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Abstract: Invasive alien species (IAS) threaten global biodiversity; they are the major cause of species extinction on offshore islands. Management of IAS requires data on the ecology of species in their new environment, how these species respond to management, and how these processes interact. Often, however, there is a paucity of information on key biological parameters that are critical to making management decisions. We sent a questionnaire to professionals and organizations managing invasive species and asked the respondents to prioritize a list of information they required to carry out eradication of invasive species. We analysed responses to assess the level of agreement among experts. Then, we compared them to a survey ranking available information in the peer-reviewed literature. We did this for 8 globally-important mammal species to identify gaps in available knowledge. We suggest that many of the shortfalls in knowledge can be best addressed through adaptive resource management (i.e., collecting data during the process of carrying out eradication itself, analyzing and processing these data, and using the information to make objective decisions that can be fed back into field operations). We recommend a modelling approach to enable the forecasting and testing of different scenarios when manipulative experimentation is impossible. As this process evolves, it should assist successful eradication of IAS on larger islands.

Key words: exotic species, human–wildlife conflicts, invasive species, questionnaire, survey

Invasive alien species (IAS) are currently regarded as one of the greatest threats to global biodiversity (Diamond 1984, Atkinson 1996, Vitousek et al. 1997*a*). This is particularly true on offshore islands, where floras and faunas are more vulnerable to the impacts of IAS (Cronk, 1997, Simberloff 2000). Throughout recorded history, most extinctions have occurred on oceanic islands (Primack 1998). Due to high levels of endemism, island biotas form most of the biodiversity hot spots, accounting for 45% of all bird, plant, and reptile species (Krajick, 2005). Conserving these is recognized as the most cost-effective way of conserving global biodiversity (Myers et al. 2000*b*). Eradication of IAS is frequently highlighted as an important conservation technique (Diamond 1984, Atkinson 1996, Myers et al. 2000*a*, Cruz et al. 2005, Genovesi 2005). However, eradications have been limited to a small number of widespread species, while the number of IAS continues to grow. In the future, eradications must target larger areas and novel IAS, both of which will present new challenges to wildlife managers. For example eradication schemes must become more collaborative (Donlan et al. 2003, Genovesi, 2005) and cost-effective (Buhle et al. 2005).

Despite the existence of some information on the biology of invaders and their impacts, more needs to be done toward understanding how best to manage or eradicate IAS. The lack of information can lead to indecision and inaction (Simberloff 2003). Many eradications are carried out in the absence of easily-accessible data sources incorporating both life-history parameters of the IAS and its response to culling efforts. Such knowledge is easily available for most mammalian species (Oli and Dobson 2003) and could be used to target different life stages (Buhle et al. 2005). This could greatly assist larger eradication efforts, which can take place over many years.

Many authors, government agencies, non-governmental organizations (NGOs), and wildlife managers recognize a gap in the information available to IAS management, and several authors have developed broad guiding principles that should be considered in the planning stages of an eradication scheme to increase the probability of success (Bomford and O'Brien 1995, Bomford and Sinclair 2002, Genovesi 2005). Moreover, it appears that few eradication attempts have been preceded with a formal model of either the control or the economics of the attempted eradication. One notable exception is the coypu (*Myocastor coypus*) eradication in England, where the planning involved a population model and included an economic bonus for the trappers if eradication was successful (Gosling and Baker 1987, 1989). This modelling of the actual control effort also is being used in other eradication attempts in the UK (Moore et al. 2003, Smith et al. 2005). This approach should be particularly useful for new species for which there is limited experience or when the eradication is to be conducted over extensive areas. Similar modelling techniques are routinely used in assessing the risk of invasion, evaluating the containment, or eradication of exotic (invasive) diseases (Garner and Lack 1995, Horst et al. 1997, Smith and Fooks 2006). Such techniques have even been used to simulate the impacts of a disease of an invasive species on an indigenous species of conservation concern (Rushton et al., 2000). These techniques could also be extended to include economics (Born et al. 2005, Shogren and Tschirhart 2005).

The aim of this paper is to develop a simple but formal technique to identify gaps in the available knowledge that can be applied to IAS management. We summarize the broad requirements that need to be met to successfully carry out an eradication of an IAS, how these requirements are perceived by those involved in IAS management, and how this relates to the peer-reviewed information available for eight of the most common IAS globally: American mink (*Mustela vison*), black rat (*Rattus rattus*), domestic cat (*Felis catus*), grey squirrel (*Scuirus carolinensis*), goat (*Capra hircus*), European rabbit (*Oryctolagus cuniculus*), domestic hog (*Sus scrofa*), and Javan mongoose (*Herpestes javanicus*). We identified the information gaps, highlighting areas where future research should be concentrated. Finally, we made suggestions about how this research could be carried out so that the information is readily available to IAS managers and can be incorporated into IAS management decisions.

Table 1. Results of survey showing types of ecological information needed in a campaign to manage or eradicate invasive species, arranged into technical components (right column) under broad groupings of the different components of invasive species management (left column).

Research and management categories	Technical information needed
Field operations	Removal rates greater than rate of increase.
	Technique targets all individuals.
	Spatial scale of operation greater than movement patterns of individuals.
	Field techniques well-designed, alternatives researched.
Risk assessment and planning	Detection of individuals at low density.
	Impacts of species studied and monitored.
	Immigration to cleared area is zero.
	Potential pathways for reinvasion must be monitored at source.
	Nontarget effects of control.
Biology directly relevant to eradication	Species population ecology, and rate processes.
	Species spatial ecology, e.g., habitat use.
General biology	Species physiology.
	Species trophic ecology, e.g., diet and role as disease vector.
	Social behavior of species.
	Seasonal changes in species ecology.

Methods

For this analysis we used 3 publications listing the different categories of information required to carry out the successful eradication of an invasive species (Wittenberg and Cock 2001, Bomford and O'Brien 1995, Genovesi 2005). From these categories, we synthesized a specific list of technical components to create a comprehensive list (Table 1). For the purposes of this paper, we included only the biological aspects of this list, while leaving out the social and economic aspects. We kept the categorization of information broad and germane to the scenario of eradicating mammal species on islands.

We then circulated the list in an e-mail questionnaire to 20 experts currently involved in invasive species management and research, asking them to rank the different technical components on the basis of how important they were in eradicating invasive species. We selected correspondents from a wide variety of backgrounds, including those involved in practical field eradication, academia, policy, and modelling. We further ground-truthed the questionnaire by conducting telephone interviews with 6 individuals to ensure data quality (White et al. 2005). To assess the level of agreement among the different correspondents and to create an overall ranking of the data, we carried out a Kendall's coefficient of concordance on the rankings (Zar 1996). We calculated the rankings for the broader components into which the individual technical components fell, and we analysed this in the same way using Kendall's coefficient of concordance, to assess the level of agreement for the broader categories.

We then compared the questionnaire rankings with information available for eight of the most common mammal invaders with the largest global distribution. These 8 species were selected from the website database of the Invasive Species Specialist Group (ISSG) (see <*http://www.issg.org*>), a group of the International Union for the Conservation of Nature (IUCN). We then carried out a literature search for the Latin name of each species using the Information Sciences Institute (ISI) Web of Knowledge (see <*http://wok.mimas.ac.uk*>). We then collected the 100 most recent peer-reviewed publications for each species and categorized them according to both the broad categories and also according to each of the technical components listed in Table 1. We calculated the proportion of publications falling within each of these technical components and into each of the broader categories, then ordered and ranked them (with lower figures signifying higher ranks). We allowed publications to fall within >1 technical component or category and recorded them as such. We carried out a Spearman's rank correlation among the overall ranking produced by the questionnaire and the ranking of the literature for each of the species (Zar 1996).

Results

Of the 20 questionnaires we sent out, 12 (60%) were returned; the response rate is similar to the average calculated by White et al. (2005). Of the returned questionnaires, respondents' representations were as follows: field-based practitioners (4), modellers (3), policy staff (3), and academics (2). Those who did not complete the questionnaire gave several reasons, which we refer to in the discussion. Despite the small sample size, there was a high level of agreement among the correspondents who did respond with regard to the broad categories (Kendall's $W = 0.478$, $\chi^2 = 17.2$, $df = 3$, $P < 0.001$), with average rankings in the following order: field operations, 1.67; risk assessment and planning, 1.83; biology directly relevant to eradication, 3.00; and general biology 3.50.

There was also a high level of agreement among the correspondents about the different technical components (Kendall's $W = 0.389$, $\chi^2 = 65.3$, $df = 14$, $P < 0.001$). Thus, we continued the analysis to provide an overall ranking of the 15 different technical components (Table 2). Overall, correspondents tended to give field operational components, such as removal rates and targeting all individuals, the highest ranks and components, such as species biology, ecology, and behavior, the lowest ranks. Components, such as reinvasion and immigration rates and detection at low density, fell in the middle.

There were sufficient papers published for each IAS in the last 10 years to allow all species to be included in the analysis. Papers relating to species being invasive on island or mainland ecosystems were scarce. Those we found, however, ranged from 7% (for rabbits) to 43% (for black rats).

There was a high level of agreement about the ranking of the broad categories (calculated from the proportion of papers in each category) for the different species (Kendall's $W = 0.771$, $\chi^2 = 18.5$, $df = 3$, $P < 0.001$), and the literature was broadly ranked from most numerous to least numerous, thus: general biology, 1.00; risk assessment and planning, 2.44; biology directly relevant to eradication, 2.88; and field operations, 3.69.

The rankings of the literature for individual species were negatively correlated with the overall ranking given by the questionnaire

Table 2. Ranking of survey participant responses indicating, by order of importance, the different technical information components needed in an invasive species eradication campaign compared to rankings of the extant literature for 8 invasive species. Lower figures equal higher ranks.

Technical information needed	Overall ranking participants	Rat	Squirrel	Rabbit	Mink	Mongoose	Cat	Goat	Pig	Combined species rankings
Removal rates	3.58	12	13	12	10	12	13	12	11	11.88
Techniques/alternatives	5.46	4	12	6	8	5	5	6	6	6.50
Target all individuals	5.67	12	13	12	11	12	10	11	11	11.50
Impacts of species	5.75	2	3	8	3	7	2	6	5	4.50
Immigration is zero	6.00	12	13	12	9	12	15	12	11	12.00
Operational spatial scale	6.13	12	8	9	10	9	10	12	11	10.12
Detection at low density	6.92	8	10	9	6	9	7	10	6	8.12
Nontarget effects	7.54	10	10	11	10	12	13	12	11	11.13
Pathways for reinvasion	7.71	6	8	12	11	9	10	4	6	8.25
Species spatial ecology	8.71	5	5	5	7	7	8	6	6	6.13
Population ecology	9.88	8	5	4	5	5	6	2	4	5.25
Trophic ecology	10.38	1	1	3	2	2	4	2	2	2.13
Seasonal ecology	10.96	10	7	6	9	4	9	6	6	7.13
Social behavior	12.29	7	2	2	4	3	3	3	3	3.34
Physiology	13.04	3	3	1	1	1	1	1	1	1.50
Spearman's correlation coefficients of literature and participant ranking		-0.41	-0.76	-0.82	-0.61	-0.80	-0.56	-0.7	-0.77	
% papers relating to species as invasive		43	8	7	12	25	36	9	9	

correspondents (see Spearman's rank correlation in Table 2), indicating that more publications focused on areas considered a low priority by IAS practitioners, while few papers focused on the topics considered of high practical importance from an IAS perspective. The rankings of the literature available in each technical component for the 8 species had a high degree of concordance among themselves (Kendall's $W = 0.838$, $\chi^2 = 93.8$, $df = 14$, $P < 0.001$). Overall, we found that the species' physiology and general ecology ranked highest, with population and spatial ecology in the middle (Table 2). The impacts of exotic species both on native ecosystems and native species ranked fairly high (fourth), although few papers presented experimental studies with extensive pre- and post-eradication monitoring. Most papers in this category presented anecdotal results showing increases in populations of native species after eradication. Field operational components, such as removal rates and targeting all individuals, had the lowest ranks, with very few papers published in this subject area. The only species that had papers published for these categories were mink, mongooses, cats, and goats.

There was very little agreement among the rankings provided by questionnaire participants and the combined ranks of the literature for the different species, with the biggest deficit in information found in field operations followed by a minor deficit in risk assessment and planning (Figure 1). As Figure 1 also shows, there is reasonable availability of information on species' biology directly relevant to eradication, and a wealth of information on the general biology of the species.

A more detailed assessment of the technical components reveals the precise details of the deficits (Figure 2). Within the category of field operations, the largest deficits in information are in removal rates, followed by information on ensuring that techniques target all individuals and information on immigration rates. Within the category of risk assessment and planning, the biggest information deficit is in ensuring that the spatial scale of operations matches the spatial scales of the movement patterns of the species concerned, followed by a lack of information on the nontarget effects of control.

Discussion

Where eradication of an invasive species is possible, the work often has to be carried out with finite resources within a finite time scale. In addition to this, it is often not possible to conduct pilot studies or test experimentally, with sufficient replication whether IAS are the agents causing the decline of native flora and fauna (Tyler et al. 2004) or how best to control them. There simply is not enough time to conduct pilot studies or extensive research before carrying out the control or eradication (Atkinson 1996). IAS managers are increasingly turning to the scientific literature to aid decision making on resource allocation and the use of appropriate techniques and tools to achieve eradications successfully. Unfortunately, we found that where invasive mammals are concerned, there is a paucity of specific components of appropriate information.

Many of the papers in the literature dealt with aspects of species biology that were not related to the species being invasive. Also, the literature survey did not take into consideration information that, although not peer-reviewed, is available to IAS managers in specialist form, such as technical reports or region-specific journals that are not cited in the literature search engines. This grey-area literature may fill the knowledge gap to some extent, but its availability is hard to quantify and standardize.

Finally, this survey did not give an indication about the quality of the paper for use as an information source for an eradication scheme. For example, several papers merely referred to the impacts of an invasive species but did not offer qualitative or quantitative evidence, and very few had pre-eradication baseline data with which post-eradication information could be compared.

Generally, there is a paucity of information on successful eradications, both in terms of population ecology of invasive species and the techniques applied. There is also very little information on failed eradication attempts and techniques (Thorsen et al. 2000, Seymour et al. 2005), and this, too, needs to be recorded to help future eradication schemes avoid repeating mistakes, often at great expense (Nogales et al. 2004, Howald et al. 2007).

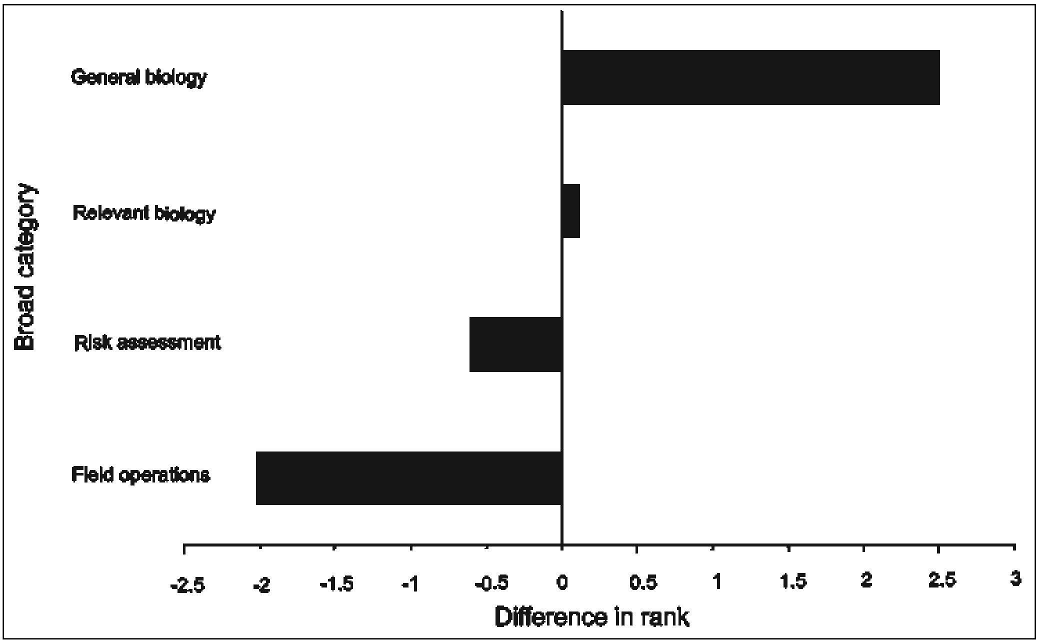

Figure 1. Results of survey, showing differences in rank between broad categories of researchers and managers involved in an invasive species eradication campaign and the combined literature ranks (by order of importance of information needed) for 8 species. Negative results show a deficit in information.

The main gaps in the information available to IAS managers were found in information categories of field operations, followed closely by risk assessment and planning. When we examined this in more detail, we found that the main shortfalls within the field operations category were on removal rates, whether or not techniques were targeting all individuals, and immigration rates. In the risk assessment and planning category, the main shortfalls were on whether the scale of removal operations is appropriate for the species targeted, the effects of techniques on nontarget species, detection of individuals at low density, techniques used to remove animals, and adequacy of monitoring the potential pathways through which invasive species can arrive to a new location. These information gaps need to be addressed to plan, budget, and allocate resources and subsequently carry out successful eradication schemes.

Several of the field operational gaps can be effectively addressed only by carrying out control and subsequently recording detailed information on removal rates, immigration rates, and whether or not the techniques appropriately target all individuals. Such information cannot be gathered adequately through hypothesis-testing research alone, as they can be adequately assessed only once the target population has been perturbed. Perhaps some of the more peripheral pieces of information that would not normally be gathered during a removal campaign alone could be gathered through scientific projects built into the eradication campaign (Moore et al. 2003).

The process of learning by doing has been described as adaptive management or adaptive resource management (MacNab 1983, Walters and Hollings 1990, Atkinson 1996), and in the past it has been criticized as pseudo-science where projects have not been well-designed or had little scope for robust analysis (Raffaelli and Moller 2000). In these instances, they do not achieve either the basic ecological or conservation goals or the increased information gathering and dissemination they set out to accomplish (McLain and Lee 1996). Data from projects using adaptive resource management techniques often do not compare well scientifically to data produced through conventional science, due to the multidisciplinary nature of resource management, high levels of uncertainty, and confounding factors across different levels of spatial scale (Walters 1997).

It is important to remember, however, that

Table 2. Results of survey showing difference in the ranking of available information (by topic) needed by researchers and managers in an invasive species eradication campaign. Negative differences show a deficit in information.

Detail	Experts	All species	Difference
Removal rates	3.58	11.87	-8.29
Target all individuals	5.67	11.50	-5.83
Immigration is zero	6.00	12.00	-6.00
Pathways for reinvasion	7.71	8.25	-0.54
Field techniques	5.46	6.50	-1.04
Low densities detection	6.92	8.12	-1.20
Operational spatial scale	6.13	10.12	-3.99
Monitor impacts	5.75	4.50	1.25
Population ecology	9.88	5.25	4.63
Physiology	13.04	1.50	11.54
Spatial ecology	8.71	6.13	2.58
Trophic ecology	10.38	2.13	8.25
Social behavior	12.29	3.34	8.95
Seasonal ecology	10.96	7.13	3.83
Nontarget effects	7.54	11.13	-3.59

adaptive resource management is not a scientific technique for hypothesis testing or resolving the issues of cause and effect, but rather a practical management strategy that optimizes management and application of resources to a problem that already has a scientific basis. Adaptive resource management is an evolving process that uses new information as it arises, enabling managers to be flexible to the changes and uncertainties that are inevitable in the management of natural resources (Hilborn 1987), particularly in the case of novel species in a novel ecosystem. It also makes it easier to include valuable information from conventional science into a management regime (Haney and Power 1996). Using this approach in future management needs could influence the direction of specific scientific paradigms (Rogers 1998). Adaptive resource management also is a stepping-stone toward the much larger, more multidisciplinary strategy of integrated natural resource management that incorporates a wider remit of subjects, such as stakeholder participation, consumer behavior, and socioeconomics (Lal et al. 2002). It should also be noted that natural resource management is expensive. With limited funds, the most cost-effective way to gather key information is to conduct research while undertaking management actions; many of the failures noted by Walters (1997) are institutional (Rogers 1998).

With regards to the information gaps that fall within the risk assessment and planning category, some of the information can be obtained only through the process of carrying out the eradication itself (or at least during extensive control operations), with more emphasis placed on the planning stages of the operation. Information on spatial scale of operations can be made more accessible by incorporating GIS systems into eradication operations and through spatial modelling. In the same way, information on the impacts of particular techniques on nontarget species needs to be better recorded in the literature. Also within this category, the minor shortfalls seen in information relating to the actual techniques used in eradications and in monitoring the potential pathways for reinvasion can be addressed by adequate recording of techniques in the literature, even if these are published only as technical notes.

For information on monitoring the potential invasion pathways of a species, again large-scale spatial modelling can address this, using easily-accessible, shared databases of island archipelagos and coastlines; several such databases are in development. In addition, formal techniques for assessing the risk of invasion by nonnative species are being applied to mammalian invaders (Dickman et al. 1993, Molsher et al. 1999). Some of these are being interpreted from formal systems currently used to assess the risk of plant and insect invaders (Heimbach et al. 2002, Schrader 2004).

In the absence of formal experimentation, modelling is a useful technique that enables managers to predict the outcomes of different management strategies on a system. It, thus, provides a useful medium through which managers can develop some of the techniques of adaptive resource management. Even the most basic population models can be progressively developed to do this. Modelling is already a well-established technique to predict population processes and population size, and, for many invasive species, a sufficient amount of biological data is available for predicting natural population growth. To predict the effect of an eradication attempt, it is necessary to model the additional effects of the management regime on population, in particular: (1) culling or removal of individuals dependent on the labor and method(s) of control and (2) the population response (density-dependence) to culling. Biological parameters can be obtained either from historical data on the invasive species in the environment to be controlled, data from other invaded areas, or from the species' original range. Data from the latter source, although potentially less accurate, can be supplemented with data collected during the eradication to reduce the uncertainty of predictions.

Estimates of culling efficacy (e.g., capture rate per trap night) appear to be the largest shortfall in available data, and culling efficacy will change as the population size is reduced, as there are fewer animals per unit area to be caught, and remaining animals may become increasingly trap shy. One approach that can be adopted is to calculate the culling efficacy as the proportion of the population removed per person per time unit (see Smith et al. 2005) until more refined estimates are available.

For all 3 parameters (biological, cull efficacy, and density dependence), data collected during the eradication can be used to improve the model, and, thus, reduce the uncertainty in future predictions. Improved precision can lead to improved confidence and more robust decision making in the eradication campaign, if performed iteratively, following adaptive resource management principles. Similar iterative approaches can be used to obtain improved data on other parameters, such as the scale of removal.

Invasive species management is a growing field. The land areas being covered by eradication schemes are becoming larger and are incorporating an increasingly multidisciplinary approach involving information from social science, economics, geography, and climatology. Current approaches are working well in many island eradications, but as island population size increases, eradication becomes more difficult, and successful eradication will become less frequent unless the gaps in our knowledge can be addressed and the information is used to improve field management. IAS can be managed quickly and effectively when the need arises only if decisions are made using sound and objective techniques based on a growing pool of information.

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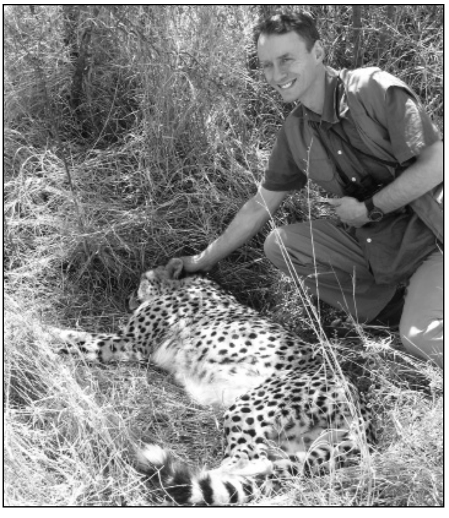

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