Eradication revisited: dealing with exotic species

Judith H. Myers, Daniel Simberloff, Armand M. Kuris and James R. Carey

Invasions of nonindigenous species threaten native biodiversity, ecosystem functioning, animal and plant health, and human economies. The best solution is to prevent the introduction of exotic organisms but, once introduced, eradication might be feasible. The potential ecological and social ramifications of eradication projects make them controversial; however, these programs provide unique opportunities for experimental ecological studies. Deciding whether to attempt eradication is not simple and alternative approaches might be preferable in some situations.

Judith Myers is at the Dept of Zoology and Faculty of Agricultural Sciences, Centre for Biodiversity Research, University of British Columbia, 6270 University Blvd, Vancouver, BC, Canada V6T 1Z4 (myers@zoology.ubc.ca); Daniel Simberloff is at the Dept of Ecology and Evolutionary Biology, University of Tennessee, Knoxville, TN 37996, USA (dsimberloff@utk.edu); Armand Kuris is at the Marine Science Institute and Dept of Ecology, Evolution and Marine Biology, University of California, Santa Barbara, CA 93106, USA (kuris@lifesci.ucsb.edu); and James R. Carey is at the Dept of Entomology, University of California, Davis, CA 95616, USA (jrcarey@ucdavis.edu).

The attempt to remove or reduce the density of a species, even an exotic one, is a challenging undertaking. Eradication is the removal of every potentially reproducing individual of a species or the reduction of their population density below sustainable levels. Many eradication programs are carried out over thousands of hectares, although others are restricted to localized sites. Large-scale projects have greater potential for nontarget impacts and, consequently, tend to be more costly and controversial. Programs in urban areas that involve the use of insecticides usually elicit vociferous protests by environmentalists. The decision to initiate an eradication program is, in some cases, evaluated using ecological considerations and in others is dictated by threatened trade restrictions. Whether eradication should be viewed as a potential approach to invasive exotic species depends both on an evaluation of the costs and benefits of programs[1], and on their potential to be successful. Some of the unanticipated costs of eradication programs might include expenses for public meetings required to alleviate the fears of the residents of areas to be treated with insecticide sprays, and for public relations campaigns to convince taxpayers of the need for increased taxation to support expensive eradication programs. Also, law suits following property damage from insecticide sprays might incur additional costs. Benefits are often hard to estimate if the potential impact of the exotic is difficult to predict and if the time to reintroduction of the exotic is impossible to anticipate[1].

Clearly, there is a need to evaluate the situations for which eradication is a biologically feasible, as well as a politically and environmentally acceptable, approach to exotic species. We attempt to do this by considering some recent eradication programs and by looking at the reasons for their successes and failures. We also outline several alternatives to eradication (Box 1).

The success of some large-scale eradication projects in the past suggests that eradication could have a continuing role in the future. For example, the African malaria vector, the mosquito *Anopheles gambiae*, was eliminated from a large area of northeastern Brazil in the late 1930s in a massive insecticide program[2]. The screw-worm fly (*Cochiomyia hominivorax*) was removed from the southeastern United States in 1958–1959 (Ref. 1), and more recently from Central America[3] and North Africa[4]; the oriental fruit fly (*Dacus dorsalis*) and the melon fly (*Bactrocera cucurbitae*) have been eradicated from the Okinawa Islands in Japan[5,6]. All of these flies have been eradicated using the sterile insect release technique (SIR; Box 2). But, some projects have been ecological and financial disasters. Over $200 million was spent from the late 1930s to the 1950s in futile attempts to eliminate the imported fire ant (*Solenopsis invicta*) from southern USA (Ref. 2). The broad-spectrum insecticides applied in this program had impacts on nontarget species, including humans and native ants. We can look to the lessons learned from these, and more recent, projects to determine if eradication is a procedure of the past or whether it has potential for the future.

Eradication of recent introductions

The rapid discovery of a newly introduced species might allow its elimination on a relatively small scale and with a greater probability of success owing to its less widespread distribution. The removal of the brackish water, black-striped mussel from Cullen Bay in Darwin Harbor, Australia is a recent example[7]. 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 megalitre marina were killed. The long-term environmental consequences of this eradication program are unknown, but might have been reduced because they were confined to a manmade, dredged marina. Regular surveys of international ports in Australia allowed the discovery of this new exotic within six months of its arrival and a rapid decision to eradicate could have prevented its spread locally.

Another recently eradicated marine exotic is the sabellid polychaete worm (*Terebrasabella heterouncinata*) (Box 3)[8]. The sabellid worm was accidentally imported to 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, eradication was achieved by manually removing parasitized and susceptible native hosts to prevent further infestation. This is an interesting example in which the goal was to reduce the density of hosts to such low levels that the parasite could

 0169-5347/00/$ – see front matter PII: S0169-5347(00)01914-5

not persist. Little negative environmental impact resulted from this program because the pelagic larvae of the native gastropods ensured the rapid recolonization of the area.

Eradication and recurrently introduced species

In some situations, repeated eradication efforts of insects are conducted to reduce the spread of the species and in response to threats of trade restrictions. In these cases the designation of the programs as 'eradication' is largely politically motivated and suppression or slowing the spread of the target species might be more realistic goals.

The Mediterranean fruit fly (*Ceratitis capitata*) or medfly, is a vagrant among fruit growing areas and it has the potential for major impacts on fruit production. Multimillion dollar eradication programs were initiated in California in 1975 by the United States Department of Agriculture (USDA) – these continue today (Box 4)[9,10]. Whether newly discovered populations of medflies are the result of new introductions or of failed eradications remains controversial. Studies of the history, distribution, 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.

The gypsy moth (*Lymantria dispar*) is native to Europe and Asia, and was introduced to Massachusetts, USA in 1869 (Ref. 11) (Fig. 1). Established populations now exist in areas of deciduous forests from eastern Canada and New England, south to North Carolina and west into Michigan. Introductions of the species to western North America continue to occur, particularly in years of cyclic outbreaks of the moths in eastern North America, Europe and Asia (Box 5)[12]. In approximately two thirds of the sites the moths do not become established. Trade restrictions from areas in which gypsy moths are established are the primary incentive for continuing eradication of populations as they are discovered. Spraying for gypsy moths using the microbial insecticide *Btk* (Box 2) in urban areas is usually associated with a public outcry that makes these eradication attempts controversial. Moths are frequently caught in eradication areas several years after treatment, indicating a lack of complete effectiveness.

Eradication attempts for established exotics

Nonindigenous vertebrates, such as rats, mice, rabbits, pigs and goats, have become established worldwide and have caused serious habitat destruction. Eradication of these vertebrates from islands has been increasingly successful with chemical poisons and hunting[13,14]. Examples of successful eradications from islands in New Zealand have included the house mouse (*Mus musculus*), the black rat (*Rattus rattus*), the Norway rat (*Rattus norvegicus*) and the European rabbit (*Oryctolagus cuniculus*), as well as feral pigs and goats[15]. A good example of a successful eradication program is the removal of Norway rats from Langara Island on the northwest tip of Queen Charlotte Islands, British Columbia, Canada (Box 6). The eradication of rats from this 3100 ha island was achieved in a matter of months through an intensive poisoning program. The removal of the South American nutria or coypu (*Myocaster coypus*) from the UK (Ref. 16) is another good example of a successful vertebrate eradication program. This is currently the model for a nutria eradication program in eastern USA.

The success of the screwworm eradication in southern USA encouraged other programs for well established, exotic insect pests. However, eradicating established insect species has proven difficult. The codling moth (*Cydia pomenella*) is native to Europe but is a serious worldwide pest of apples. In British Columbia, Canada, a pilot project was initiated in the 1970s to explore the feasibility of eradicating codling moths using the SIR technique (Box 2)[17]. Over several years of the program moth densities were reduced, but at a cost of \$225 ha^{-1} $year^{-1}$ compared with \$95 ha^{-1} $year^{-1}$ for

Box 1. Alternatives to eradication

Area-wide suppression: rather than attempting to eliminate a species, reducing the densities of an exotic pest over a large area can decrease long-term costs of control. The initial program can be expensive and requires the cooperation of all land owners. The integration of a variety of control techniques should be used to reduce the selection for resistance that can occur when insecticide application is the sole means of control.

Slowing the spread: rather than eliminating an exotic species, slowing its rate of invasion might be more cost effective. Sharov and Liebhold[25] developed a model to analyse the value of net benefits for slowing the spread. The model includes the cost of maintaining a barrier zone per length of the population front, the rate of species invasion, the average damage caused by the pest per unit area and unit time and a discounting factor. The optimal strategy resides in the spectrum from complete eradication of the target species, through limiting its spread, and finally to nonintervention, and is influenced as the area occupied by the species increases, the damage it causes decreases or the discount rate increases.

Traditional biological control: exotic species are usually introduced without their natural enemies and, therefore, often maintain much higher population densities in nonindigenous areas than in their native habitats. Introduced natural enemies might reduce the survival and density of the exotic hosts. Screening for host range and the anticipation of nontarget effects should precede the introduction of biological control agents.

Box 2. Techniques for insect control

Mating disruption: many insects find mates through chemical sex attractants. The release of large quantities of sex attractant in an area can confuse the males and prevent them from finding females. This procedure is environmentally sound because the sex attractants are species specific.

Microbial spray: *Bacillus thuringiensis* (*Bt*) occurs naturally in the soil and on the surface of leaves. At sporulation the bacterium forms a toxic protein crystal. The toxin produced by one strain, *Btk*, is specific to Lepidoptera and it is widely used as a microbial insecticide. Because *Bt* does not affect predators or parasitoids and is not toxic to vertebrates, it is preferable to chemical insecticides. The gene for the *Bt* toxin has been genetically engineered into several major crops, including maize and cotton. Insect viruses have also been developed for control and the nuclearpolyhedrovirus of the gypsy moth (Gypchek) has been used in some eradication programs in the USA.

Sterile insect release (SIR): this method is based on rearing, sterilizing and releasing large numbers of males to mate with 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 is expensive but 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.

Box 3. The South African sabellid polychaete worm

The South African sabellid polychaete worm (*Terebrasabella heterouncinata*) parasitizes abalone and other gastropods. The benthic, crawling larvae of the worms attach to the shells of hosts and stimulate them to form a calcified tube in which the worm lives. Infested hosts grow slowly and their shells become brittle and friable[8]. The worm became established at Cayucos, California, near the outflow of an abalone mariculture facility. Two native snails (*Tegula funebralis*) and (*Tegula brunnea*) were the most common and highly susceptible native hosts in the locality.

Studies of the basic biology of the worms showed three characteristics that contributed to the design of the eradication program: (1) the worms were specific to the shells of gastropods; (2) two common *Tegula* species were very susceptible hosts; and (3) large snails were the most susceptible. The goal of the program was to reduce the population of susceptible hosts below the threshold at which the population of worms could be maintained by local transmission[28]. An army of volunteers removed 1.6 million large (>10 mm) *Tegula* from the infested area. No new infections of sentinel snails were observed over two years of observation following the removal program. 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.

Box 4. The Mediterranean fruit fly

Medflies (*Ceratitis capitata*) are native to tropical west Africa and have spread to fruit-growing areas around the world. The flies lay eggs on at least 250 types of fruit and berries, and larval feeding damages the crop. Medflies were originally captured in southern California in 1975. Following a spraying program, they were not detected again in the state until 1980 (Ref. 9). 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 $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 are released weekly in an attempt to suppress reproduction of any wild flies. The potential cost of this pest to the fruit-growing industry is considered high enough to justify continued eradication attempts[29].

The extensive trapping and mapping of the invasion pattern illustrates that original medfly populations might have gone undetected for as long as 50 years, and that the spread of the species has been influenced by local topography rather than being concentric[9]. Areas where a small number of flies were captured in one year usually have more flies captured subsequently. This indicates establishment rather than new introductions. The medfly has also been eradicated several times in Florida[20].

insecticide control. At the end of this program further eradication attempts were not recommended. In spite of this, a new and enlarged eradication program was initiated in the 1980s (Box 7). After five years, codling moth densities were reduced but eradication was still not achieved. In northwestern USA an area-wide suppression program using mating disruption, biological control and SIR has been used[18], and the Canadians are converging on a similar program.

The invasion of the boll weevil (*Anthonomus grandis*) from Mexico into southern USA in the late 1800s had a major impact on cotton production. Research towards eradicating the boll weevil began in 1962 and programs continue to this day. Eradication is considered to have been successful, at least temporarily, in some areas[19]. These programs initially used large quantities of insecticides but with boll weevil suppression fewer sprays were necessary. Interestingly, planting varieties of cotton that express the *Bt* toxin (Box 2) for control of cotton boll worm (*Helicoverpa zea*) reduces insecticide spraying and leads to new increases in boll weevil populations. The estimated $100 million annual cost of the boll weevil eradication program illustrates the difficulties entailed when exotic pest species become well established over large areas. Even so, it might be more appropriately described as area-wide suppression rather than eradication.

Requirements for successful eradication programs

Six factors appear to contribute to successful eradication. First, resources must be sufficient to fund the program to its conclusion. Most eradication projects are carried out on a large scale and cost millions of dollars. This means that government agencies must be involved and additional taxation might be a part of the funding package. However, eradication of a species with a restricted distribution such as the sabellid worm (Box 3), the black-striped mussel and some small plant populations[20] might be carried out relatively cheaply.

A second requirement for successful eradication is that the lines of authority must be clear and must allow an individual or agency to take all necessary actions. Large-scale eradication programs involve treatments or regulations covering private land and across several jurisdictions (agricultural land, municipalities, government owned land and Indian reservations, etc.). 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 (Box 7). In the successful eradications of the sabellid worm, the black-striped mussel and rats from Langara Island the lines of authority were clear. 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 (Box 5), the medfly (Box 4) and the boll weevil programs.

Third, the biology of the target organism must make it susceptible to control procedures. For example, some insects might be more resilient to sterilization by irradiation than are flies and, therefore, SIR will be less effective if their vigor is reduced by the sterilization process (Box 7). The dispersal ability, reproductive biology and life history of the target exotic species will determine the ease of population reduction and its potential for reinvasion. Factors contributing to the eradication success of the sabellid worms were their limited distribution and identifiable preferred hosts (Box 3). The ability to attract the target species to baiting stations is particularly useful when attempting to eradicate vertebrates (Box 6).

Fourth, reinvasion must be prevented. Eradication will only be temporary if the influx of individuals continues. This characteristic should be part of the evaluation of the costs and benefits of potential eradication projects. Elimination of vertebrates from islands might be more successful because the probability of reintroduction is reduced. Conversely, the likelihood of the codling moth being reintroduced to

Fig. 1. The first attempts to eradicate the gypsy moth (*Lymantria dispar*) occurred in Massachusetts in the late 1800s and involved manually removing egg masses. Populations initially declined but underwent a resurgence ten years later[30].

the Okanagan Valley from other apple-growing areas is high (Box 7), and reintroductions of gypsy moths to the Pacific Northwest will continue (Box 5). 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 fifth requirement is that the pest be detectable at relatively low densities. This can lead to its early detection after introduction and before it becomes widespread. Easy detection also allows residual pockets of individuals to be identified and targeted for treatment.

Finally, environmentally sensitive eradication might require the restoration or management of the community or ecosystem following the removal of a 'keystone' target species, such as an exotic predator or herbivore[21]. 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 the 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[22]. Reversing the changes to native communities caused by exotics will often require a sophisticated ecological understanding.

Evaluating the costs and benefits of eradication

Evaluation of the ecological and economical costs and benefits of removing an exotic species is difficult, and often the benefits are exaggerated and the costs are understated[1]. Spraying programs involve nontarget impacts on other members of the ecological community and these effects can be propagated throughout the food web. The benefits of eradication will be compromised if another exotic species simply replaces the original introduced pest. One way to reduce the costs and maximize the benefits is to initiate the eradication program immediately after the discovery of a new exotic, particularly if the species is known to be a pest elsewhere. An example in which the potential for eradication was lost involves the marine alga, *Caulerpa taxifolia*, which was discovered at Monaco in 1984. Eradication was called for in 1991 when its distribution was still limited and removal might have been possible. However, this was not carried out and by now it is widely distributed throughout the area[23,24]. This contrasts with the rapid eradication of the black-striped mussel. The value of a program will also be influenced by the ability to prevent reintroduction.

In some cases, slowing the rate of spread might be more feasible and cost effective for an established species than eradication (Box 1). Whether eradication or slowing the spread yields higher total net benefits is influenced by the size of the population that can potentially be eradicated. Sharov and Liebhold[25] developed a model for the gypsy moth in eastern USA, and concluded that eradication of small populations was more cost effective than slowing their spread across the invasion front. Predictions of models are only as good as their estimated parameter values, and estimating the cost and rate of spread of an exotic is difficult. However, formalizing the comparison of eradication to slowing the rate of spread of an exotic species is a very useful exercise.

For established exotic pests, particularly insects, area-wide suppression (Box 1) is an alternative to eradication, but a more achievable goal. It is difficult to reduce species with high fecundities to such low densities that populations are eliminated, but a concerted control effort over a large area can reduce the long-term impact of an exotic species. The coordinated use of mating disruption, SIR,

Box 5. The gypsy moth

Following its introduction in 1869, eradication attempts for the gypsy moth (*Lymantria dispar*) began in the late 1800s (Fig. 1). These did not stop the gypsy moth becoming established and populations have continued to spread from eastern to western North America[31]. Between 1978 and 1998 gypsy moths were captured at 120 sites in British Columbia, Canada, and 20 eradication programs have been carried out[12]. The largest gypsy moth eradication program in British Columbia followed the capture of 17 male Asian gypsy moths in 1992. Twenty thousand ha were aerially sprayed three times with the microbial insecticide, *Btk* (Box 2). The cost of this program was approximately six million Canadian dollars. Local Agriculture Canada officials predicted that the treatment would eradicate the Asian gypsy moth, but in 1995 two male Asian gypsy moths were captured. The European (North American) form of gypsy moth has been increasing in density in recent years in the vicinity of Victoria, British Columbia, and in the summer of 1999 a $3 million aerial spraying program was carried out.

These programs are interesting because some Canadian authorities consider the gypsy moth to be primarily a potential nuisance pest of 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 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.

Box 6. The Norway rat

Langara Island in the Queen Charlotte Islands was formerly the site of one of British Columbia's largest sea bird colonies with six species of burrow nesting birds (auklets, murrelets and petrels). Between 1971 and 1980, breeding populations of four of these bird species disappeared from the island[32] and populations of the ancient murrelet (*Synthliboramphus antiquus*) were greatly reduced. The Norway rat (*Rattus norvegicus*) was the suspected culprit[33,34]. Two factors prompted a rat eradication program in response: (1) a new anticoagulant rat poison, brodifacoum, had recently been shown to be very effective for rat eradication in New Zealand[35]; and (2) mitigation for the Nestucca oil spill in 1993 resulted in $2.5 million for seabird enhancement.

In July 1995, 3905 bait stations were placed on the island and by August 1995 most rats were gone. No rats were captured in 1996, 1997 or 1998 (Refs 35,36). However, the rapid success of the program was accompanied by some detrimental side effects. Approximately half of the ravens on the island were killed after they learned to extract the poison pellets from bait stations. Eagles would not feed on dead rats, but did eat poisoned ravens and thus also died. Recovery of sea birds has been slow but this might be expected. Some of the factors which made this program successful were available funding, an effective poison, territorial behavior of the rats (which facilitated the distribution of poison to all individuals), the isolated nature of the island and the fact that the rats were already under pressure owing to limited food resources.

Box 7. The codling moth

In the late 1980s a multimillion dollar, sterile insect release (SIR; Box 2) eradication program was initiated for the codling moth (*Cydia pomenella*) in the Okanagan Valley of British Columbia[1,37] by Agriculture Canada and the British Columbia Fruit Growers Association. Five years after the initial sterile male releases in 1994 the percentage of traps with wild moths declined from 98% to 38%. In 1999 levels of fruit damage were very low (Codling moth news. Okanagan–Kootenay Sterile Insect Release Program, http:// www.bctree. com/~oksir/). However, eradication has remained elusive for a variety of reasons. The sterilized males released in the spring did not fly vigorously and did not compete well with wild males for mates. To maximize the ratio of sterile to wild males it was necessary to initially reduce codling moth populations through insecticide applications and to remove sources of moths from outside orchards. This initial reduction phase was slower and more expensive than anticipated. The delayed success of the program caused growers to turn to other controls, such as mating disruption (Box 2) and chemical sprays. After five years the feasibility of eradicating codling moths was re-evaluated and in the winter of 1998 the program goal was changed from 'eradication' to area-wide suppression with the long-term goal of eventual eradication[38].

increasing natural enemies and microbial insecticides reduces the selection for resistance that occurs when chemical insecticides are used in isolation (Box 2).

Traditional biological control (Box 1) has historically been an approach to exotic pests and has led to numerous successes. However, recently discovered, nontarget impacts of several biological control agents have highlighted the need for caution when advocating the introduction of more exotic species to reduce the impact of past introductions[26]. Careful host screening and conservative choices of potential agents should allow biological control a continuing role in dealing with exotic pests.

Prospects

Removing an exotic species is possible, but only under some circumstances and with potentially unpredictable results. The process of eradicating one species will almost certainly have a negative impact on nontarget species, and increasingly vocal and well educated environmental groups protesting these nontarget impacts are capable of putting programs off track. Eradication projects can be doomed to failure if careful planning is abandoned in the zealous attempt to promote the cooperation of taxpayers. Because the eradication of established species is so difficult, agencies should be cautious about promising success if they wish to maintain credibility.

Where possible, eradication projects should be viewed as ecological experiments in which the addition and subtraction of species can reveal community processes. Unfortunately, it is often difficult to obtain quantitative data about past eradication programs. Future and ongoing eradication programs provide excellent research opportunities for ecologists to study the roles of species in communities[27], the impact of the nonindigenous species, and the behavior and population dynamics of exotics for which eradication is being considered.

Acknowledgements

*This article is a summary of papers presented by the authors at a symposium organized by J.R. Carey entitled 'Eradication Revisited', which was part of the International Congress on Ecosystem Health held in Sacramento, CA, USA on 16 August 1999. The congress was supported by the US Environmental Protection Agency. Full-length papers will be published in the proceedings of the congress '*Managing for Healthy Ecosystems*'. J. Cory, A. Ricciardi and two referees kindly provided helpful comments on this article.*

References

1 Myers, J.H. *et al.* (1998) Eradication and pest management. *Annu. Rev. Entomol.* 43, 471–491

2 Dahlsten, D. and Garcia, R. (1989) *Eradication of Exotic Pests: Analysis with Case Histories*, Yale University Press

3 Galvin, T.J. and Wyss, J.H. (1996) Screwworm eradication program in Central America. *Ann. New York Acad. Sci.* 791, 233–240

4 Anonymous (1992) *The New World Screwworm Eradication Programme: North Africa 1988–1992,* Food and Agriculture Organization of the UN

5 Koyama, J. and Tanaka, K. (1984) Eradication of the oriental fruit fly (Diptera: Tephritidae) from the Okinawa Islands by a male annihilation method. *J. Econ. Entomol.* 77, 468–472

6 Kuba, H. *et al.* (1996) The successful eradication programs of the melon fly in Okinawa. In *Fruit Fly Pests: A World Assessment of their Biology and Management* (McPheron, B. and Steck, G., eds), pp. 534–550, St Lucie Press

7 Bax, N. *et al.* Stemming the tide of marine pests: rapid eradication of an introduced dreissenid bivalve in Australia. *Bioinvasions* (in press)

8 Kuris, A. and Culver, C. (1999) An introduced sabellid polychaete pest of cultured abalone and its potential spread to the California gastropods. *Invert. Biol.* 118, 391–403

9 Carey, J.R. (1996) The incipient Mediterranean fruit fly population in California: implications for invasion biology. *Ecology* 77, 1690–1697

10 Carey, J.R. (1996) The future of the Mediterranean fruit fly, *Ceratitis capitata,* invasion of California: a predictive framework. *Biol. Conserv.* 78, 35–50

11 Elkinton, J. and Liebhold, A. (1990) Population dynamics of gypsy moth in North America. *Annu. Rev. Entomol.* 35, 571–596

12 Myers, J. and Rothman, L. (1995) Field experiments to study regulation of fluctuating populations. In *Population Dynamics: New Approaches and Synthesis* (Cappuccino, N. and Price, P., eds), pp. 229–250, Academic Press

13 Bell, B. (1999) The good and bad news from Mauritius. *Aliens* 9, 6

14 Donlan, C. *et al.* (1999) Island conservation action in northwest Mexico. In *Proceedings of the Fifth California Island Symposium* (Browne, D. *et al.*, eds), pp. 330–338, Santa Barbara Museum of Natural History

15 Veitch, C. and Bell, B. (1990) Eradication of introduced animals from the islands of New Zealand. In *Ecological Restoration of New Zealand Islands* (Towns, D. *et al.*, eds), pp. 137–146, New Zealand Department of Conservation

16 Gosling, L.M. (1989) Extinction to order. *New Sci.* 121, 44–49

17 Proverbs, M.D. *et al.* (1982) Codling moth: a pilot program of control by sterile insect release in British Columbia. *Can. Entomol.* 114, 363–376

18 Calkins, C. (1998) Review of the codling moth areawide suppression program in the western United States. *J. Agric. Entomol.* 15, 327–333

19 Smith, J. (1998) Boll weevil eradication: area-wide management. *Ann. Entomol. Soc. Am.* 91, 239–247

20 Simberloff, D. (1997) Eradication. In *Strangers in Paradise: Impact and Management of Nonindigenous Species in Florida* (Simberloff, D. *et al.*, eds), pp. 221–228, Island Press

21 Towns, D. *et al.* (1997) Restoration of New Zealand islands: redressing the effects of introduced species. *Pac. Conserv. Biol.* 3, 99–124

22 Dash, B. and Gliessman, S. (1994) Non-native species eradication and native species enhancement: fennel on Santa Cruz Island. In *The Fourth California Islands Symposium: Update on the Status of Resources* (Halvorson, W. and Maender, G., eds), pp. 505–512, Santa Barbara Museum of Natural History

23 Meyer, U. *et al.* (1998) Invasion of the accidentally introduced tropical alga *Caulerpa taxifolia* in the Mediterranean Sea. In *Plant Invasions: Ecological Mechanisms and Human Responses* (Starfinger, U. *et al.*, eds), pp. 225–234, Backhuys Publishers

24 Meinesz, A. (1999) *Killer Algae,* University of Chicago Press

25 Sharov, A. and Liebhold, A. (1998) Bioeconomics of managing the spread of exotic pest species with barrier zones. *Ecol. Appl.* 8, 833–845

26 Cory, J. and Myers, J. (2000) Direct and indirect ecological effects of biological control. *Trends Ecol. Evol.* 15, 137–139

27 Ricciardi, A. *et al.* (1998) Impending extinctions of North American freshwater mussels (*Unionoida*) following the zebra mussel (*Dreissena polymorpha*) invasion. *J. Anim. Ecol.* 67, 613–619

28 McKendrick, A. (1940) The dynamics of crowd infections. *Edinburgh Med. J.* 47, 117–136

29 Siebert, J.B. and Cooper, T. (1995) Embargo on California produce would cause revenue, job loss. *California Agric.* 49, 7–12

30 Anonymous (1906) *The Gypsy and Brown-tail Moths*, *Bulletin No. 2*, Office of the Superintendent for Suppressing the Gypsy and Brown-tail Moths, Commonwealth of Massachusetts, Wright and Potte

31 Driestadt, S.H. and Weber, D.C. (1989) Gypsy moth in the Northeast and Great Lakes states. In *Eradication of Exotic Pests* (Dahlsten, D.L. and Garcia, R., eds), pp. 229–256, Yale University Press

32 Hobson, K. *et al.* (1999) Norway rats as predators of burrow-nesting seabirds: insights from stable isotope analyses. *J. Wildl. Manage.* 63, 14–25

33 Bertram, D. and Nagorsen, D. (1995) Introduced rats, *Rattus* spp. on the Queen Charlotte Islands: implications for seabird conservation. *Can. Field Nat.* 109, 6–10

34 Drever, M. and Harestad, A. (1998) Diets of Norway Rats, *Rattus norvegicus*, on Langara Island, Queen Charlotte Islands, British Columbia: implications for conservation of breeding seabirds. *Can. Field Nat.* 112, 676–683

35 Taylor, R. Eradication of Norway rats for recovery of seabird habitat on Langara Island, British Columbia. *J. Restoration Ecol.* (in press)

36 Kaiser, G. *et al.* (1997) *The Langara Island Seabird Habitat Recovery Project: Eradication of Norway Rats (1993–1997)*. Canadian Wildlife Service, Pacific and Yukon Region, British Columbia, Technical Report Series No. 304

37 Winston, M. (1997) *Nature Wars: People Versus Pests*, Harvard University Press

38 Fisher-Fleming, B. *et al.* (1998) *Report to the SIR Board, 4 December*, Okanaga–Kootenay SIR Technical Committee