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GUEST EDITORIAL

The role of research for integrated management of invasive species, invaded landscapes and communities

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Summary

1. Invaded landscapes and ecosystems are composed of multiple interacting networks and feed-back loops, sometimes leading to unexpected effects of management actions. In order to plan management for invaded systems we need to explicitly consider management goals before putting actions in place. Actions taken must be justified in terms of their amelioration of impacts of invaders, contribution to the management goals and the costs incurred.

2. This Special Profile brings together papers on the management of invasive plants, transgenes, animals and diseases, leading to conclusions with clear policy and management relevance and contributing to some of the hottest current topics in invasion ecology: unexpected impacts of invaders, restoration of invasion resistance, distribution mapping, spatial epidemiology, escape of transgenes, community interactions and complex effects of management.

3. As papers in this Special Profile demonstrate, management for amelioration of the impacts of invasive species will include a wide range of manipulations, not just of the invader itself but of both abiotic and biotic components of the system. In fact, several papers in this Special Profile show that indirect management of the community may be more effective than removal of the invader alone.

4. As little information is generally available at the beginning of a management programme, an adaptive approach should be taken and the management objectives/goals revised throughout the management process. New methods are emerging for adaptive management; an example is presented in this Special Profile where a Bayesian model used for assessing eradication goals can be updated throughout the management process leading to refinement of management.

5. *Synthesis and applications.* Applied research should be directed at providing decision support for managers throughout the management process and can be used to provide predictive tools for risk assessment of new invaders. The science of invasion ecology has much to contribute to the new challenge of natural or enhanced movement of organisms in relation to climate change. Methods and information from invasion ecology can be used to assess management goals, management actions and the risks of potential translocations before they are put in place.

Key-words: climate change, dispersal, epidemiology, GMO, invasive, policy, restoration, spatial, transgene, translocation

Introduction

Management of invasive species is a growing and persistent problem worldwide as ‘novel ecosystems’ become more common and difficult to return to natural states (Hobbs *et al.* 2006). The management problem is complex: it occurs over diverse spatial and temporal scales; invaders have multiple impacts in interactive community networks; managers have several and sometimes competing management objectives; technical solutions are challenging, money for management is scarce and motivation amongst stakeholders, decision-makers and planners can be low.

Current advances in the field of invasion ecology are dealing directly with the complexity of real ecosystems and landscapes where both biotic and abiotic factors determine impacts and management options, and several papers in this Special Profile take this integrated approach. Several of the themes identified in the last Special Profile on Biological

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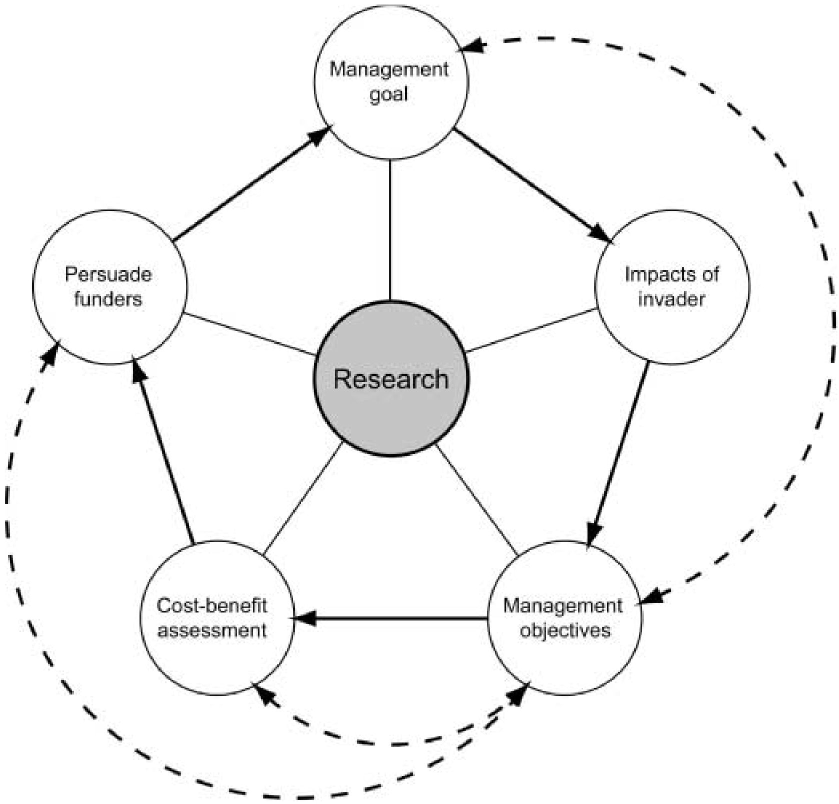

Fig. 1. The contribution of applied ecological research at different phases in the invasive species management process. The solid lines indicate progress through the management process, with dashed lines showing revision of the management objectives and goal throughout the process. The majority of applied work on invasive species has focused on technical solutions to enable the management objectives. A more pragmatic approach to invasive species management would involve a greater focus on the other stages of the management process to support decisions of what management (if any) to put in place.

Invasions for *Journal of Applied Ecology* (Hulme 2006) are carried through the papers here, including: the importance of considering landscape scale processes, interactions with other members of the invaded community, and how these can be manipulated to achieve successful management conclusions. This Special Profile brings together papers on the management of invasive plants, transgenes, animals and diseases, leading to conclusions with clear policy and management relevance and contributing to some of the hottest current topics in invasion ecology (unexpected impacts of invaders, restoration of invasion resistance, distribution mapping, spatial epidemiology, escape of transgenes, community interactions and complex effects of management). I identify here where I see applied ecological research contributing to the complex problem of invasive species management (see Fig. 1 for an overview).

Goals of invaded system management

Invasive species management must be done within the scope of the broader ecosystem management goal with its associated management objectives. The overall goal of the management may be to restore a particular ecosystem service, production value, functional or species diversity, community structure, or conservation of a particular species of concern. In order to achieve this management goal the following steps need to be taken (also see Fig. 1).

1. Assess the impact of the invasive species on the management goal, e.g. effect of rat *Rattus rattus* predation on endangered seabird (*Sula dactylatra* and *Sula leucogaster*) and sea turtle *Chelonia mydas* populations (Caut, Angulo & Courchamp 2008).

2. Develop management objectives. These should be measurable tasks which contribute to the overall goal, e.g. detectable establishment of a biocontrol agent (Meurisse *et al*. 2008), eradication of invasive Asian musk shrew *Suncus murinus* (Solow *et al*. 2008) and monitoring of habitats particularly susceptible to invasion (Chytry *et al*. 2008) or high risk invasion pathways (Hulme *et al*. 2008).

3. Particular management actions can then be developed to achieve the objectives of the management plan, e.g. a new trapping technology (Meurisse *et al*. 2008) or restoration of native vegetation to increase propagule pressure of natives relative to invasives (Chadwell & Engelhardt 2008; Dewine & Cooper 2008).

4. Cost-benefit assessments of the management actions, in terms of monetary costs, opportunity costs or loss of some other desired ecosystem property or service, should be undertaken to determine that a net benefit of management is achieved, e.g. economic analysis of different management actions to control mute swans *Cygnus olor* in North America (Ellis & Elphick 2007).

5. Of course, management is generally impossible without funding by, or participation of, the stakeholders. Persuasion to change policy, support an action or provide funding can take place not just at the end of the process but throughout the management planning activity (Sutherland *et al*. 2006; Lawton 2007). For example, use of a parameterized spread model of a glyphosate-resistant weed led to the recommendation that landscape scale co-ordinated action by multiple landholders may be necessary to manage spread (Dauer *et al.* 2007).

By responding to new information and adaptively managing the invaded ecosystem the management objectives (and possibly the management goal) may change throughout the management process, setting off a new cascade of actions. Framing research questions to give decision support to managers is an important though often neglected part of the contribution of research to invasive species management. One important problem that has received recent attention in this context is when to terminate eradication programmes, e.g. for plants (Regan *et al.* 2006) and, in this issue, for the invasive Asian musk shrew *Suncus murinus* (Solow *et al.* 2008). The provision of stopping rules, or probabilities of untrapped individuals remaining, can enable managers to decide the scope and length of an eradication programme at the beginning of the process, and can also enable them to revise management objectives as data accumulates that can more accurately parameterize the decision support models (Solow *et al.* 2008).

Targeting the invasive population directly as a management objective before proceeding through the steps above may not lead to a sustainable shift in the ecosystem to a more desirable state for a number of reasons. The invasive species may not be the causal agent of change in the ecosystem, it may just be a symptom of underlying processes of ecosystem degradation such as eutrophication or disturbance (MacDougall & Turkington 2005). The management process itself may promote reinvasion by the same or a different invasive species (Zavaleta *et al.* 2001; Courchamp *et al.* 2003; Hulme & Bremner 2006; Buckley, Bolker & Rees 2007; Cox & Allen 2008), or recovery of the native community may be dependent on ecological processes such as propagule supply which need to be actively restored as demonstrated by Dewine & Cooper (2008) in this Special Profile. Management objectives will therefore not necessarily involve reduction of the population density of the invasive species directly, but instead may involve alteration of successional trajectories (Buckley *et al.* 2004; Dewine & Cooper 2008) or manipulation of abiotic factors to reorganize competitive hierarchies (Chadwell & Engelhardt 2008).

Considerable progress has been made in the area of identification of impacts of invaders (Parker *et al.* 1999; Levine *et al.* 2003) and the definition of management goals and objectives in relation to invasions. However, routine assessments of control actions rarely report on the broader ecosystem goals (such as native community recovery, but see Cox & Allen 2008) but rather focus narrowly on invader density reduction under the assumption that this will contribute to the overall management goal. In this Special Profile, Cox & Allen (2008) demonstrate that removal of exotics alone, even with habitat restoration attempts, may not be enough to achieve their management goal to restore the coastal sage scrub community in California. The variability of the coastal sage scrub environment also added to the difficulty of evaluating management success, a problem that will be common in invaded ecosystems which may be characterized by high disturbance and fluctuating resources (Davis, Grime & Thompson 2000).

Impacts of invaders may be more diverse than originally perceived as Caut *et al.* (2008) demonstrate in this Special Profile. Using stable isotope techniques in combination with conventional diet analysis, they found that invasive rats can switch their diet from seabirds (*Sula dactylatra* and *Sula leucogaster*) to sea turtles during the few months when the birds are unavailable and the sea turtle hatching season occurs. The ability of rats to switch their diet may help to maintain rat populations during times of primary food source shortage and lead to unexpected impacts of the invader population and management activities on other members of the community.

Ecosystem management: biotic and abiotic elements

Commonly, multiple interacting factors need to be managed for successful control, as demonstrated by four papers in this Special Profile, be it multiple demographic stage transitions (Tenhumberg *et al.* 2008), or management of both biotic and abiotic factors (Chadwell & Engelhardt 2008; Dewine & Cooper 2008; Gutierrez *et al.* 2008). Dewine & Cooper (2008) found that while native box elder was more competitive than the invasive tamarisk, managing propagule pressure of the more desirable native was also necessary for the successful succession of box elder. Restoration of natural water flow regimes or planning flows to maximize the establishment of box elder were recommended as part of the management of tamarisk. Simple removal of the invasive could be ineffective without an integrated view of the ecosystem components. Chadwell & Engelhardt (2008) demonstrated the importance of considering both biotic and abiotic effects of invasion resistance and facilitation by a native competitor. While the native was a superior competitor in mesocosm experiments, higher nutrient fluxes in field experiments negated its competitive advantage. Facilitative effects of the native in promoting establishment of the invader were also demonstrated in mesocosm experiments, but were not found to be important in the field.

Gutierrez *et al.* (2008) show that abiotic effects of weather control the abundance and distribution of a pest of grape vines, the vine mealybug *Planococus ficus*. Weather, in combination with biotic interactions, determine the success of biological control of vine mealy bug using parasitoids and a predator. This modelling approach enables explanation of why biocontrol to date has not been particularly successful and that new management actions should involve additional biocontrol agents and reductions in the size of spatial and temporal refuges for the pest. This study clearly shows the importance of evaluation of management actions (biocontrol) in terms of the management objective (reduction of population densities of vine mealy bug across its entire distribution) in order to adaptively manage the system.

General management guidelines robust to the inherent uncertainty of the systems being managed are essential for invaded systems. Population modelling has been used extensively to predict invasive plant responses to management; however, management recommendations arising from these models are context-dependent and sensitive to the parameters used (Shea *et al*. 2005). All too often in invasion ecology we have uncertain estimates of parameters because of the need to act before the system is well known. Recent approaches have attempted to determine the robustness of management strategies to parameter uncertainty or known stochasticity (Buckley *et al*. 2005; Davis *et al*. 2006; Ellis & Elphick 2007; Tenhumberg *et al*. 2008) and in this Special Profile Tenhumberg *et al*. (2008) present useful Monte Carlo methods for assessment of uncertainty in commonly used matrix population models.

Management goes spatial: scope, scale and solutions

By including spatial aspects of fox *Vulpes vulpes* movement and rabies transmission into models Eisinger & Thulke (2008) show that lower population vaccination thresholds can be effective in reducing disease incidence. Their modelling approach compares an analytical nonspatial population model with spatially explicit and nonspatially explicit individual-based simulation models. It is clear that the introduction of spatial population processes (local dispersal and transmission) lead to the lower threshold estimates. The rabies–fox–vaccination system is a good example of the management process described above (Fig. 1): there is a clear management goal (the eradication of rabies from Europe), leading to management objectives (reduction of the incidence of rabies in wild fox populations, a threshold level of the population should be resistant) with associated management actions (baiting with oral vaccine). Updating a previous modelling approach with spatial information, Eisinger & Thulke provide compelling evidence that the management objective can be revised, with the threshold reduced from 70% effective vaccination to 60%, resulting in a more favourable cost-benefit analysis and clear policy recommendations.

Particular elements of the landscape can provide both habitat and dispersal pathways for invasive species. In this Special Profile, Jodoin *et al*. (2008) show how roadsides act as linear wetlands, providing optimal high-nutrient habitat for the invasive genotype of *Phragmites australis*. The provision of this high-quality habitat (for invaders) throughout the landscape may provide source populations and propagule pressure for the invasion of more pristine habitats of higher ecological value. The management goal may not simply be protection of the roadside habitat but the value of 'invasion-proofing' lies in the prevention of spread of the invader along roads and into undisturbed natural wetlands.

Landscape-scale analyses can help to delineate the initial extent of an invasion and three papers in this Special Profile (Peltzer, Ferriss & Fitzjohn 2008; Pivard *et al*. 2008; Zapiola *et al*. 2008) look specifically at the risk of escape of genetically engineered organisms and/or their transgenes into wild populations at the landscape scale. Zapiola *et al*. (2008) looked directly at the escape of transgenic glyphosate-resistant creeping bentgrass (GRCB, *Agrostis stolonifera*) and documented escape and establishment through both seed and pollen movement up to 4·6 km from the initial source, 3 years after the initial source was removed. This study indicates the ease with which some transgenic organisms will move into wild populations at the landscape scale, despite stringent sowing and harvesting guidelines, which will now need substantial revision. While the horse has well and truly bolted for GRCB, it will serve as a useful case study for other genetically engineered wind-pollinated perennial grasses.

In contrast, Peltzer *et al*. (2008) and Pivard *et al*. (2008) utilize information on conventional naturalized *Brassica* crops to assess the factors contributing to the movement and establishment of feral populations in order to provide baseline information for risk assessment of genetically engineered varieties. Using a rapid assessment of the distribution of feral populations, robust models were constructed of population presence/absence (Peltzer *et al*. 2008). However, these models failed to predict well in the following year, indicating that prediction of movement and establishment of feral *Brassica*s will be difficult, complicating monitoring for, and management actions to prevent, transgene escape. Variability between years was indicated to be due to persistence of local populations in seed banks rather than increased rates of long-distance transport and seed spillage. A more fine-grained distribution modelling exercise by Pivard *et al*. (2008) found evidence for the importance of long-distance dispersal and seed banks for population founding and persistence in the landscape. These studies indicate the strong potential for movement of transgenes around the landscape, their persistence between years and their contribution to future populations, even after cropping has ceased and the original sources have been removed.

Two further papers in this Special Profile, Chytry *et al*. (2008) and Hulme *et al*. (2008), use analysis of spatially extensive databases to assess the susceptibility of habitats in Europe to plant invasion and the routes of biological invasions, respectively, with the aim of informing policy at a broad level. While regions in Europe shared very few invasive species, there was consistency at the level of habitats across regions which were more or less susceptible to invasion (Chytry *et al*. 2008). Contrary to some of the expectations of biotic homogenization (Olden *et al*. 2004), at the European scale there does not appear to be homogeneity in the identity of invaders: invaders of the same habitat type in different regions will not generally be of the same invasive species. Hulme *et al*. (2008) identify the routes of invasion of broad groups of organisms enabling clearer planning for policy to monitor, reduce or manage these routes or the organisms introduced through particular pathways. While intentional release pathways may be easier to regulate, conflicts remain between stakeholders who commercially exploit intentionally introduced organisms (agriculture, horticulture, ornamental display) and those who suffer the unintended consequences of their introduction.

Explicit consideration of not just the absolute costs and benefits of these introductions but the distribution of costs and benefits among different members of society is essential in order to resolve conflicts and manage intentional releases appropriately.

Invasion ecology as a predictive science: locking the stable door before the horse has bolted

We are moving towards invasion ecology as a sound predictive science. Studies in this Special Profile aim to predict susceptibility of habitats at a continent-wide scale to invasion (Chytry *et al*. 2008), where and how new invaders will appear (Hulme *et al*. 2008), and the risk of escape of transgenes (Peltzer *et al*. 2008; Pivard *et al*. 2008; Zapiola *et al*. 2008). Invasion ecology also has much to contribute to future debates on species translocations in response to climate change; for example, we know a considerable amount about the spread and establishment of novel species, and about the risks associated with, and appropriate management of, the resulting novel ecosystems. The tools and approaches developed for invasion ecology and management should be applied to the equally complex landscape and ecosystem management problem of the movement and establishment (natural or human assisted) of plants, diseases and animals in response to climate change (Hulme 2005). In particular, the goals of species translocation in response to climate change need to be explicitly discussed before the technical solutions to achieve those objectives are put in place.

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