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REVIEW PAPER

We can eliminate invasions or live with them. Successful management projects

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Abstract Pessimism about the prospects of eradicating invasive species or managing them at acceptably low densities is fostered by publicity about failures, but it is often unwarranted. Many species, including insects, plants, and aquatic invaders of various taxa, have been eradicated, and a variety of management techniques have maintained others at low densities for long periods. Many of these projects entailed low-tech, scorched-earth approaches, often using mechanical, physical, or chemical means. Others required sophisticated scientific research. There are at best rough guidelines rather than general rules about what approach to undertake. It is therefore important in each case to consider the full range of possible methods for eradication or long-term control, including the possibility of marshalling a massive amount of physical labor.

Keywords Biological control · Eradication · Maintenance management

Introduction

Ironically, just when the public finally recognizes the scope of biological invasions, there is widespread pessimism that much can be done to alleviate the problem, both because of the inevitable increase in trade and travel and the seemingly endless ways in which some invaders circumvent attempts to control them. David Quammen (1998) expresses this view in his article "Planet of Weeds", envisioning a globally dominant biota comprising the animal and plant weeds of the world. In fact, there are many successful examples of eradication and long-term management of invasives at low densities, but these are often not well-known to the public, and sometimes even to scientists. Partly this is a function of the news media. Ex-Secretary of Defense Rumsfeld (U.S.) frequently complained about the invasion of Iraq that newspapers and television quickly publicize the bad news and largely ignore all the good things happening there. One can say the same about invasions generally. To take just one example, the invasion of the northwest Mediterranean by the tropical Pacific "killer" alga *Caulerpa taxifolia* (M. Vahl) C. Agardh generated headlines throughout Europe and even in the United States, featuring failed attempts to control the invader (Simons 1997; Naik 2001; cf. Meinesz 2001). Its arrival in California waters was publicized with alarm, and early failures to eradicate it highlighted (Perry and Mehta 2000; Scoch 2000). Yet the successful eradication in 2006 of *C. taxifolia* in California, in spite of its far wider distribution than the original invasion in the Mediterranean, was reported only on an interior page of the local press (Lin 2006) and not at all in Europe. That the media

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tend to report disasters and not triumphs has contributed to the sense of doom about biological invasions.

A second reason why successful management of biological invasions is often not well known is that managers are usually rewarded for managing, not for publishing (Simberloff 1999). Many successful eradication and maintenance projects entail quite low-tech science, often just basic natural history (Simberloff 2003), and many resource management agencies and organizations have little tradition of publication in refereed journals, so their efforts—both successes and failures—are in the gray literature at best: agency reports and the like.

However, a number of programs have succeeded in eliminating or reducing populations of introduced species, even in circumstances that appeared quite hopeless at the outset. Of course, the most effective way to deal with potential invaders is to exclude them, but I will treat only invasions that are already underway.

Eradication

The possibility of eradicating introduced species is seductive, but scientists are often pessimistic (e.g., Dahlsten 1986; Whitten and Mahon 2005), especially for invertebrates, plants, and aquatic species in general. Part of the pessimism is due to a few highly visible, expensive, failed eradication campaigns with notable non-target damage, such as efforts to eradicate the red imported fire ant *Solenopsis invicta* Buren (Buhs 2004) and the gypsy moth *Lymantria dispar* L. (Spear 2005) in the United States.

Nevertheless, many pests have been eradicated, including many invertebrates and some plants (Simberloff 2002a). Tse-tse flies (*Glossina* spp.), probably native, were first eradicated on the island of Principe between 1911 and 1914, and again in 1956 after reinvasion (Lapeyssonie 1988). By the use of hybrid sterility, native tse-tses were also eradicated from a discrete 26 km^2 area in east Africa (Klassen and Curtis 2005). Subsequently, various species of *Glossina* have been eradicated from several African areas over 1,000 km^2 by variants of the sterile-male technique (SIT) in combination with trapping and insecticides (Klassen and Curtis 2005).

Other early insect eradications included the native screw-worm (*Cochliomyia hominivorax* (Coquerel)) from Curaçao by SIT in 1954–1955 (Baumhover et al. 1955), and more recently from Puerto Rico, the Virgin Islands and the southern U.S. through Mexico and all the way to Panama by 2001 (Klassen and Curtis 2005). Introduced fruit flies have also been eradicated from many islands and some mainland areas by various combinations of SIT, trapping, male annihilation, and insecticides: for instance, the Oriental fruit fly (*Dacus dorsalis* (Hendel)) was eradicated from Rota and Guam between 1962 and 1965 (Steiner et al. 1965, 1970) and the melon fly (*Bactrocera cucurbitae* (Coquillett)) by 1993 from the Ryukyu Archipelago, including Okinawa and Amami-oshima (Iwahashi 1996; Kuba et al. 1996). The Queensland fruit fly (*B. tryoni* (Frogatt)) was eradicated from an incipient infestation of 125 km^2 in Western Australia, while the Mediterranean fruit fly (*Ceratitis capitata* (Weidemann)) has been eradicated from 20 Florida counties (Ayers 1957), as well as small areas in western Australia and South Australia and a large part of the US, all of Mexico, and half of Guatemala (Klassen and Curtis 2005).

The giant African snail (*Achatina fulica* Bowdich) was eradicated by manual and chemical means from small areas in south Florida (Mead 1979) and Queensland, Australia (Colman 1978). A recent dramatic molluscan eradication was that of the Caribbean black-striped mussel, *Mytilopsis salei* (Recluz), discovered in 1999 in Cullen Bay (12.5 ha), Darwin Harbor, probably within 6 months of arrival (Wittenberg and Cock 2001). The bay was quickly quarantined and treated with bleach and copper sulfate, and the mussel has not been seen since.

It is often said that plants cannot be eradicated, particularly if they have a soil seed bank (Rejmánek and Pitcairn 2002), but there have been a few notable successes, such as elimination of sandbur (*Cenchrus echinatus* L.) from Laysan (Flint and Rehkemper 2002; E. Flint, pers. comm. 2007) and *Bassia scoparia* (L.) A. J. Scott (kochia) from a large area in Western Australia (Randall 2001). Mack and Lonsdale (2002) cite several eradications of plants from small areas of Australia, New Zealand, and the United States, but they observe that there are few such examples.

Many eradications are from small islands, but there have been notable successes on much larger islands. For instance, nutria (*Myocaster coypus* Kerr) has been eradicated from Great Britain (Gosling 1989) and the yellow fever mosquito (*Aedes aegypti* (L)) from Cuba (Fenner et al. 1988). Rat eradication has succeeded on islands of increasing size (Towns and Broome 2003), with planning now underway for an attempt to eradicate *Rattus rattus* (L) and *R. exulans* Peale from 274 km^2 Great Barrier Island, New Zealand (J. Ogden, pers. comm. 2007). Having eradicated various combinations of introduced mammals from many islands in the Gulf of California (Tershy et al. 2002), Island Conservation, a California non-governmental organization, has undertaken, with collaborators, eradication of pigs and goats from much larger islands in the Galapagos. They have already eliminated pigs and goats from Santiago Island (58,000 ha) and are close to success with goats on 400,000 ha Isabella Island (Campbell et al. 2005; J. Donlan, pers. comm. 2006). At a continental scale, the African malaria vector, *Anopheles gambiae* Giles, was eradicated from 31,000 km^2 of northeastern Brazil (Soper and Wilson 1943; Davis and Garcia 1989).

What common features can we draw from these and other examples to suggest when to mount an eradication attempt and how to proceed?

Five main features characterize most successful eradications (cf. Myers et al. 2000; Mack and Lonsdale 2002; Simberloff 2002b; Mack and Foster 2004):

a) Detecting an invasion early, and acting quickly to eradicate it.
b) Sufficient resources allocated at the start to finish the project, including post-eradication surveys and follow-up, if necessary.
c) Existence of a person or agency with the authority to enforce cooperation. Eradication cannot succeed even if the great majority of stakeholders cooperate in the campaign so long as a small minority allow the invader to persist on property they control.
d) The target species must be studied well enough to suggest vulnerabilities. Often basic natural history suffices.
e) Project leaders must be energetic, optimistic, and persistent in the face of occasional setbacks.

The importance of acting quickly and decisively and the need for post-eradication surveys and follow-up are exemplified by the successful eradication of the Pacific alga *Caulerpa taxifolia* from two substantial areas in southern California (Merkel & Associates, Inc 2006) and the failure to eradicate the same species in Europe (Meinesz 2001). A small infestation of the alga first appeared in 1984 just offshore of the Oceanographic Museum of Monaco. The French and Monacan government agencies argued first about who was responsible for the infestation, then about whether it would become invasive, and finally, as it became apparent that an invasion was underway, about how to deal with it. The upshot is that *C. taxifolia* now infests over 10,000 ha off the coasts of Spain, France, Monaco, Italy, Croatia, and Tunisia. In California, by contrast, within six months after the alga was discovered, the Southern California *Caulerpa* Action Team (a public–private partnership) was established and proceeded to garner public support for a brute-force eradication campaign. The effort entailed extensive diving to locate all infestations, then covering them with tarpaulins and pumping in chlorine. When monitoring uncovered infestations that had escaped initial detection, these too were covered and poisoned. No further *Caulerpa* was seen after 2 years of intensive monitoring, and on July, 12, 2006, the State of California celebrated the success of the effort, which cost ca. US$7 million.

Finding invasions early and acting promptly is not an absolute sine qua non for eradication, as witness both the global eradication of smallpox (Fenner et al. 1988) and great progress in attempting to eradicate witchweed (*Striga asiatica* (L.) Kuntze) from the United States after a long, widespread establishment (Eplee 2001). It is therefore important not to have hard-and-fast thresholds of establishment beyond which eradication will never be undertaken. However, the cost of eradication is likely to rise dramatically when invasions are widespread; both the smallpox and the witchweed campaigns cost over US$100 million. One would therefore expect great interest in early-warning systems. However, even New Zealand, the nation with the most comprehensive strategy on introduced species, recognizes monitoring for rapid detection of invaders and an adequate structure for a rapid response as two weaknesses in their approach (Parliamentary Commissioner for the Environment 2000). In the United States, the 2001 draft action plan of the Federal Interagency Committee for the Management of Noxious and Exotic Weeds for a national early warning and rapid response system for invasive plants has yet to be incorporated in a revision of the National Invasive Species Management Plan, approved by the National Invasive Species Council in 2001.

It is frustrating not to be able to provide very specific guidance about when and how to undertake an eradication campaign. However, it is a fact that ecological knowledge is generally accrued through amassing a catalog of case studies, each of which is, to an extent, sui generis, but which together can give guidance about the ways to approach study and management of a new system (Simberloff 2004). Ecology also lacks general laws, except at levels so high (e.g., the laws of thermodynamics) that they cannot provide management guidance (Simberloff 2004). Invasion biology, as a branch of ecology, is similarly often criticized as just a collection of special cases (see Williamson 1999), but it is simply the nature of the beast that invasions are sufficiently complex and different from one another that there will likely be many exceptions to any general rule that might be formulated by examination of the growing catalog of cases. As an example, many invasion biologists and managers, mostly working with plants, advocate attacking peripheral, nascent foci first, then gradually attacking large, central populations. This notion is based on common sense (e.g., Fuller and Barbe 1985), several empirical experiences (see Mack and Lonsdale 2002), and two theoretical treatments (Moody and Mack 1988; Higgins et al. 2000). However, recent, spatially explicit models for Himalayan balsam (*Impatiens glandulifera* Royle), giant hogweed (*Heracleum mantegazzianum* (Sommier & Levier), and Old World climbing fern (*Lygodium microphyllum* (Cav.) R. Br.) suggest that the specifics of particular invasions and costs of various management options could lead to exactly the opposite recommendation (Wadsworth et al. 2000; Duke-Sylvester 2006). A model similar to that of Moody and Mack (Whittle et al. 2007) also leads to a result different from theirs.

As noted above, failed eradications are often widely reported, while successful campaigns may be noted only in the gray literature. This is not a phenomenon restricted to *Caulerpa* eradications. A successful 9-year campaign to eradicate a major part of the Chicago invasion of the Asian longhorned beetle (*Anoplophora glabripennis* (Motschulsky)) was barely noted, and then only in the local press. By contrast, the failed campaign to eradicate northern pike (*Esox lucius* L.) from Lake Davis (California) was reported in national newspapers (e.g., Nieves 2002) and is even the subject of a documentary film (Elmendorf et al. 2005). Even more damaging to the development of a technology of eradication, less dramatic failed eradication attempts are often not reported except perhaps in the grayest of literature, hindering the ability of scientists to learn from previous efforts.

Maintenance management

Many introduced species have been controlled for long periods at low densities, but, as for eradication, there is often great pessimism that such an approach can succeed, and some efforts, both successes and failures, are not published in the scientific literature. For instance, musk thistle (*Carduus nutans* L.) is well controlled in Kentucky by supervised crews of drunk-driving convicts, a program that required optimism and persistence in the face of a soil seed bank (J. Bender, pers. comm. 2000). Nature Conservancy policies precluding herbicides led to a successful campaign to control European beachgrass (*Ammophila arenaria* (L.)) manually at the Lanphere-Christensen Dunes Preserve, California (now part of the Humboldt Bay National Wildlife Refuge). This program used a state public works program plus a convict alternative work plan and has kept the site clear of beachgrass for a decade save for small, easily removed infestations (Pickart and Sawyer 1998; A. Pickart, pers. comm. 2005). This plant can also be kept at low density with herbicides (Aptekar 2000). A collective in Tennessee, The Farm, with a policy of not using herbicides, managed to control kudzu (*Pueraria montana* var. *lobata* (Willd.) Maesen & S. Almeida) using prescribed burns plus manual labor, followed by annual monitoring for survivors and recruits (Rohrbach 2003).

Very substantial areas can be kept clear of invaders for the long term, as witness the control of water hyacinth (*Eichhornia crassipes* (Mart.) Solms) in Florida. In 1960, this plant infested 51,000 ha. After failed attempts at mechanical and biological control, the state of Florida reduced water hyacinth to ca. 2,000 ha (with locations changing annually) primarily by using the herbicide 2,4-D (Schardt 1997). Importantly, the cost and health issues associated with 2,4-D waned as the amount required quickly fell to less than 1% of the early usage. Florida has recently engaged in an ambitious campaign to reduce Australian paperbark (*Melaleuca quinquenervia* (Cav.) S. F. Blake) from its peak of ca. 202,000 ha in the late 1980s (Ferriter 2004). The main tool is aerial spraying of herbicides with manual application to sprouts and survivors, and with some manual and physical methods (Laroche 1994; Anonymous 2005). As paperbark on public lands has dwindled, a weevil and a psyllid from Australia have been released with the aim of preventing re-establishment and controlling this tree on private lands. Though more than a third of infested areas have been cleared, there is also substantial research on more effective, less costly methods (e.g., Myers et al. 2001; Laroche and McKim 2004). An important aspect of the success of the Florida programs for water hyacinth and paperbark was consistent, adequate funding, mostly from the state, to prevent these plants from re-establishing during a lull in management activity.

Also noteworthy is the Alberta Rat Patrol, a provincial program that has successfully maintained Norway rats at very low levels through use of anticoagulant baits and aggressive hunting by a team of officers (Bourne 2000).

Successful maintenance management for both agriculture and conservation sometimes entails classical biological control. For instance, on the island of St. Helena, the introduced lady beetle *Hyperaspis pantherina* Fürsch probably saved the endemic gumwood tree, *Commidendrum robustum* (Roxb.), from extinction by the South American scale insect *Orthezia insignis* Browne (Wittenberg and Cock 2001). In Florida, rapidly spreading aquatic alligatorweed (*Alternanthera phyloxeroides* (Mart.) Griseb.) is now well controlled by introduced natural enemies, especially the flea beetle *Agasicles hygrophila* Selman & Vogt (Center et al. 1997). Such successes have led to a popular view that biological control is a panacea for metastatic invasions, especially because, when it works, biological control may operate in perpetuity without further human intervention.

However, biological control is not without limitations (Simberloff and Stiling 1996). It usually fails to control the target species (Williamson 1996), and some introduced natural enemies threaten species of conservation or commercial importance. A recent worrisome example is the spread of the South American cactus moth *Cactoblastis cactorum* (Berg) through the southeastern United States towards Mexico, after it island-hopped from the Lesser Antilles to the Florida Keys long after introduction to Nevis for control of pest cactus. This moth may now affect many species of *Opuntia* prickly pear, including species of agricultural, horticultural, and conservation concern (Zimmermann et al. 2001). Such mishaps can be rendered less likely by extensive host-testing and avoiding release of any species that is not narrowly host-specific, but biological control will always entail risks, and, unlike chemical and mechanical control, an errant biological control release is generally irreversible. For this reason, the full panoply of possible approaches should be considered for any introduced species requiring management, and biological control should perhaps be seen as a last resort.

Discussion

Many successful eradication and maintenance management campaigns are decidedly low-tech and rely on massive use of manual labor (Simberloff 2003). In an age when manual labor is viewed as old-fashioned and governments as well as industry struggle to minimize labor costs, it is important to note two sources of low-cost labor that have already been widely used in invasive species management and could doubtless be employed even more extensively. Many projects use convict labor, including those to control musk thistle, beachgrass, and paperbark (Campbell and Carter 1999) discussed above. Most convicts pull, dig, or cut invasive plants, but other uses are possible. In Oregon, convicts construct pheromone traps used in campaigns to eradicate the Asian race of the gypsy moth, *L. dispar* (Manzano 1995).

Volunteers can be enlisted in wealthy nations to provide a huge manual labor force for both eradication and maintenance management. In the United States, the Nature Conservancy uses volunteers frequently for such purposes (Randall et al. 1997), while in the both Canada and the United States schoolchildren often engage in projects to manage invasive plants, thereby sensitizing the populace as a whole to the issue of biological invasions. Ecotourists pay over US$1,000 to rid scenic areas (such as national parks) of introduced plants (Newman 2004). Probably the major limitation on use of volunteers, as for convicts, is the requirement for supervision and training. However, it is evident that approaches that might have been rejected on grounds of sheer personpower requirements are, in fact, feasible under many circumstances.

Paid labor is also possible but seems difficult to justify for environmental rather than agricultural uses in the dominant political climate nowadays. However, such climates change, and the example of the South African Working for Water Programme suggests how a public works program can greatly aid the battle against introduced species while fulfilling other socioeconomic goals as well. Initiated in 1995, this project has employed tens of thousands of previously destitute citizens and effectively controlled many invasive plants (McQueen et al. 2000; van Wilgen et al. 2000).

Critical to the success of projects using massive manual labor, whether paid, volunteer, or convict, is the fact that often highly detailed knowledge of the target species is unnecessary, and a crude, scorched earth approach suffices (Simberloff 2003; Krajick 2005). However, not every problem will yield to such methods, and some high-tech methods employing sophisticated science have been remarkably effective. For example, efforts to eradicate goats from the Galapagos Islands with the Judas goat technique were stymied on large islands when females typically became pregnant within a month of release and went off to be alone to deliver and nurse their kids. To solve this problem, Karl Campbell developed a method of producing super-Judas goats by capturing females, inducing abortion, sterilizing them by Fallopian tube clips, and giving them a hormone injection that produces estrous for over 100 days (Campbell et al. 2005). This procedure is performed in the field in minutes.

A recent exciting project entailing sophisticated science concerns the sea lamprey (*Petromyzon marinus* L.) in the Great Lakes. Management has focused to date on use of lampricides and dams, and although there has been moderate success in decreasing lamprey numbers, these methods are expensive and have non-target impacts. Peter Sorensen and his colleagues (Sorensen and Vrieze 2003; Sorensen and Stacey 2004; Sorensen et al. 2005) have developed an entirely new approach. The sea lamprey is anadromous, and adults returning from the ocean or large lakes to breed avoid streams with no larvae. Sorensen suspected larvae emit an attraction pheromone, and his team has concentrated it from water containing larvae, characterized it chemically, and synthesized it. Larvae can be lured into traps or diverted into blocked or poor-quality streams with this pheromone. Widespread use of the pheromone is currently prevented by a patent fight between two organizations that funded the research.

Many effective maintenance management projects and successful eradications employ chemicals, alone or in concert with mechanical or physical methods. Expense of chemicals, especially when used for environmental purposes over large areas, and the evolution of resistance are frequent and valid concerns, but chemicals also generate opposition that seems ideological (Williams 1997). All environmentalists have been heavily influenced by Rachel Carson's masterpiece, Silent Spring (1962), which aroused the public about non-target impacts of pesticides. However, pesticides and herbicides registered today, if used properly, have far more limited non-target impacts, and in some instances they may be the only means currently available to stop irreversible damage from an invasion, at least until some other method is developed.

Such is the case with the explosion in the late 1980s of the introduced yellow crazy ant (*Anoplolepis gracilipes* F. Smith) on Christmas Island, threatening the ecological keystone species of the island, the native red land crab (*Gecarcoidea natalis* (Pocock)), as well as many other aspects of the island ecosystem (O'Dowd et al. 2003; Abbott 2004). What appeared to be a hopeless case and a conservation disaster was controlled by the use of the bait Fipronil in a fish protein base (<http://www.deh.gov.au/parks/christmas/fauna/crazy.html>, accessed 8/29/06).

Part of the pessimism about controlling invasions arises from widely publicized management failures, especially failed eradications. Worse, many cases of successful eradication and maintenance management are unpublicized or barely mentioned in the popular press or scientific literature. Nevertheless, the catalog of successful cases, of which the above cases are just a sample, is now sufficiently large and known at least to professional managers and invasion biologists that one would expect the public to demand more implementation and policymakers to respond. However, the fraction of invasions for which eradication is seriously attempted is minuscule, and many maintenance management programs are so sporadically funded that damage remains high. Why is the effort not greater?

One possibility is that scientists and managers with relevant expertise have simply not been assiduous or effective enough at publicizing the success stories. It is a common lament in conservation biology and environmental science generally that scientists lack the expertise and sometimes the desire to interact with the public and policymakers. Without judging the merits of this complaint, I suggest that the problem for invasion management in general is somewhat different, and the failure in particular to implement eradication and ongoing control problems sufficiently frequently is part of this problem. The effective approaches outlined above all require preventive action of some sort, at some expense. The most effective way to prevent damage from invasions would be better exclusion; although exclusion is not addressed in this paper, it is widely known by scientists and the public that exclusionary measures are quite weak. The single biggest difficulty of implementing the next line of defense—eradication—is absence of an ongoing early warning system; that is, a rigorous, comprehensive, ongoing monitoring program to detect new invasions. The next issue is that, for the great majority of invaders whose presence is already known, there is little evidence of current harm, but the frequent occurrence of a lag time before major invasions, often a substantial lag time, is well known (e.g., Crooks 2005). Yet, because of the great complexity of the forces controlling invaders, and the many idiosyncrasies of each invader, we cannot predict with much assurance which established introductions are going to lead ultimately to damaging invasions. Finally, with many eradication campaigns, the harmful impact disappears in the initial stages of the campaign, even before the target species has been eradicated. Similar, many successful maintenance management campaigns reduce the impact of a pest to a level at which it is not in the public eye.

In each of the above matters, what is required is preventive measures against events that will happen only probabilistically: exclusionary rules and machinery to keep out species, only some of which would become problematic; ongoing surveys that will certainly detect many introductions that may never become pests; eradication campaigns against species that are not currently problematic and may never be; continued maintenance measures against species that are currently controlled and that may not bounce back if the ongoing funding level and resulting control measures were decreased. Yet it is far more difficult to generate public fervor and support from policymakers for prevention than for cures to existing problems. Insurance companies balk at paying for vaccines, despite studies showing ultimate cost savings. Bridges collapse for lack of infrastructure maintenance, to be rebuilt at great cost on a crash schedule. It appears to be a fundamental aspect of human nature that preventive measures, even those demonstrated to be cost-effective, are not easily implemented if they are expensive, and sometimes even if they are not very expensive. It is unlikely that preventive measures for damage from biological invasions will be implemented nearly as widely as they might be until the public has fully grasped the overwhelming, daily cost imposed by some invasions, plus the notion of probabilistic events. This will be a hard sell, and it is unfair to indict invasion specialists for not having had great success to date.

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