The need for spatially explicit quantification of benefits in invasive-species management

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Abstract

Worldwide, invasive species are a leading driver of environmental change across terrestrial, marine, and freshwater environments and cost billions of dollars annually in ecological damages and economic losses. Resources limit invasive-species control, and planning processes are needed to identify cost-effective solutions. Thus, studies are increasingly considering spatially variable natural and socioeconomic assets (e.g., species persistence, recreational fishing) when planning the allocation of actions for invasive-species management. There is a need to improve understanding of how such assets are considered in invasive-species management. We reviewed over 1600 studies focused on management of invasive species, including flora and fauna. Eighty-four of these studies were included in our final analysis because they focused on the prioritization of actions for invasive species management. Forty-five percent (n = 38) of these studies were based on spatial optimization methods, and 35% (n=13) accounted for spatially variable assets. Across all 84 optimization studies considered, 27% (n = 23) explicitly accounted for spatially variable assets. Based on our findings, we further explored the potential costs and benefits to invasive species management when spatially variable assets are explicitly considered or not. To include spatially variable assets in decision-making processes that guide invasive-species management there is a need to quantify environmental responses to invasive species and to enhance understanding of potential impacts of invasive species on different natural or socioeconomic assets. We suggest these gaps could be filled by systematic reviews, quantifying invasive species impacts on native species at different periods, and broadening sources and enhancing sharing of knowledge.

Introduction

Invasive species are a leading driver of environmental change across terrestrial, marine, and freshwater environments (Clavero & García-Berthou 2005). Invasive species cost billions of dollars annually in ecological damages and economic losses (Pimentel et al. 2005; McDermott et al. 2013). In response to these environmental and economic damages, the world's governments have identified them as 1 of the top priority areas for research and assessment under the scope of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES 2015). Given the enormity of the problems caused by invasive species and the limited resources available to control them, planning processes are needed to identify cost-effective solutions that minimize the negative impacts of invasive species and account for multiple benefits that can be returned to socioecological systems through management (Buckley 2008; Giljohann et al. 2011).

Research aimed at identifying effective solutions for invasive-species management has largely focused on economics and theory (e.g., developing ecological models for invasive species and evaluating costs associated with managing or eradicating them). This may reflect the historical focus of invasive-species management of agricultural species, where action was weighed up as a function of economic costs of control versus economic losses due to inaction. In this way, the management decision has been framed primarily as a single benefit problem compared with a more complex decision-making process that considers multiple spatially variable natural and socioeconomic assets, such as species persistence or recreational fishing that can benefit from actions to mitigate invasive species. A growing number of authors have discussed the need for, and benefits of, accounting for spatially variable assets when planning and managing for invasive species (e.g., Januchowski-Hartley et al. 2011; Buckley 2008; Adams and Setterfield 2015). However, we are not aware of any comprehensive assessments or syntheses outlining current best practice for accounting for spatially variable assets in planning for and management of invasive species.

We sought to highlight the need for improved approaches to accounting for spatially variable assets in invasive-species planning and management. We drew on evidence from over 1600 publications (Supporting Information) to determine the prevalence of studies focused on prioritization of actions for invasive species management and those focused on prioritization that explicitly considered spatially variable assets. Based on our findings, we further explored the potential costs and benefits to invasive species management when spatial assets are explicitly considered or not. We drew on examples from our review and a case study to provide insights and recommendations for advancing decision science and more cost-effective and equitable invasive-species management.

Evidence from invasive-species planning and management literature

We conducted a comprehensive search of ISI Web of Science (WoS) (1972 to April 2017) with the following keywords: *invasive species* AND (priorit* OR *optimal*). We used this database because it searches articles over a longer period than other databases such as Scopus (limited to articles since 1995) and returns more consistent results than Google Scholar (Nash and Graham 2016).

Our search returned 1615 publications (Supporting Information). We examined each to determine whether the study was spatial in nature or considered management of invasive species. Fifty-six percent (n = 910) met our criteria to be considered as a spatial study or a study focused on management of invasive species. Of these 910 studies, 91% (826) (Table 1) did not focus on the prioritization of management actions, which left 84 studies for further consideration. Of the excluded studies, 152 were unrelated to invasive species, and the remainder were topically related but did not meet our inclusion criteria of consideration of management (Table 1). For each of the 84 articles retained for detailed review, we determined the type of prioritization method used and whether the study accounted for spatially variable assets. If the study did not account for spatially variable assets, we noted whether a reason was provided.

Prioritization methods used to allocate invasive-species management actions

Of the 84 studies that focused on the prioritization of actions for invasive species management, 45% (n = 38) were based on spatial optimization methods (Table 2). The spatial approach taken in these studies meant that they explicitly accounted for the spatial location and variability of invasive species occurrence (Bode et al. 2009; Januchowski-Hartley et al. 2011). Studies in which spatial optimization methods were used often also accounted for the spatial variability of costs associated with management action (Januchowski-Hartley et al. 2011, Adams and Setterfield 2015; Rout et al. 2011). One study also integrated information on the spatial variability of feasibility for management action in their spatial optimization method (Tulloch et al. 2014) and another similarly integrated the potential for eradication success (Russell et al. 2016). To a much lesser extent, studies that focused on prioritization of invasive-species management actions also used bioeconomic methods (nonspatial, 21% of studies, and spatial, 4% of studies), cost-benefit analyses (7% of studies), ranking methods (spatial, 6% of studies, and nonspatial, 3% of studies), and spatial simulation (4% of studies) (Table 2).

Although the most prevalent method was spatial optimization, more than half (65%) did not account for spatially variable assets. Similarly, 78% of the other prioritization studies did not account for spatially variable assets (Supporting Information). Studies that did not account for spatially variable assets tended to focus on minimizing cost of invasive species management (e.g., Januchowski-Hartley et al. 2011; Kerr et al. 2016). Importantly, none of the studies that did not account for spatially variable assets discussed the reasons for this or provided justification for the simplifying assumption of uniform benefits.

Reasons for managing invasive species

Given the inherently spatial nature of invasive-species management and the costs and benefits associated with actions, there is a need for methods and tools that accommodate these complex data and related questions (Januchowski-Hartley et al. 2011; Tulloch et al. 2014). Studies are increasingly accounting for complex interactions between the costs and benefits of invasive-species management, but we found a relatively low percentage of studies (27% of the 84 prioritization studies) explicitly accounted for spatially variable assets, and most of these were quite recently published. For example, authors of more recently published studies on the prioritization of invasive-species management (e.g., Tulloch et al. 2014; Adams and Setterfield 2015) used methods that explicitly considered both spatially variable costs and assets associated with management actions. Adams and Setterfield (2015) built on the approach of Januchowski-Hartley et al. (2011) to consider benefits returned to spatially variable assets from actions reducing invasive-species abundance. Adams and Setterfield (2015) demonstrated that by applying a spatial optimization method and explicitly accounting for multiple assets in their planning process, they could deliver greater benefits to these assets than when targeting features based on costs alone. Tulloch et al. (2014) further demonstrated that in addition to accountancy of spatially variable assets, accountancy of spatially variable feasibility of management (based on both social and economic aspects) improved cost-effectiveness and returned greater benefit to native species threatened by an invasive carnivore.

Importance of Accounting for Spatially Variable Assets

We found there is increasing attention being given to estimating and resolving trade-offs between costs and benefits of alternative invasive-species management actions. If spatial variability of assets is ignored in decision making, opportunities to maximize benefits of invasive-species management could be overlooked. The implications of these oversights are poorly understood, but as demonstrated by Adams and Setterfield (2015) and Tulloch et al. (2014), each asset is likely to respond differently to reductions in area occupied by an invasive species (Fig. 1). For example, benefits returned to different assets could scale exponentially, as a power function, or linearly as the amount of area occupied by an invasive species is reduced (Fig. 1). It follows that the optimal area of management depends on the natural or socioeconomic assets considered. For example, a manager might set an objective of ensuring 80% of a native species' persistence (exponential benefit assumed [Fig. 1]), which would require eradicating the invasive species from roughly 15% of the total infested area (150 km^2). In contrast, if the objective were to secure 80% of recreational fisheries (linear benefits assumed [Figure 1]), then 80% of the infested area would need to be managed. Protecting 80% of the native species' range (power law assumed, following the species-area relationship [Figure 1]) would require managing roughly 40% of the infested area. In this example, we assumed the 3 assets are uniformly distributed and only the scaling of benefit returned to these assets changes. Even under these simple conditions, identifying the assets of interest and establishing objectives underpinning invasive-species management is essential to quantify the effort needed and the resources required to achieve the objectives.

It is also important to clarify what assets are of interest in invasive-species planning and management. Consider a scenario where an invasive macrophyte has established in a river network (Figure 2 a). Accounting for economic costs of managing the invasive species alone would focus efforts in the headwaters of the river network because it would be more cost-effective to allocate actions to upstream infestations than to invest in downstream reaches prone to reinfestation from upstream sources (Figure 2 b). However, when social assets, such as recreational fishing, are explicitly considered in the spatial optimization, the selected priority areas for management action could shift to focus management on both local and distant impacts (Figure 2 c). Accounting for both social and ecological assets could generate yet another set of spatial priorities (Fig. 2 d). Ultimately, assets are spatially variable both within and across systems. Explicitly accounting for multiple spatially variable assets is necessary to ensure maximum benefit is returned at minimum cost (Adams et al. 2014; Cattarino et al. 2016).

Gamba Grass Management in Northern Australia

To further explore how different types of assets can be spatially variable in a landscape, we considered the extent of overlap of different natural and socioeconomic assets and invasive species in a case study of the Coomalie – Litchfield region, Northern Territory, Australia. Gamba grass (*Andropogon gayanus*) is an Australian weed of national significance that poses a major threat to ecological and socioeconomic assets in northern Australia. Gamba grass is a perennial C4 grass that forms large tussocks over 4 m high and that displaces the much shorter native vegetation (Flores et al. 2005; Brooks et al. 2010). The Coomalie-Litchfield region in the Northern Territory was the site of original gamba grass plantings and has a significant gamba grass infestation. The region includes towns of Bachelor and Daly, which are priority areas for managing gamba grass fires to protect human life and socioeconomic assets. The region also includes key ecological assets such as Litchfield National Park, which supports extensive gallery rainforest vegetation and contains 5 recognized sites of conservation significance.

Fire is the primary determinant of ecosystem structure and function in northern Australia (Scott et al. 2009). The most significant ecological impact of gamba grass is increased fire severity leading to a reduction in tree canopy and severe negative impacts on the understory (Setterfield et al. 2010). These impacts are detrimental to native vegetation communities and the fauna they support. Changes in fire severity also have negative economic impacts. For example, invasion from gamba grass results in increased fire risk due to substantial increases in fuel load, which in turn requires an increase in the direct costs of fire management (Setterfield et al. 2013).

The natural and socioeconomic assets in the region are affected negatively in different ways by the infestation, which means the benefits to these assets will also accrue at different rates. For example, a primary metric of success of weed management in Litchfield National Park may be the percentage of the park infested. For every hectare of gamba grass eradicated, the benefit is uniform and the expected response curve of management would be linear. However, other assets of concern include the biodiversity zone within Litchfield National Park, of which only a small proportion is infested. If these sites are strategically targeted for management, then the benefit might accrue in an exponential manner with a high return on management prioritized to benefit these assets over others. Finally, if the assets being prioritized are important for tourism, then, similar to biodiversity sites, only a portion of these sites are infested. Strategic action to prioritize sites important to tourism over other sites will return a rapid increase in benefits. The benefit of management at these sites might be a binary function; that is, the sites must be fully managed for access to be regained and benefit returned to tourism.

Future Directions

The majority of pertinent studies we reviewed did not account for spatially variable assets and did not reveal the reasons for this omission. This suggests that scientists and managers are not aware of the need to account for spatially variable assets to capture the benefit returned from management actions; do not have access to data or information needed to account for these assets; or implicitly or explicitly assume benefits from management are spatially uniform across multiple assets.

The potential for additional information to improve decision making is constrained by the money and time needed to acquire it (Grantham et al., 2009; Januchowski et al. 2010). In many regions of the world, environmental and ecological data needed to quantify the benefits obtained from invasive-species management are not available at the regional or local scales at which management is undertaken (Adams & Setterfield 2016). This limitation reduces the scope for explicitly accounting for both costs and benefits of invasive-species management.

Limitations of time and money aside, there remains a need to address ecological knowledge gaps by exploring environmental responses to invasive species (Buckley 2008) and to make this information available to practitioners. One approach to overcome limitations in access to case-specific information is to carry out systematic reviews of ecological and environmental science literature on invasive species management. Such reviews could identify the information and data needed for explicit consideration of benefits returned to different assets from invasive-species management.

At broader spatial scales, species-distribution modeling could be used to model distributions of native species with and without management of invasive species. This approach could be used to estimate past, current, and potential future impacts of invasive species on species distributions, which could in turn be used to quantify potential benefits gained from managing invasive species (Guisan et al. 2013). Planners and decision makers should also tap into knowledge sources not often considered in conservation science, such as indigenous and local knowledge, which can enhance understanding about impacts of invasive species on different natural or socioeconomic assets (Adams and Setterfield 2016).

In addition to direct actions that conservation planners and decision makers can take, there is an opportunity to enhance knowledge sharing and communicating best practice when it comes to planning for and management of invasive species. Initiatives and platforms such as the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) could offer experts an opportunity to bring together existing knowledge and data to improve the ability to make more cost-effective and efficient decisions for invasive-species management. Finally, a diversity of decision-support tools exists for guiding and informing decision making about invasive-species management. Through platforms such as IPBES, there remains an opportunity to bring conservation-decision scientists, who primarily lead spatial optimization analyses for invasive species management, together with managers, ecologists, social scientists, and other invasive-species experts to develop more robust decision-making strategies that give explicit consideration to benefits returned to spatially variable assets.

It is well understood that natural and socioeconomic assets vary spatially across land- and waterscapes (Tulloch et al. 2014), as do threats, such as invasive species. The benefits of actions taken to address threats such as invasive species are defined by both the spatial variability of assets and threats. Deciding where to manage invasive species, much like other conservation decisions, is a function of the spatial benefits returned from action, the costs associated with action, and the likelihood of action success (Newburn et al. 2006; Tulloch et al. 2014). Yet, inclusion of spatially variable assets in prioritizing invasive-species management remains a major gap, as identified by our review of the literature. Our review is the first step in identifying progress toward bridging this critical gap and highlights specific research needs. Given the strong international commitment to mitigate negative impacts from invasive species, it is critical that explicit consideration be given to different assets when designing conservation strategies to ensure equitable and effective solutions.

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Table 1. Publications that were not focused on invasive species management (*n*=826), and reasons for their exclusion from detailed review.

Reason for study exclusion	**Count**
About invasive species, but management not explicitly considered	347
Not about invasive species	152
Ecological study	107
Conceptual or review study	103
Invasive species impact assessment	70
Agricultural study	47

Table 2. Publications that focused on prioritization of actions (*n* = 84) for invasive species management, and the type of prioritization method used.

Type of optimization	**Count**
Spatial optimization	38
Bioeconomic, non-spatial	18
Optimization	6
Cost benefit analysis, non-spatial	6
Bioeconomic, spatial	4
Spatial ranking	4
Spatial simulation	4

Multicriteria decision analyses, spatial	2
Ranking, non-spatial	2

Figure 1. An example of how benefits can be returned to different assets, such as a native species or recreational fisheries, when an invasive species is managed. The amount of benefit returned can scale differently depending on the asset considered and the relationship between benefit and area of invasive species eradication. Here the probability of persistence of a native plant species *P* increases exponentially with the area managed, *A*: — , where the probability of persistence is 100% in absence of the invasive species. The total number of species that benefit *S* increases with the power law, $S = 10 * A^{0.25}$; and the revenue for recreational fishery increases linearly, $R = A/15$.

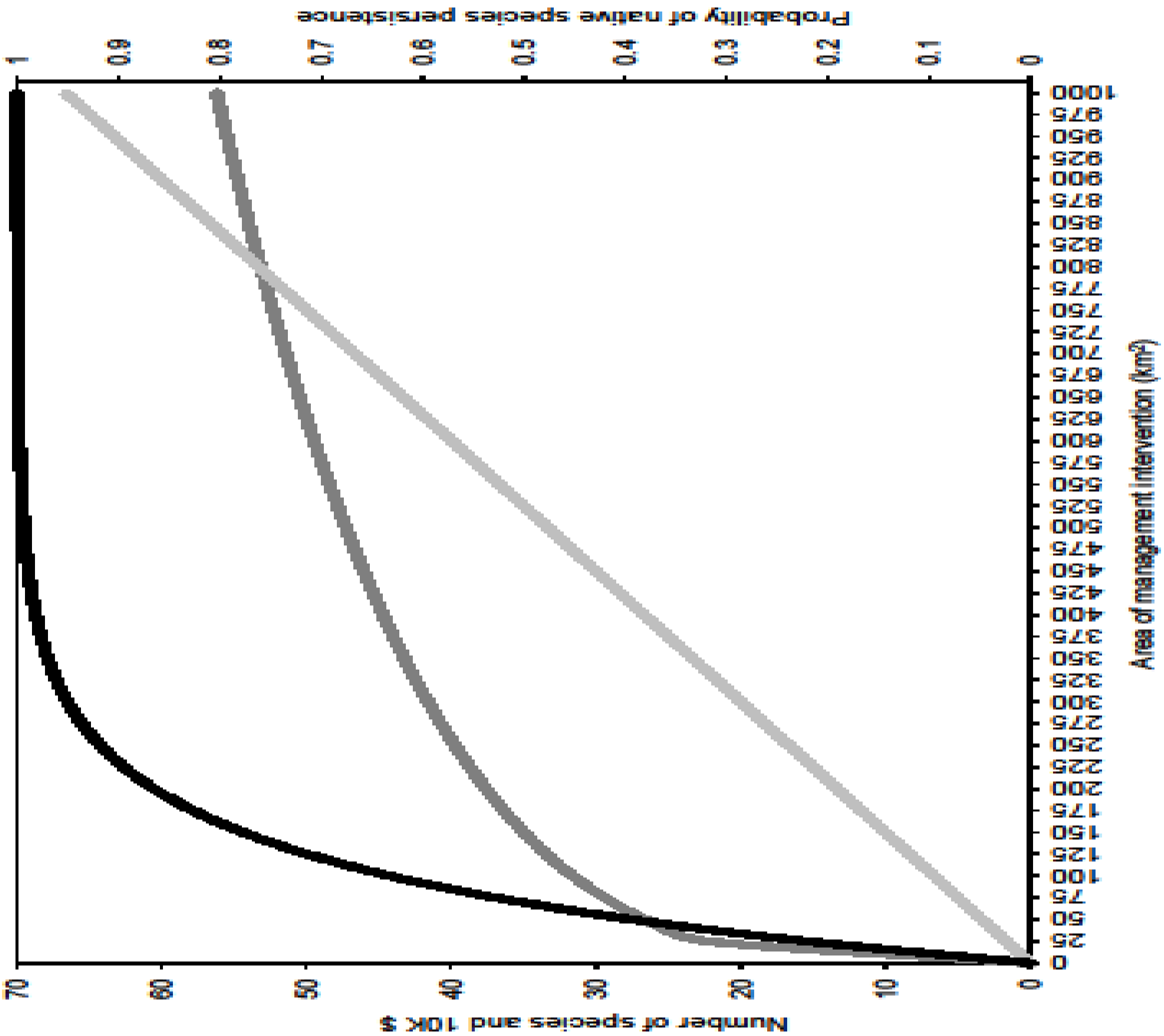
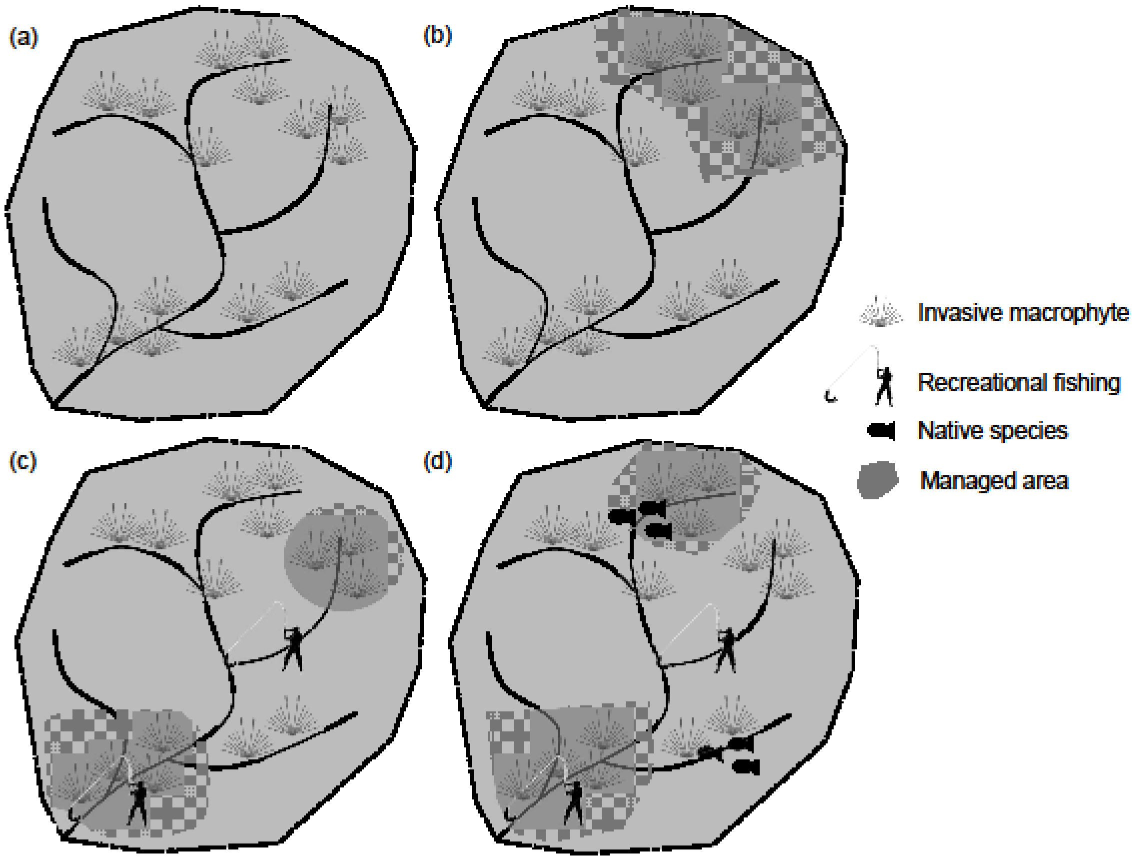


Figure 2. A hypothetical scenario (a) where a semiaquatic invasive plant has a negative impact on social (recreational fishing) and ecological (native species) assets in a river catchment. In subsequent scenarios (b-d) the focus of management strategies on social and ecological assets varies and the selection of managed areas changes based on the level of consideration given to spatially variable assets. Priorities (depicted as managed area) change depending on the focus of management: (b) minimize the spread and amount of area occupied by the invasive species; (c) maximize the benefit returned to a single social asset; and (d) maximize the benefit returned to both a social and an ecological asset.



(a)
(b)
(c)
(d)
Invasive macrophyte
Recreational fishing
Native species
Managed area