of these came to be used on a worldwide scale.

In the early 1950s, the toxicity of many of these chemicals for vertebrates, including humans, and the presence of pesticide residues in food became matters of concern. At about the same time, resistance of target species to the effects of some of the more widely used insecticides became a problem. Thus, since the 1970s the use of a number of very effective agricultural insecticides, including DDT and the organophosphates, has been phased out, primarily because of concern for their danger to humans, but also because it was shown they were only slowly degradable, posing threats to wildlife.

As far as vertebrates are concerned, early in the twentieth century, in both New Zealand and Australia, strychnine was used in baits for rabbits and rats, phosphorized raspberry jam or pollard baits for rabbit control, and later warrens were gassed with carbon bisulfide, calcium cyanide, or chloropicrin. More recently, warfarin (an anticoagulant) has been widely used for the control of rodents and sodium fluoroacetate (“1080”) for the control of rabbits and foxes, both being administered in baits. However, these poisons are nonspecific, and the widespread use of 1080 in the field poses serious risks to other animals that may take the baits.

5.2.5. Autocidal Control

Autocidal methods include the sterile male release technique and the use of sex pheromones, mostly used in applied entomology. The sterile insect release (SIR) is based on rearing, sterilizing, and releasing large numbers of males to mate wild females, who will then produce inviable eggs. Sterilized males must be vigorous competitors with wild males for obtaining mates (but mass rearing and irradiation can cause deterioration in the vigor of sterilized males). This technique, although expensive, causes no environmental contamination or nontarget impacts. In some programs, an initial reduction of wild males was achieved by attracting males to insecticide permeated traps—the “male annihilation” technique. The release of large quantities of sex attractant in an area can confuse the males and prevent them from finding females. Again, this procedure is environmentally sound because the sex attractants are species specific.

5.2.6. Habitat Management

Habitat management consists of either making the habitat undesirable for the invader or making the habitat desirable for the natural enemies of the invaders. Many of the
modern agricultural practices such as the removal of competing plants and trees, use of biocides, large monocultures, use of fertilizers, irrigation, and planting of uniform genotypes have created simplified environments that are now susceptible to invading species but are unfavorable to natural enemy activity. The trend in modern forestry with respect to fiber production is also toward habitat simplification, and is likely to result in problems similar to those seen in agriculture.

Adding diversity to agriculture environments by growing crop plants together in polycultures may provide the necessary ecological requisites for some natural enemies. Diversity in the form of undesirable plants may also been important. Although many plants compete with the crop, there also are positive attributes. Noncrop plants can be the source of food for natural enemies either by providing alternate prey or pollen or nectar. Insects, such as aphids, living on noncrop plants may produce honeydew and this, too, can be used as food by various parasites. Some noncrop plants may provide refuges for natural enemies, while others may attract natural enemies to an area. It has been shown that parasitization of corn earworm eggs by small wasps (*Trichogramma* sp.) can be increased by spraying fields with extracts of a plant (*Amaranthus* sp.). In forestry, it has been shown that native parasites of an invading species, the European pine shoot moth (*Rhyacionia buoliana*) had increased longevity and fecundity due to herbaceous plants, some of which are considered noxious weeds. The two parasites, *Exeristes comstocki* and *Hyssopus thymus*, have been effective at times in depressing shoot moth populations and their success depends, in part, on the availability of an energy source. Nectar from the wild flowers provides this energy source.

Artificial structures have been used to encourage and increase natural enemies of pests. Attempts have been made to create nesting shelters for arthropods such as *Polistes* wasps, which are predators of some agricultural pests, and artificial nesting sites for ants, *Formica rufa*, in forest environments in Europe. Nesting boxes designed to encourage cavity-nesting insectivorous birds have been used extensively in the forests of Europe and more recently in the western USA. It has been demonstrated that bird populations can be increased rather readily with nest boxes; however, the documentation of the impact of the birds on selected forest insect populations is sparse.

5.3. A Comparative Evaluation of Methods

Methods for the management of invasive species should be socially and ethically acceptable, efficient, nonpolluting, and should not damage native flora and fauna, humans, domestic animals, and cultivars. Although it is sometimes difficult to meet all of these criteria, while still achieving effective control of the invasive species which is being targeted, genuine attempts should be made to do so. The circumstances of control (location, habitat type, target species, presence of vulnerable nontarget species) are so variable that it is only possible to give broad guidelines on suitable methods. Specific methods of any kind are better than broad spectrum ones. Specific biological control is generally preferable to chemical or other methods, since it is permanent, nonpolluting, and ethical. The specificity of biological control agents must, however, be thoroughly checked before their introduction. Mechanical removal can be an excellent option for clearing small areas of invasive species, especially where volunteer labor (local conservation groups, schools etc) can be used. Screening for host range and the
anticipation of nontarget effects should precede the introduction of any biological control agents. Chemical used for control should be as specific as possible in their action against the target species, safe to use, nonpersistent, and not accumulative in food chains. Chemicals should always be used in strict accordance with the manufacturer's guidelines. Making up of extra-strength solutions and mixing of chemicals may be unsafe to users and the environment. Unused chemicals and their containers should be safely disposed of; not dumped or tipped down drains or into waterways. Control methods for animals should be as humane as possible, consistent with the aim of effective control.

5.4. When is Eradication a Workable Strategy?

There is no doubt that, when achievable, eradication is the best management option for dealing with invasive species: it removes the need for perpetual control and ongoing financial and environmental costs that control can entail. However, eradication is likely to be successful only in the earliest stages of an invasion or in "island" systems of manageable size.

First, the best opportunities for eradicating an invasive species are in the early stages of invasion, in the "lag" phase before populations increase and spread. Some NIS can evidently remain relatively uncommon and seem harmless for long periods of time before suddenly becoming invasive, perhaps following a genetic change, local environmental change, or the arrival of another NIS which, for example, can act as a food source, pollinator, or seed disperser. Early detection of new biological invasions is therefore important and rapid action is required to eradicate or contain the new invader once it is detected.

Local knowledge and awareness (including the help of botanical societies and conservation groups) should be utilized, and immediate reporting to local biosafety authorities encouraged, in order to detect invasions as early as possible. Rapid response teams of local experts could be formed, in order to detect and evaluate new infestations at the earliest stage and to make recommendations for action. In these instances, procrastination is likely to be disastrous. The principle to be exercised should be: where there is a perceived threat to biological diversity, local ecosystems or any other locally relevant resource, act rapidly.

The removal of the brackish water, black-striped mussel from Cullen Bay in Darwin Harbor, Australia, is a recent example. This species is native to the Caribbean but now occurs in harbors in Singapore and Fiji, where it forms monospecific clumps up to 15 cm thick and weighing 100 kg m$^{-2}$. Within nine days of its discovery in the spring of 1999, Cullen Bay was quarantined and treated with 160 t of bleach and 54 t of CuSO$_4$. All living organisms in this 600 ML marina were killed. The long-term environmental consequences of this eradication program are not known, but might have been reduced because they were confined to a humanmade, dredged marina.

Second, the successful programs are only those where the area of invasion is relatively small. There have been several large-scale eradication attempts against well-established invading species, but in all these cases we record an extremely high failure-to-success
ratio; in addition these projects are very costly in terms of money and manpower, and, since chemical pesticides are almost always used, they are dangerous for human health and have environmental side-effects. Example of controversial large-scale programs is the introduced fire ant (Solenopsis invicta) eradication project in the southern USA. Over US$200 million was spent from the late 1930s to the 1950s in futile attempts to eliminate this invasive ant. The broad-spectrum insecticides applied in this program had impacts on nontarget species, including humans and native ants. Similarly, in the eradication program conducted in the southern USA against the boll weevil (Anthonomus grandis) native to Mexico and having a major impact on cotton production. Since 1962, US$100 million has been spent, but the result can be more appropriately described as area-wide suppression rather than eradication.

A more specific example comes from the codling moth (Cydia pomonella). It is native to Europe and is a serious worldwide invader, destroying apple cultivation. In British Columbia, Canada, a pilot project was initiated in the 1970s to explore the feasibility of eradicating codling moths using the SIR technique. Over several years of the program, moth densities were reduced, but at a cost of US$225 ha$^{-1}$ y$^{-1}$ compared with US$95 ha$^{-1}$ y$^{-1}$ for insecticide control. A new and enlarged eradication program was initiated in the 1980s. After five years, coding moth densities were reduced but eradication was still not achieved. The feasibility of eradicating codling moths was thus re-evaluated and in the winter of 1998 the program goal was changed from eradication to area-wide suppression.

A further requirement that should be fulfilled in conducting an eradication project is that the ecosystem concerned is sufficiently isolated from potential sources of recolonization and is not opened up for invasion by another latent invasive species, that is the immigration of invaders should be zero. In California, at least four programs against insects (the Japanese beetle, the gypsy moth, the apple maggot, and the boll weevil) seem destined to failure—even if the eradication attempts are successful—since recolonization from bordering states is almost inevitable. Combining "vector" control (e.g., regulations on exchanging ships' ballast water or on the importation of potentially infested raw lumber) should be a component of eradication programs.

A controversial case is the eradication program against the medfly (Ceratitis capitata). Native to tropical west Africa, the medfly is a vagrant in fruit-growing areas and has the potential for major impacts on fruit production: it lays eggs on at least 250 types of fruit and berries and larvae feed heavily on the crop. Multimillion dollar eradication programs were initiated in California in 1975 by the U.S. Department of Agriculture (USDA) and these continue up tp 2002. Medflies were originally captured in southern California in 1975. Following a spraying program, they were not detected again in the state until 1980. Eradication programs using a protein bait and/or malathion spray were initiated in both southern and northern California in 1980–1982 at a total cost of US$100 million. However, medflies were captured every year between 1986 and 1994. A preventive program was initiated in 1994 in the Los Angeles Basin and surrounding areas, in which up to 500 million sterile medflies were released weekly in an attempt to suppress reproduction of any wild flies. Whether newly discovered populations of medflies are the result of new introductions or of failed eradication remains controversial. Studies of the history, genetics, and dynamics of this exotic species in
California indicate that populations might remain at low and undetectable densities before they are discovered or before some event triggers their resurgent recolonization following suppression.

As a further constraint to eradication, before starting any program, managers should be fully aware that (a) adequate funds and commitment exist to complete the eradication, (b) monitoring of the species is feasible to ascertain that the population size really decreases and that all individuals in the population are susceptible to the eradication (e.g., fast detection of bait- or trap-shy animals is necessary), 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, such as an exotic predator or herbivore. This third point has been neglected in several programs. For example, the eradication of Norway rats from Mokoia Island, New Zealand was followed by greatly increased densities of mice. Similarly, the removal of Pacific rats (*Rattus exulans*) from Motupao Island, New Zealand, to protect a native snail caused increases of an exotic snail to the detriment of the native species. On Motunau Island, also in New Zealand, the exotic boxthorn (*Lycium ferocissimum*) increased after eradication of rabbits, and on Santa Cruz Island, off the coast of California, the removal of vertebrate grazers caused dramatic increases in the abundance of fennel (*Foeniculum vulgare*) and other exotic weeds.

To meet the above criteria, it seems necessary to do a careful economic analysis of the cost as compared to the returns and savings that would result from the attempted eradication. The cost of eradication should also be weighed against the ease of recolonization, as well as against external costs such as those coming from new invasions, or the elimination of competing species, or the costs associated to human health and environment damage. Most often, government agencies must be involved and additional taxation might be a part of the funding package. Establishing and maintaining public support is often a large hurdle for government agencies in the initiation of multimillion dollar eradication programs, as exemplified by the gypsy moth, the medfly, and the boil weevil programs. However, eradication of a species with a restricted distribution such as the sabellid worm, the black-striped mussel, and some small plant populations might be carried out relatively cheaply.

Then, the lines of authority must be clear and must allow an individual or agency to take all the necessary actions. Large-scale eradication programs involve treatments or regulations covering private land and across several jurisdictions (agricultural land, municipalities, government-owned land, and native reserves). An extensive program is only feasible if the lead agency has a clear mandate to carry out required procedures at all affected sites. This was not the case in the failed eradication of codling moth in British Columbia. In the successful eradication of the sabellid worm, the black-striped mussel, and rats from Langara Island, the lines of authority were, on the contrary, clear.

Special efforts should be paid to eradicating invasive species on islands with a high percentage of endemics in the flora and the fauna and in isolated areas that are centers of endemism and/or have high levels of biodiversity or threatened endemics. In addition, the eradication of feral animals must be seriously analyzed. If, on one hand, these can be some of the most aggressive and damaging species to the natural
environment, they may have value as an economic or genetic resource in their own right, or be of scientific interest. Where a feral population is believed to have value, but is threatening native vegetation and fauna, the conservation of the native flora and fauna should always take precedence. Removal of the feral animals to captivity or domestication elsewhere is a valid alternative.

A further issue is to look for any conflicts of interest in the eradication program, as discussed in Section 4.4. One example is provided by the gypsy moth (Lymantria dispar). The moth could displace the California oak worm (Phryganidia californica) in urban areas and although it has a broader host range than the oak worm the end result may be swapping one invader for another at no additional cost. Foresters may find in the gypsy moth a positive influence, since the black oak in California and red alder and willow in Oregon and Washington are desired hosts. Although the gypsy moth feeds on conifers at high population levels, it may result in reducing the number of hardwoods in mixed conifer stands and save the foresters the money that they would normally spend on herbicides to control the hardwoods.

6. Failures and Successes: Four Case Studies

6.1. The Gypsy Moth in North America

Following its first introduction in 1869 into Massachusetts from Europe and Asia, eradication attempts for the gypsy moth (Lymantria dispar) began in the late 1800s. These did not stop the gypsy moth from becoming established and populations have continued to spread from eastern to western North America. Between 1978 and 1998, gypsy moths were captured at 120 sites in British Columbia, Canada, and 20 eradication programs have been carried out. The largest gypsy moth eradication program in British Columbia followed the capture of 17 male Asian gypsy moths in 1992. Twenty thousand hectares were aerially sprayed three times with the microbial insecticide, Btk. Spraying for gypsy moths using the microbial insecticide Btk in urban areas is usually associated with a public outcry that makes these eradication attempts controversial. The cost of this program was evaluated at CAN$6 million. Local Agriculture Canada officials predicted that the treatment would eradicate the moth, but, in 1995, two male Asian gypsy moth were captured.

The European form of gypsy moth has increased in density in recent years in the vicinity of Victoria (British Columbia) and in summer of 1999 a CAN$3 million aerial spraying program was carried out. Canadian authorities consider the gypsy moth to be primarily a potential nuisance for urban and recreational areas in western Canada. However, if eradication of the moth is not attempted, export trade to the USA will be prevented unless goods are inspected or fumigated. Although the U.S. Department of Agriculture (USDA) considered the Asian form of the gypsy moth to be a serious threat in the Pacific Northwest, the potential impacts of the moth to coniferous forests are likely to have been exaggerated.
6.2. Household Rodents in Britain

No easy solutions exist for dealing with household rodents. In Britain, the Ministry of Agriculture surveyed more than 62,000 buildings between 1976 and 1979 and discovered that house mice (Mus domesticus) and brown rats (Rattus norvegicus) each infested 4% of the sites. These low figures seem to suggest that perhaps they are under control, but the definition of control is vague. It depends on which level of infestation we will tolerate. Rats do damage costing millions of pounds each year. The rodents eat crops and stored grain but, far more important, they often gnaw through electrical cables. Actuaries blame rats for as many as half of the unexplained fires on farms. Despite this, the cost of trying to eradicate rats, even in towns, is too high to be worthwhile. Control, however, is important, because they are risky to human health, and this risk is increasing: in 1988 there were 133 cases of Weil’s disease, a violent jaundice caused by a bacterium excreted in rats’ urine. Nineteen people died.

There are difficulties in reducing rodent populations to acceptable numbers. The usual way to kill them is using poison, but they very quickly learn to avoid harmful substances. House mice explore new objects, but although they taste many new things, they eat only small amounts of strange foods. If the substance is toxic, they usually survive, learning to avoid it in future. Brown rats are more cautious when presented with something new. They are more likely to avoid than to taste a bait. Where traps and poisonous baits are used to kill rats, the survivors are much warier than in areas where no attempts are made to eradicate them. Rodents are protected not only by their natural caution but also by a growing resistance to the poisons most widely used.

Anticoagulants such as warfarin, developed in the 1950s, made control easy. In 1958, researchers detected the first resistance to warfarin in rats in Scotland. By 1972, there were many pockets of resistance and the industry had to develop new types of poisons. A second generation of anticoagulants, such as difenacoum and bromadiolone, emerged in the 1970s. These are effective against rats resistant to warfarin; but already rats are resistant to both generations of anticoagulants in one area in Hampshire. The spread of behavioral resistance could be serious; researchers do not know how it develops or how it spreads. However, research on rodent control must concentrate on achieving a better understanding of the biology of rodents and baiting methods, rather than looking for more toxic poisons.

6.3. The Coypu in East Anglia

The coypu campaign is one of the rare success in reversing an environmental mistake accomplished by humans. It succeeded largely because of the investment in applied population biology, which was vital in planning and guiding the campaign. A number of elements contributed to the success of this intervention: (a) eradication was feasible because the invasive population was detected while it was still spatially restricted and a rapid response minimized the chance of spread of that population (the coypu was confined to a fairly well-defined part of England, East Anglia); (b) ecological costs may have accrued if other potential hosts had been haphazardly removed, or if chemical treatments had been applied; (c) private, public, regulatory, and scientific communities cooperated; and (d) the program’s efficacy was constantly monitored.
In addition, long-term research on population ecology enabled researchers to predict the outcome of particular strategies. This research, which included studies of alternative control strategies, showed that there was a good chance of eradicating coypus from Britain. It also allowed the Coypu Control Organization to plan how long the campaign would take and how much it would cost. Then, biologists guided and monitored the progress of the campaign and designed the criteria for judging when it should end.

Research on population ecology began in 1970, and, as coypus began to multiply, the relationships between trapping effort and the number of coypus were understood. The research suggested that, in the worst case, about 20 trappers would be enough to keep the population stable and that a larger force might be able to eradicate the coypu altogether. To understand how the population varied in size, models were constructed that took into account variables such as birth and death rates and allowed manipulation of the factors affecting the variables. The key to the success of such models was the data used to feed into it. Accurate information was obtained by sampling the population; figures were provided by the number of coypus caught and the large number of animals to study. At post mortem, researchers collected measures of age, fat reserves, and elements of female reproductive performance, such as the size of a litter, natural embryo deaths, and projected dates of littering. Information was accumulated through censuses, that is the reconstruction of the population in the past using the number and ages of the animals killed.

The coypu was introduced into Britain to satisfy the demand for nutria, a fashionable fur in the 1920s. Nutria means otter in Spanish, but the species providing its skin for fashion was a rodent native to South America, the coypu. As demand increased, fur farms spread throughout the world. Many of these farms were ramshackle affairs and many animals escaped; being semiaquatic animals, in the wetlands of Norfolk coypus found a habitat similar to their native swamps. They started to breed and as numbers increased began to cause serious damage to agriculture and to the environment. Coypus weigh as much as 8 kg and their burrows are large; their tunneling into the banks of ditches and rivers caused particular concern in low-lying East Anglia. Then, coypus ate a large number of crops—sugar beets, brassicas, and cereals—and native wetland plants, such as the flowering rush (Butomus umbellatus) and cowbane (Cicuta virosa), which became rare when the population of coypus reached a maximum of ~200 000 in the late 1950s. Coypus devastated large areas of the reed swamp fringing many of the broads and rivers.

In 1962, the Ministry of Agriculture launched a three-year campaign to trap coypus and set up the Coypu Research Laboratory to carry out research support of the control program; the winter of 1962 to 1963 was the coldest for more than two centuries and ~90% of the coypus perished and many of the outlying colonies disappeared. But, in the remaining years, up to 1965, the population declined only slowly and when the campaign finished there were still ~5000 animals in east Norfolk. After 1970, the number of coypus began to double each year. More intensive trapping showed the increase but could not stop it: by 1975 there were ~19 000 animals. In 1980, the Ministry of Agriculture announced a new campaign. Twenty four trappers and three supervisors were employed and the ministry provided half of the necessary £2.5 million; the local water authority, Anglian Water, and the Internal Drainage Boards provided the
rest. It seemed clear that a financial incentive was needed that to some extent compensated the trappers for their eventual loss of employment. In the early 1980s, the trappers stood to win a bonus of up to three times their annual salary if they eradicated coypus within six years of the start of the trapping campaign; after six years, the bonus would gradually decline to encourage the trappers to bring the campaign to an early conclusion.

Several techniques were explored, but field trials showed that the method of trapping in cages was remarkably effective and selective (moorhens and water voles that sometimes entered the traps were released), and the traps were more effective if set on baited rafts. In April 1981, there were more than 5000 adult coypus. By April 1986 there were fewer than 40. At that point the problem changed from one of reducing the size of this population to one of finding the last few individuals. This part of the campaign was relatively unpredictable; on January 1989, 21 months had passed without any evidence of coypus other than two elderly males. At this point the campaign ended. However, isolated individuals could have survived, so the ability to detect and catch any such animals for a while was required.

6.4. The European Rabbit in Australia

The European rabbit is unique among vertebrate invaders in that during the last century a number of biological control tools have been explored to halt its spreading especially in Australia and New Zealand, where it is the most important noxious species for both the agriculture and the environment.

Introduced into Australia in 1788, with the dramatic spread of this species in the 1870s the enthusiasm of the landholders for the sport of hunting rabbits was replaced by anxiety due to the heavy damages this species were causing to the crops. With no experience and little biological understanding to guide them, the authorities tried to cope with the situation in various ways, primarily by requiring landholders to control rabbits on their properties. In 1869, the member for the Western District of Victoria tried to have a clause inserted into the Local Government Act to make the destruction of rabbits compulsory, but it was 1878 before a bill was introduced in Victoria, and this proposed introducing an inspection fee of two pence an acre to see whether land was infested. The landholders were outraged, and this provision was replaced by a bonus scheme. The first Rabbit Destruction Act was passed in South Australia in 1875 to ensure that landholders met their obligations to control rabbits, control being supervised by district councils or rabbit district boards.

In 1880, the New South Wales government introduced a levy on landholders to pay scalp bonuses, but soon after amended the law to make it compulsory for landholders to control rabbits, with penalties for failures. In 1884, the farmers demanded that a bonus system should be reintroduced, but, by 1887, newspaper editors and farmers alike called for its abolition, on the grounds that the US$30 million spent that year “might as well have been thrown into the sea.” At the same time, a thriving trade had developed in rabbit carcasses and skins, and a new occupation was born, the rabbiter, who trapped rabbits for bonuses, and later for the meat and skins. Initially the rabbiterades made fortunes from bonus payments and later planned their trapping so as not to destroy their
resource, by siting their traps in such a way as to take bucks preferentially and moving on after they had harvested ~40% of the population.

Since indigenous predators that could affect rabbit numbers were so rare in Australia, the earliest attempts at biological control of the rabbit involved the release of nonindigenous predators: stoats, weasels, mongoose, and especially cats. In Australia, only the latter thrived. In the late 1880s, they were bred and released in thousands specifically to control rabbits, and excess kittens bred on stations "went wild." In New South Wales, goannas (large lizards of the genus *Varanus*) were declared enemies of the rabbit and protected in the Rabbit Nuisance Act 1883; a conference in Brisbane in 1888 resolved that because of their value for rabbit control, goannas, carpet snakes, native cats, and feral cats should be protected.

Among the most bizarre methods of biological control of rabbits proposed was that advocated with great persistence by William Rodier in New South Wales and Victoria between 1905 and 1925. In the press and by private publication, he promoted "The Rodier Method," which consisted of catching as many rabbits as possible, killing all females and releasing the males. The reasoning was that “when the males exceed the females in numbers they will persecute them and prevent them from breeding, they will kill what young ones may be born and when they largely exceed the females in numbers, they will worry the remaining ones to death; by this means all the females are exterminated, and when this is done the males will die off by old age.”

Other methods also proved ineffective at decreasing populations to a valuable extent, such as trapping, shooting, and fencing. Baits containing strychnine, cyanide, arsenic, and phosphorous were also used for rabbit control; all poisons were indiscriminate weapons, often causing death of nontarget species such as birds and native mammals, and they were dangerous for humans as well. In 1950, a more effective poison, sodium fluoracetate ("1080"), an acute metabolic poison, was introduced. Other systems proposed were fumigation with cyanogas, produced from calcium cyanide. Certain other poisons, such as chloropicrin (trichloronitromethane), which had been developed for gas warfare in the First World War, and phosphine (hydrogen phosphide) were used for fumigation, a procedure in which gas is introduced into a burrow in which most entrances have been blocked.

The use of myxoma virus for biological control of rabbits was first proposed by the Brazilian scientist H. de Beaurepaire Aragão in 1919, but at first the Australian government rejected his scheme, primarily on the grounds that it might constitute a health hazard and that it wouldn’t work. Fourteen years later, Jean MacNamara persuaded the Australian government to commission a preliminary study of the feasibility of using this disease for biological control of the rabbit and, in 1950, myxoma virus was largely employed all over Australia.

Three factors appear to have played part in persuading the government to have recourse to this biological agent:

- Concern about its specificity: one of the great advantages of biological control is that it is likely to be more specific than chemical methods.
• Economic factors: after 1945, with the explosion in rabbit numbers and the knowledge that myxomatosis might be a "magic bullet," there were no substantial economic factors inhibiting the introduction of myxomatosis.

• Psychological factors: the economic and ecological cost of rabbit infestations in Australia outweighed ethical sensitivities.

The initial effect of myxomatosis on rabbit populations was dramatic at the beginning of its introduction, but its efficacy was soon reduced because of the development of genetic resistance in the rabbits. In 1984, a new lethal disease of rabbits, rabbit haemorrhagic disease, was reported in China and Europe, and five years later investigations were commenced in Australia to see whether the causative virus could be used for biological control of rabbits in Australia and New Zealand. It was introduced into Australia in 1995 and very high kills were reported. At the beginning of the twenty-first century, it is the main biological control agent of rabbits in Australia.

7. The Future: An Integrated Action Between Scientists and Managers

A review of the eradication and control programs conducted in the past shows that, apart from a few cases, a disproportionate amount of money was 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. Since a very small portion of resources is allocated into the scientific research, these programs become highly institutionalized, are orientated towards public relations, and the organization of the project becomes an end in itself. The information given to the public is geared to portraying the invader as a dangerous species and simplistic economic analyses are used to show how great the losses will be. The agencies insist on a single narrow viewpoint rather than an open, honest appraisal of the problem.

On the other hand, a number of successful projects aimed, for example, at eradicating the sabellid polychaete worm or the coypu, were based on the sound knowledge of the biology and population dynamics of the species under concern; without any doubt, this knowledge had a strong contribution to the appropriate design of the eradication procedure.

A second weakness of most eradication and control programs is the absence of data on the ecosystem impact of the invasive species; the potential risks associated with the introduction of eradicating or control agents may thus appear high compared to the "no action" scenario. Without additional data from long-term monitoring (and even short-term monitoring), we are largely left with "expert opinions" and can only hope that by involving natural resource managers and scientists from different agencies and disciplines in decision-making processes we can avoid most conflicts of interest. Ideally, investigations on the ecological effects of NIS have to go beyond the "simple" impact evaluation on communities, must involve cross-disciplinary teams of scientists, and should incorporate many different taxa and different trophic levels. At present, our knowledge, particularly about higher order interactions and indirect effects, is extremely limited. Of particular value will be standardized, well replicated, and sophisticated monitoring studies that hold up to rigorous statistical analysis and interpretation.
Developing such programs for a number of different species may reveal important generalizations about the invasion process.

Three approaches are desirable to gain insight into the correlation among measures of impact: (a) to synthesize the quantitative data on different impact response variables estimated for the same suite of species (for example, in order to evaluate the impact of the introduced plants in Great Britain it would be helpful to discover the kind of correlation existing among geographic distribution, herbicide-related costs in agricultural systems, local abundance, cost of control in nature reserves, and a subjective score of "perceived weediness"); (b) to encourage studies that measure impacts at multiple scales and multiple levels of organization, while most empirical studies have focused on a single measure of impact; and (c) to guide much-needed empirical work through analytical modeling. A steady accumulation of standardized data on impacts coupled with theoretical investigations will allow us to generalize, and perhaps even predict, which species will be most likely to have the greatest impacts.

Third, it has often been claimed that a scientific prediction of the outcomes of eradication and control projects is impossible and that any intervention involves a great amount of guesswork. This belief explains why actions against NIS have often resulted in uncontrolled experiments and their success has produced quite unexpected results. For example, there has been an explosion of the population of the exotic vine *Operculina ventricosa* after removal of pigs and goats from Sarigan Island and a significant increase in geckos, responding to honeydew produced by a scale insect on two plants that flourished on Korapuki Island (New Zealand) after rabbit eradication. There have been very few short-term studies (and no long-term studies) indicating that, at the very least, investigations of potential side effects should be a regular part of all the management programs, while environmental disruptions have often been inadvertently documented.

In our opinion, where possible, eradication and control projects should be viewed as ecological experiments in which the addition and subtraction of species can reveal community processes. Future and ongoing eradication programs can provide 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 (a) defining the danger of NIS in terms of impacts on agricultural productivity and environmental damage; (b) determining objectives and performance indicators; (c) identifying and evaluating management options; and (d) implementing, monitoring, and evaluating the management program.

**Glossary**

**Autocides:** A number of methods to control invasive species, especially used against insects; autocidal methods include the sterile male release technique and the use of sex pheromones.
Barriers: The spread of an invasive species may be decreased or prevented by constructing and maintaining a barriers: by fencing (if they are large), by netting (if they are small), and by screening (in the case of insects). Other barriers are national or international laws that have declared invasive species noxious, and making it illegal to sell, keep or cultivate them.

Biocides: A general term (synonymous with pesticides) that covers all the chemicals used to control invader and noxious organisms, including insecticides when used for the control of insects, herbicides when used for the control of plants and, for vertebrates, rodenticides (for rats and mice) or just poisons (for large animals, such as foxes and rabbits).

Biological control (or biocontrol): A collective term that includes a wide range of interventions aimed at reducing the population density of invasive species. It is characterized by the use of biotic agents that are the natural enemies of the invader.

Eradication: Literally, tearing out by the roots; its widespread definition 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."

Invasive species: Usually a NIS, which becomes established in natural or seminatural ecosystem or habitat, is an agent of change, and threatens native biological diversity. According to the “tens rule,” one imported species in ten appears in the wild, one in ten of these becomes established, and one in ten of these becomes harmful to native populations, species, communities, and ecosystems.

Nonindigenous species (NIS): A species occurring outside of its natural range and dispersal potential (i.e., outside the range it occupies naturally or could not occupy without direct or indirect introduction by humans) and includes any part, gametes, or propagule of such species that might survive and subsequently reproduce.

Pests: An ambiguous word; it is generally used to describe an animal that conflicts with human interests.

Sterile insect release (SIR): An autocidal method based on rearing, sterilizing, and releasing large numbers of males to mate wild females, who will then produce inviable eggs.

Situationalization: The procedure through which those situations are scientifically evaluated to make any intervention biologically feasible, as well as acceptable under ecological, economical, political, and ethical viewpoints.

Weeds: Plants that grow where they are not wanted and can be harmful to agriculture and human activity in general.

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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 months) 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.
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