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*Synthesis*

# Assessment and Management of Invasive Alien Predators

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ABSTRACT. Although invasive alien species have been identified as the second greatest threat to biodiversity after habitat loss, characterizing and quantifying their impacts on native species and habitats remains a fundamental problem in conservation biology. Here, I review the techniques that are currently used to assess the impact of invasive alien species on biodiversity, highlighting both their uses in invasive species ecology and their limitations in establishing a causal relationship. Adopting a hypothesis-driven experimental approach to impact assessment, and to eradication efforts through adaptive management, would benefit our ecological understanding of invasive species without delaying critical management action that could reduce the spread of invasive species populations.

## INTRODUCTION

Invasive alien species (IAS) are considered one of the most important threats to global biological diversity (Earth Summit, Rio Convention 1992 (http://www.biodiv.org); Vitousek et al. 1996). Alien species have colonized virtually every ecosystem type on Earth and affected the native biota (Vitousek et al. 1997). They have contributed to the local and global extinction of hundreds of species (cf. Witte et al. 1992, Vitousek et al. 1996, Fritts and Rodda 1998, IUCN Council 2000). The ecological cost of some invasions is the irretrievable loss of biological diversity and the transformation of ecosystems (IUCN Council 2000). Invasive alien species are found in almost all taxonomic groups. Some of the most dramatic invasions involve predators, such as the Nile perch (*Lates niloticus*), introduced to Lake Victoria in the 1950s and a contributing factor in the extinction of more than 200 endemic fish species (Witte et al. 1992). The introduction of alien predators can have particularly marked consequences on island ecosystems because of the evolutionary isolation of native species (Courchamp et al. 2003). Current measures to reduce the threat posed by IAS include: prevention, early detection, and assessment and management. This synthesis focuses on assessment and management.

Although the threats posed by IAS can be severe, there is considerable uncertainty about the nature of their impacts on species and ecosystems, and how these impacts can be reduced or reversed through human intervention. Many studies have detailed the effects that IAS have on indigenous communities and the possible consequences for biodiversity (e. g., Fritts and Rodda 1998, Mack and D’Antonio 1998, Ricciardi and Maclsaac 2000). However, there has been little discussion concerning the techniques used to quantify these effects (but see Caughley and Gunn 1996, Calver et al. 1998, Parker et al. 1999, Courchamp et al. 2003). In this paper, I assess the uses and limitations of such techniques, focusing particularly on the impacts of IAS predation on wildlife, and show how impact assessment and management could be improved through the use of hypothesis-driven experiments and adaptive management, respectively.

## IMPACT OF INVASIVES

The term “invasive alien species” has been defined by the International Union for Conservation of Nature and Natural Resources (IUCN 2000) as “an alien species which becomes established in natural or semi-natural ecosystems or habitat, is an agent of change, and threatens native biological diversity.” This terminology focuses on the impacts on biodiversity, as does this review. However, other impacts that IAS can have, for example, on the economy through effects on agriculture, forestry (e. g., grey squirrels, *Sciurus carolinensis*, in Europe (Bertolino and Genovesi 2002)), and fishing (e. g., Nile perch (Witte et al.

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1992)), and through structural damage (e. g., zebra mussels, *Dreissena polymorpha* (New York Sea Grant 1994)), can also be severe.

The effects of IAS on native flora and fauna can be direct or indirect. Ebenhard (1988) suggested that the following six kinds of interactions (or combinations of them) are usually involved: herbivory, predation, competition, acting as a vector of disease or toxic effects, hybridization, and acting as prey for native predators. Invasive alien species can also alter habitat structure and disturbance regimes, for example, the rooting and wallowing habits of feral pigs, *Sus scrofa*, have caused extensive damage to soil and vegetation in the many countries to which they have been introduced (cf. Maguire 2004). Invasive plants can have profound ecosytem effects by, for example, altering disturbance regimes, lowering water tables, and increasing soil salinity levels (cf. Mack and D'Antonio 1998, D'Antonio 2000, Le Maitre et al. 2002). Synergistic interactions among IAS may accelerate their negative impacts on native species, a process that has been referred to as "invasional meltdown" (Simberloff and von Holle 1999). They can have a top-down impact on an ecosystem through predation, herbivory, or disease, for example, the impacts of brown trout, *Salmo trutta*, on invertebrate populations (Huryn 1998); the predatory impacts of European green crab, *Carcinus maenas*, on coastal communities (Grosholz and Ruiz 1996); or the impacts of herbivory on New Zealand forests (Nugent et al. 2001). However, they can also have a bottom-up impact by limiting resources, for example, the impacts of alien invasive trees on water resources (Le Maitre et al. 2002); the competition and predatory effects of vendace, *Coregonus albula*, on fish communities (Bohn and Amundsen 2001); or the impacts on horned lizard, *Phrynosoma coronatum*, populations caused by the Argentine ant, *Linepithema humile*, invasion (Suarez and Case 2002).

## MANAGEMENT ACTION ON INVASIVES

How do we respond to IAS, given the impact that they can have? Although species do not recognize country boundaries, the measures employed to deal with IAS are implemented by individual countries, and these measures vary widely. International conventions, such as the Convention on Biological Diversity (Earth Summit, Rio de Janerio, 1992), can provide a framework for international cooperation and agreements on joint action on IAS. Current action can be broadly divided into prevention, early detection, and the assessment and management of established species (Global Invasive Species Programme (GISP), http://www.gisp.org).

### Prevention

It is widely agreed that preventing entry of IAS, or alien species that are likely to become invasive, is more effective than attempting to manage them once they have arrived (IUCN 2000). The GISP online toolkit (Wittenberg and Cock 2001, http://www.cabi-bioscience.ch/wwwgisp/gtcsum.htm) outlines pathways for alien species introductions, and how these can be tackled using risk assessment for deliberate introductions, such as black or white lists (Shine et al. 2000). Whereas black lists prohibit the introduction of species known to be invasive, the recent, more precautionary, approach of white lists allows the introduction of only those species that are not considered harmful. Pied or gray lists can provide a combination of both approaches.

### Early Detection

Because many biological invasions are characterized by a relatively slow colonization period followed by rapid range expansion (Crooks and Soule 1996), attempts to eradicate IAS populations are most likely to succeed if control measures are undertaken at an early stage (e. g., coypu, *Myocastor coypus* (Gosling and Baker 1989); invasive plants (Hobbs and Humphries 1995); invasive seaweed, *Caulerpa taxifolia* (Meinesz 1999)). Therefore, alien species provide a good example of a case where the precautionary approach (e. g., Foster et al. 2000) is particularly appropriate. The effective detection of IAS requires systematic and regular monitoring by trained personnel. Public awareness campaigns for particular pests, such as the Colorado beetle (*Leptinotarsa decemlineata*) in the UK, can also increase the probability of an introduction being detected and reported, and eradication measures being employed swiftly. This system can be quite effective for known agricultural pests. However, where the invasive status of a species is less clear, or the species is able to command public affection, eradication measures are often delayed to allow further research or wider consultation. "Many introductions that could probably have been quickly stemmed ultimately went out of control because of demands for deeper study of whether they were likely to become invasive"

(Simberloff 2003). Detailed knowledge of population biology may not always be crucial for successful eradication or effective management (Simberloff 2003). In some situations, knowing which herbicides are most successful, or the frequency with which bait traps should be deployed, can be more critical to management success than the detailed population biology (Simberloff 2003). The consequences of delaying early control to stop the spread of species likely to become invasive is well illustrated by the example of the grey squirrel in Italy (Bertolino and Genovesi 2002) and the feral goat, *Capra hircus*, in the Galapagos (Herrero 1990, 1997). In both cases, delay resulted in large increases in the abundance and range of the alien species, with a consequent increase in the cost of eradication and a reduction in its feasibility.

### Assessment and Management of Established Species

Given the potential impacts of IAS and the dangers inherent in allowing potential IAS to establish and spread, why not eradicate all alien species? Some factors that may influence decisions about management of alien species are detailed below:

1. IAS may provide economic benefit or an important resource.
2. IAS may have some cultural value (e. g., Pacific rat, *Rattus exulans*, in New Zealand) that may make eradication unpopular as a management goal.
3. Only a small proportion of alien species become invasive (e. g., Williamson 1996). Management would be better directed at those species known to be, or likely to become, invasive. Therefore, it is important that we be able to assess the impacts of alien species.
4. Eradication may not be considered feasible, and resources may be better directed toward containment or other mitigating measures.
5. Eradication may have undesirable consequences (e. g., mesopredator release, see “Experimental removal,” below).

The last three factors listed here relate to the uncertainty about the impact of IAS and the consequences of eradication, and suggest the need for further research. In the next section, the techniques available for assessing impacts of invasive species are reviewed.

## ASSESSING IMPACTS OF INVASIVE ALIEN SPECIES

Why does it matter how the impacts of IAS are assessed? Indeed, why does it matter whether the precise nature of the cause-and-effect relationship between invasives and native wildlife is understood? For wildlife managers responsible for an eradication program, it may matter very little unless such knowledge improves management or alters a management decision. In recent years, it has been recognized that understanding the mechanisms governing interactions between alien and native species can increase the effectiveness of management action (Martin et al. 2000, Kiesecker et al. 2001). For organizations and individuals charged with securing resources and support for IAS management programs, impact assessment can be far more important. The decision to eradicate or remove an IAS population is often controversial (e. g., Rainbow lorikeets, *Trichoglossus haematodus*, in New Zealand (http://www.rainbow.org.nz/); grey squirrels in Italy (Bertolino and Genovesi 2002)). Although antipathy for any specific eradication is often related to the popular appeal of the species, doubts over the perceived impact of that species can also be an important factor. Ensuring that the science underpinning the decision to eradicate is sound can be an important first step in securing political and public support.

### Why are Impacts Hard to Evaluate?

Despite the fact that some alien species are known to have detrimental effects, these effects are not always easy to characterize or quantify. For example, it is assumed that IAS have a negative impact on the population growth rate, $r$, of one or more native species, but a direct measure of $r$ is rarely attempted (cf. Juliano 1998, Dumitru et al. 2001, Keitt et al. 2002). Some of the best documented examples of the impacts of IAS come from studies of islands (e. g., the brown tree snake, *Boiga irregularis*, on Guam (Fritts and Rodda 1998); invasive plant species on Hawaii (Mack and D’Antonio 2003)), recent and current invasions (e. g., North American mink, *Mustela vison*, in the UK (Aars et al. 2001); purple loosestrife, *Lythrum salicaria*, in North America (Blossey et al. 2001)), charismatic or endangered species (e. g., the red fox, *Vulpes vulpes regalis*, and the Californian clapper rail, *Rallus longirostris obsoletus*, in the United States (Harding et al. 2001)), or species of economic importance (e. g., zebra mussel in the Great Lakes (New York Sea Grant 1994)). However, even in well-documented cases, there is often a lack of basic biological information on the introduced species (Hager and McCoy 1998, Parker et al. 1999). Characterizing and quantifying the impacts on native flora and fauna can be problematic because of the timing of the study in relation to the invasion, the complicating effects of multiple invasions, the scale of the study in relation to the invasion, and spatial and temporal variations in impacts.

## Assessing the Impact of Invasive Alien Predators

Alien predators can have particularly severe impacts on native prey populations because of prey naivety, and because they are sometimes able to maintain themselves at high population densities, at least temporarily, through their association with humans (cats and rats for example) or because they are no longer limited by their natural predators, competitors, or parasites (the Enemy Release Hypothesis—Elton 1958, Dobson 1988, Torchin et al. 2003). The direct effects of predation on prey dynamics will depend on the predator's functional and numerical responses to changes in prey abundance (Begon et al. 1990, Solomon 1949). Most invasive alien predators are generalists, whose numbers are not greatly limited by the decline of any one prey species (see Table 1, Dietary Studies). Predation may also have sublethal effects on prey behavior and physiology through stress (e. g., Boonstra et al. 1998). Prey populations may respond to predation by shifting their habitat use or range, what Ebenhard (1988) termed "abundance shifting predation." This may have consequences for the predators and prey of the native species, and, in extreme cases, lead to a "trophic cascade" process (e. g., Charlebois and Lamberti 1996, Townsend 1996, Nystrom et al. 2001), in which impacts that directly affect one trophic level have knock-on effects that filter through to other levels. Alien predators may also cause apparent competition between introduced and native prey species, whereby an introduced prey population exerts a negative effect on the population dynamics of a native prey population through a shared predator species (e. g., Norbury 2001). For example, native skink, *Oligosoma* spp., populations in New Zealand are believed to suffer from apparent competition with introduced rabbit, *Oryctolagus cuniculus*, populations that support high densities of introduced ferrets, *Mustela furo*, and cats (Norbury 2001). Norbury (2001) found that predation of skinks increased markedly after sudden declines in rabbit abundance, because predators remained abundant, but switched to feeding on skinks.

Techniques that have been used to assess or predict the impact of an alien predator include: predictions from studies in other geographical locations, correlational analysis of abundance data, dietary analysis, demographic and behavioral studies, and experimental removal or exclusion of the alien species. Each of these approaches provides information on different aspects of the relationship between alien and native species, and these are described below and summarized in Table 1.

## Predictive Techniques

Extrapolating the observed impacts of a particular IAS to a different situation (e. g., different geographical area) is probably the quickest way of assessing the possible impacts that this species may be having or may have in the future. There are now several on-line databases that have been, or are being, developed to allow the invasion history of particular species to be investigated. The Global Invasive Species Database (http://www.issg.org/database/welcome), developed by the IUCN and the Invasive Species Specialist Group (ISSG), contains information on the ecology, distribution, impact, and management for a large number of IAS. It also contains a habitat-matching model that may enable researchers to predict regions most at risk from invasion. Individual countries may also have invasive species databases (e. g., the National Biological Information Infrastructure in the USA, http://invasivespecies.nbii.gov). These databases are particularly useful for widespread IAS where the impacts on a range of native species or communities are well described, and may help in preventative action or priority setting for conservation action. They cannot, however, provide any information on the impact that an IAS is having on a particular system, and, as such, the presence of a species in a database cannot be taken as evidence of the nature of any impact, nor should its absence suggest that a negative impact is unlikely.

## Correlations in Abundance and Range

Examples of correlations include situations where an increase in the abundance of an IAS correlates with a decrease in the abundance or range of a native sympatric species, or where the introduction of an IAS coincides with the extirpation of a native species.

**Table 1.** Techniques used to assess the impact of predatory invasive alien species

| Technique | Description/methods/outputs | Advantages | Disadvantages |
|---|---|---|---|
| Predictive techniques* | Use of information from species that have invaded different geographic areas or ecosystems[1] | Quick | Cannot inform about new situations, impacts or mechanisms of impact. |
| | Use of invasible ecosystems[2, 3] and invasive species characteristics[4–6] | Inexpensive | |
| | Food web analysis[7] | Aid for prioritizing action | |
| Correlations in abundance and range | Correlation between the timing of arrival or increase in range or abundance of IAS with the extirpation or decrease in range or abundance of a native species | Data can be relatively easy to collect or past records of abundance or range may be used. | Cannot derive causal relationship.<br>Cannot inform on the mechanism of impact. |
| | | Where experimental manipulation is not considered feasible, it may be the only source of information. | Problem in some studies with independence of multiple sites[9–10] |
| | | Can provide persuasive circumstantial evidence provided relationship is found at multiple independent sites and confounding variables can be eliminated[8] | Potential confounding variables (e. g., habitat loss, overhunting, pollution) over same period as introduction[11] |
| Dietary Analysis | Analysis of IAS diet used to assess which species may be affected through herbivory, predation, or competition | Qualitative and quantitative information on potential species affected by introduction and spread of an IAS | Bias in dietary analysis can lead to under- or over-representation of particular species or groups |
| | Methods: direct observation,[12] prey items returned to den or nest sites,[13] stomach contents,[14] fecal/scat analysis,[15] marks left on carcass/eggs,[16] stable isotope analysis of IAS tisssue samples[17] | In combination with mathematical modeling, using a prey population model can provide an assessment of likely impact[19, 20] | Number of individuals, or proportion of prey population taken, is not a measure of impact although this is sometimes implied[11, 17, 21] |
| | Potential outputs: number of prey items taken,[18] proportion of prey population taken,[10] energetic contribution to IAS diet[16] | | |

| | | | |
|---|---|---|---|
| Demographic/ behavioral studies | Investigation of demographic or behavioral traits that may be attributed to IAS under laboratory, semi-field, or field conditions | May provide first indication of impact | Potential confounding variables (e. g., habitat loss, overhunting, pollution) over same period as introduction |
| | Potential outputs: differences in survival,[22] sex ratios,[23] population age structure, [24] behavioral traits[25] between areas/replicates, etc. | May inform on potential future impact[25] | Without experimental manipulation, a causal relationship cannot be established |
| | | May inform on mechanism of impact[24] | |
| Experimental Removal | Removal,[26] reduction, [27, 28] or exclusion[29] of IAS from monitored areas | May be used: to test impact of IAS, to assess a trial eradication, as part of an adaptive management strategy[37] | Lack of response from native population may result from: inadequate design or sample size, inappropriate timescale, need for other restorative measures[38, 39] |
| | Methods: differences in, e. g., population size, survival, etc. can be monitored using before/after or removal/non-removal areas. A combination of both provides the most rigorous design[30] | May derive causal relationship | Possibility of mesopredator release,[40] and other secondary effects[41] |
| | Potential outputs: changes to survival, breeding,[26, 31, 32] or foraging success, population size,[27, 33–36] or changes in demographic characteristics | May reduce impact for the duration of the study | |

* Examples cited as “Predictive techniques” are not specifically related to predatory IAS, but invasive species in general). As some of the techniques described represent a wide range of assessment tools, methods and potential outputs are not included for all those listed.

[1]Global Invasive Species Database (IUCN), [2]Lodge 1993, [3]Lonsdale 1999, [4]Williamson 1996, [5]Kolar & Lodge 2001, [6]Kolar & Lodge 2002, [7]Memmott 1999, [8]Caughley & Gunn 1996, [9]Strachan et al. 1998, [10]Ferreras & MacDonald 1999, [11]Newman & McFadden 1990, [12]Brown et al. 1993, [13]Redpath & Thirgood 1999, [14]Drever & Harestad 1998, [15]Chanin 1980, [16]Jackson & Green 2000, [17]Hobson et al. 1999, [18]Apps 1984, [19]Cuthbert & Davis 2002, [20]Dumitru et al. 2001, [21]Cole et al. 1995, [22]Crossland 2000, [23]Leslie & Spotila 2001, [24]Cree et al. 1995, [25]McDonald et al. 2001, [26]Craik 1998, [27]Harding et al. 2001, [28]Allen et al. 2001, [29]Jackson 2001, [30]Parrish & Ussher 2002, [31]Imber et al. 2000, [32]Cruz & Cruz 1987, [33]Nordström et al. 2002, [34]Nordström et al. 2003, [35]Kinnear et al. 2002, [36]Killion et al. 1995, [37]Innes et al. 1999, [38]Rushton et al. 2000, [39]Foin et al. 1997, [40]Courchamp et al. 1999, [41]Zavaleta et al. 2001.

These correlations cannot be used to infer cause and effect: the two events may be entirely unlinked, or they may both be responses to another causal agent, such as habitat fragmentation. Correlational information is often used in studies of IAS in freshwater and marine environments, where it is frequently not possible to manipulate a system experimentally (e. g., Witte et al.1992). Where experimental manipulation of the system is not feasible, an assessment of the geographical and temporal consistency of correlative information can strengthen the hypothesis that the IAS is the causal agent of decline (Caughley and Gunn 1996). Caughley and Gunn (1996) posed a series of questions that should be asked in any such assessment:

1. Did the decline begin after the introduction of an alien species?
2. Does an increase (in range or abundance) of the IAS correlate with a decrease in the native species?
3. Can these temporal–spatial relationships be observed at multiple independent locations?
4. What are the potential confounding variables?

It may be reasonable to infer that the invasive species is the causal agent of decline if the answers to questions 1–3 are "yes," and if potentially confounding variables (such as habitat destruction, pollution, over-hunting by humans) can be controlled for or discounted.

## Dietary Analysis

Analyzing the dietary intake of an IAS provides evidence of what is being eaten and can provide information on which native species are most likely to be affected by its presence through herbivory, predation, or competition. It is important to monitor dietary intake over appropriate time scales as the impact may only occur at specific times of year, and diet can change dramatically throughout the year. The most common method of investigating diet is to identify as many prey items as possible from fecal or gut samples and calculate the relative abundance of prey items in the samples to be assessed. Both fecal and gut analyses provide a short-term dietary picture, and are biased toward distinctive prey items that are harder to digest, whilst other prey items may go unrecorded (Litvaitis 2000). In some cases, correction factors have been derived to account for some sources of bias in fecal analysis (e. g., Brzezinski and Marzec 2003). Stable isotope analysis of tissues can provide a longer-term picture of diet, but generally cannot provide information on specific prey species of interest (but see Hobson et al. 1999). The contribution of different prey species can also be expressed in terms of energy; using calculations of the energetic requirements of the IAS, the numbers of individuals consumed can be derived. For prey species with known population sizes, the proportion of individuals taken can also be calculated (e. g., Ferreras and Macdonald 1999). For some species, it may be possible to directly observe predation events or monitor prey items that are brought back to regular feeding areas after foraging trips. This can yield useful information not provided by other methods. Behavioral observations can also provide the proof that an IAS is responsible for killing a prey species, rather than scavenging (e. g., cats on Dassen Island (Apps 1984)). Whatever the advantages and disadvantages of each of these methods, dietary analysis, or monitored predation events, can at best reveal the relative quantities of different prey species eaten by a predator; on their own, they cannot be used to assess the impact of the predator on prey, although this is often inferred or stated (e. g., Cole et al. 1995, Hobson et al. 1999, Ferreras and Macdonald 1999). Dietary information can also be used in combination with prey population models to provide a prediction of the impact of that level of predation on the prey population (e. g., Cuthbert and Davis 2002, Dumitru et al. 2001).

## Demographic and Behavioral Studies

These can often provide the first indication that, for example, a population is undergoing range contraction or a decline in abundance. They can also suggest the mechanism through which the impact occurs, as is illustrated below using the example of the sphenodontian reptile, the tuatara, *Sphenodon punctatus punctatus*, and the Pacific rat (or kiore). When the ages of tuatara from kiore-inhabited and kiore-free islands were compared, it was found that up to a third of the individuals captured on kiore-free islands were juveniles or small adults, whereas no juveniles were found on islands with kiore (e. g., Cree et al. 1995). The hypothesis arising from this observation, that kiore impact on tuatara populations through predation on juveniles or eggs, was then tested by experimental removal of kiore (e. g., Towns 1988). Experimental studies in which demographic or behavioral data are collected under manipulated conditions can provide clues as to the mechanism of impact, or alert researchers to *potential* risks of IAS range expansion bringing the alien species into contact with a currently unaffected native species. Concern over the effect that the introduced European green crab would have if it invaded the nursery grounds of the native Dungeness crab (*Cancer magister*) led researchers in the USA to set up laboratory experiments that showed that green crabs can out-compete Dungeness crabs for food and shelter (McDonald et al. 2001). Subsequent field and laboratory enclosure experiments showed that juvenile Dungeness crabs emigrate from their favored habitat as a result of both competition from and predation by the green crab (McDonald et al. 2001). The organisms of concern and the impact being tested will largely dictate what kind of experimental manipulation is possible—these range from laboratory experiments designed to test specific rates or behaviors under different conditions, to semi-field or field studies that may allow the whole response of a species or community to be investigated under differing degrees of control.

The techniques described thus far may be able to provide varying degrees of probabilistic evidence for an IAS being responsible for, e. g., a decline in another species. They can also be very useful in providing information with which to form a hypothesis that can then be tested. Ultimately, however, experimental manipulation of the system is required for the IAS to be identified as the causal agent of such a decline (Caughley and Gunn 1996).

### Experimental Removal

Does the removal or exclusion of an alien species from an area result in improvements in the survival, foraging, or breeding success of a declining native species? Is this reflected in a recovery of the population range or abundance? By experimentally removing or excluding predators from certain areas and monitoring the response of the prey species it may be possible to answer these questions directly, and to test the hypothesis that it is the introduced species that is responsible for a change in the status of another species or ecosystem. Although it may never be possible to demonstrate that a historical decline in the abundance or range of a species was due to the introduction of an alien species, manipulation of the system (i. e., experimental removal or exclusion, Table 1) can indicate that the alien species may be one reason for current low population sizes or a constricted range. Experimental removals can also inform on the feasibility and consequences of eradication, perhaps as part of an adaptive management program (see below). Unfortunately, if there is no measurable response to removal or exclusion of an alien species, it does not necessarily mean that there is no impact; it could be that the experimental design or sample size was inadequate, or that the species requires a longer time span to recover than allowed for by the experiment. Lastly, the native species of concern may require more than invasive predator removal for a positive effect to be detected, such as habitat restoration and sympathetic management strategies (e. g., Rushton et al. 2000). There is also the potential for alien predator removal to have unexpected and unwelcome effects, particularly when other alien predators are also present (Courchamp et al. 1999, Zavaleta et al. 2001). Zavaleta et al. (2001) suggest a number of ways in which the risk of adverse effects of eradication schemes may be assessed, and a well-constructed experimental removal can provide a means of testing these assessments before attempting to carry out a full-scale eradication.

## THE USE OF ADAPTIVE MANAGEMENT FOR INVASIVE SPECIES

Our wealth of experience with the consequences of delaying management action suggests that the use of the precautionary principle (adopted by the 1992 Convention on Biological Diversity) is particularly advisable in relation to IAS. The adoption of the precautionary principle for IAS stipulates that uncertainty in either the impact of alien species, or how best to remove them, should not be used as a reason to delay management action (but see Hager and McCoy 1998). Predictive techniques (using information on whether a species is invasive elsewhere, ecological similarities between its native and introduced range, invasive characteristics, etc.) are used by management and conservation agencies to help identify potentially problematic species (Table 1). Ideally, this is done before the species reaches the critical phase of range expansion, but very often it is an increase in range expansion that draws attention to the potential problem. Adaptive management has long been considered a useful framework for managing natural resources (Holling 1978, Walters 1986, 1987, Walters and Holling 1990), and has been heralded as a potential solution to complex large-scale issues, including socio-economic and ecological considerations (Nichols et al. 1995, Salafsky et al. 2002); for example, agriculture, fisheries, land management, harvesting, water resources, and species conservation (e. g., Leiva and Castilla 2001, Brook et al. 2002, Stankey et al. 2003). The potential for adaptive management or "active adaptive management," as a framework for the management of IAS is now starting to be recognized, but is currently under-utilized (Shea et al. 2002, Miller and Gunderson 2003, 2004). We have seen in the previous section how an experimental approach can be used to test hypotheses concerning the impact of a particular alien species. Similarly, adaptive management can be used to test hypotheses about the response of IAS populations to control measures, and about the feasibility and consequences of eradication. Adaptive management is based on two main premises: the first is that uncertainty exists in the system to be managed and reduction of uncertainty would improve the management process; the second is that, despite this uncertainty, management decisions need to be made periodically (Kendall 2001). From these criteria, it appears that invasive species control is a good candidate for adaptive management.

Adaptive management has been described as "learning by doing" (Walters and Holling 1990), which has an iterative testing process at the core of its approach to management, as opposed to a more reactive type of management. In relation to IAS, this entails more than designing strategies to control or eradicate invasive species, and either continuing with them regardless of the results or modifying the strategy as a reaction to unexpected results (the "fire-fighting approach," Shea et al. 2002). Throughout the stages of an adaptive management approach outlined below, a deliberate plan is devised that acknowledges the uncertainty that exists in the system and uses management experiments not only to reduce important areas of uncertainty, but to consider and predict outcomes of alternative management strategies. In this way, new information can be integrated into a modeling framework such that management strategies are adapted and improved in order to achieve the original objectives. The objectives of IAS management are usually fairly straightforward, as the primary goal is to minimize the size of the population. For a particular program, managers may want to be more specific and perhaps incorporate objectives relating to the size of the population reduction over a particular time period, or a particular area in which reduction should be greatest. As the ultimate aim of an IAS control program is to alleviate the impact on other wildlife, another objective may be to increase the population size or breeding success or juvenile survival, etc. of a declining species (e. g., kokako, *Callaeas cinerea wilsoni*, and introduced mammal control (Innes et al. 1999)).

The adaptive management process can be divided into three phases: assessment, system modeling, and management experimentation. Each of these is discussed in turn below, with specific reference to IAS management.

## Assessment

What is known about the system? Here, information about the system (the species or ecosystems in question, control methods, previous data or experience, expert opinion, etc.) is assessed. If one objective is to alleviate the impact of the invasive species, it would be useful to include information on the nature of the impact. Where the cause of the decline of a species is not clear, but IAS are implicated, information on both the alien species and the declining species can be used to form a working hypothesis that can then be "tested" by management action (e. g., Innes et al. 1999). Any data on the demographic characteristics of the IAS should be collated and assessed here. How these factors vary with population density is likely to be very important, as it will inform on how the population may respond to a reduction in their numbers through culling or removal. Variability of demographic characteristics over space can also have important implications for where management actions may best be targeted (Travis and Park 2004).

## Modeling the System

At this stage, construction of dynamic computer models can integrate the pertinent data and information from the assessment phase in order to provide a mathematical representation of the system as it is currently understood, and predict the outcomes of particular management strategies. There are a variety of ways in which uncertainty in the system can be manifested, and these are briefly outlined below (see Hilborn and Mangel (1997), Harwood and Stokes (2003) for further discussion).

1. Observation error comprises measurement error (a consequence of the way data are sampled and measured) and estimation error (which arises from the statistical method used to estimate the system parameters).
2. Process error (or process stochasticity) represents the natural demographic and environmental stochasticity in system parameters.

3. Model error—by definition all models are simplifications or approximations of reality. The consequence of choosing one model over another could potentially suggest differing management strategies that may produce quite different results.

Uncertainty in system parameters and choice of model can be incorporated into management models using a variety of statistical techniques and approaches (see Harwood (2000), Wade (2000), Harwood and Stokes (2003), and references therein). Risk assessment and decision analyses (Harwood 2000, DEFRA 2003, Maguire 2004) can be used as the model framework within which multiple management objectives (if required) and uncertainty in the system can be addressed. The purpose of these models is to make predictions about the response of the IAS population (and perhaps also affected native wildlife populations) to alternative management strategies, including the strategy of doing nothing. The modeling phase of the adaptive management has three important roles: firstly, it helps clarify the problem, the assumptions being made, and the uncertainty that exists in our understanding of the system; secondly, it allows an elimination of strategies that appear very unlikely to meet the management objectives; finally, it can inform on those areas of uncertainty that appear to be the most crucial for increasing the predictive power of the model, and have the greatest consequences when comparing predictions of alternative strategies.

## Management Experimentation

What are the management options? Here, options concerning the best time of year for culling or control operations, the methods to be used, the age or stage to target, etc., can be considered. If the impact of a specific IAS particularly affects breeding birds, for example, would it best to cull just before or during breeding season, or to concentrate removals in specific areas? What effect do these options have on the predicted outcomes? For invasive species, management experimentation should also be used to provide evidence of the impact of that IAS on other wildlife in an experimental manner, e. g., the management of invasive predators and browsers on kokako populations in New Zealand (Innes et al. 1999). Experimental trials of alternative strategies may result in novel and improved methods for eradication. For example, in recent years, dogs have been found to be be useful in locating a variety of invasive animals, particularly when they are at low densities, as other methods of catching them may be very inefficient at this time (e. g., Brown and Sherley 2002). The use of dogs has now been extended to trials to locate low-density noxious weeds that could otherwise be extremely time consuming and problematic to find (University News, Montana State University, Dec. 3, 2003).

In order to assess whether the objectives of the project have been met, it is necessary to monitor relevant measurements, such as the population size or indices of the IAS population, and particular demographic characteristics of other wildlife populations (e. g., Innes et al. 1999). In some situations, it may be possible to combine removals with an estimation of population size, for example by using distance sampling (Buckland et al. 2001). Alternatively, indices of activity levels can be derived from measures of trapping success, although it would be desirable to be able to relate this to population sizes. That follow-up monitoring is required may sound obvious, but it is often neglected in IAS management (e. g., Wooten and Renwyck 2001), making it impossible to assess whether the current management is successful, or if alternative strategies should be considered. In addition, if a program is able to demonstrate that removal of a particular IAS is leading to recovery of native species or ecosystems, support for it (and future programs) may be strengthened.

Adaptive management is an iterative process, a trial of the management strategy predicted to produce the desired result, followed by an assessment of the outcome, and the adaptation of future management actions in light of this new information (Johnson 1999, Shea et al. 2002). Uncertainty within such a context does not constitute a reason to delay action, but to manage and research simultaneously for the effective management of alien species. To date, however, examples of successful implementation of this approach in resource management are relatively few (but see Williams et al. 1999, Johnson and Case 2000). In some cases, the assessment phase of the program is successfully completed, but the experimentation phase never implemented (e. g., Gunderson 1999, Johnson 1999). Sometimes this may be due to the lack of support, long-term vision, or funding that this approach to management requires (e. g., Stankey et al. 2003). Another, more fundamental, reason is that adaptive management often involves experimenting with systems from which people gain resources and income (e. g., Maguire 2004), and this may involve increasing the amount of risk to their livelihoods. Stakeholders with differing values and objectives may be able to veto particular strategies that they feel carry too high a risk for them, resulting in a stalemate (Gunderson 1999). In contrast to resource management, the objectives and optimal control strategies for IAS are relatively easily defined, and there are usually fewer sociological aspects to consider. Exceptions to this include IAS that are seen as having cultural value, such as kiore in New Zealand (ERMANZ 2002), or as an important resource, e. g., feral pigs in Hawaii (Maguire 2004).

## CONCLUSIONS

The aim of this synthesis was to review techniques used to assess impact of invasive alien predators, to suggest how we might improve the science behind impact assessment, and to promote the use of adaptive management in invasive species management. The techniques outlined, however, are applicable to many other invasive species taxa, with the exception that dietary analysis is clearly only of use for animal species. For newly arrived alien species that may become invasive, monitoring and removal constitute the best way of preventing establishment, and many countries have legal controls and on-going surveillance to try and achieve this (e. g., the Animal and Plant Health Inspection Service in the United States). For more established species that require assessment and management, I have argued that the limitations of many of the techniques used to assess impact are not always recognized. I have suggested that impact assessment could often be greatly improved through a hypothesis-driven experimental approach, that would not only deliver better science but offer information that could also feed into adaptive management programs and contribute to the more effective management of IAS. Such experiments could also inform on likely undesirable and unpredictable outcomes of large-scale eradication operations, such as meso-predator release (e. g., Courchamp et al. 1999). Current IAS control work, which is sometimes conducted in an ad hoc manner by resource-stretched councils, could become more "adaptive" by setting management objectives, acknowledging uncertainties in the system, making predictions on the outcomes of management actions, and ensuring that follow-up monitoring allows the objectives to be assessed. As with any other research or management endeavor, adaptive management requires support and funding and often a longer-term commitment than either government agencies or funding bodies are currently prepared to give. This remains a major challenge to the future of IAS control. Adaptive management could increase the feasibility of full-scale eradication programs and reduce the costs of attempting control of long-established and widespread invasive species, an important aspect in an environment where resources are restricted. The wide-scale implementation of adaptive management in IAS programs may provide conservation benefits to both native species and ecosystems.

*Responses to this article can be read online at: http://www.ecologyandsociety.org/vol9/iss2/art12/responses/index.html*

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