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Information uncertainty influences conservation outcomes when prioritizing multi-action management efforts

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Abstract

1. In managing various threats to biodiversity, it is important to prioritize multiple management actions and the levels of effort to apply. However, a spatial conservation prioritization framework that integrates these key aspects, and can be generalized, is still missing. Moreover, assessing the robustness of prioritization frameworks to uncertainty in species responses to management is critical to avoid misallocation of limited resources. Yet, the impact of information uncertainty on prioritization of management effort remains unknown.
2. We present an approach for prioritizing alternative levels of conservation management effort to multiple actions, based on the ecological responses of species to management. We estimated species responses through a structured email-based expert elicitation process, where we also captured the uncertainty in individual experts' assessments. We identified priority locations and associated level of management of effort of four actions to abate threats to freshwater-dependent fauna, using a northern Australia case study, and quantified sensitivity of the proposed solution to uncertainty in the answers of each individual expert.
3. Achievement of conservation targets for freshwater-dependent fauna in the Daly River catchment would require 9.4 million AU$ per year, for a total of approximately 189 million AU$ investment over 20 years. We suggest that this could be best achieved through a mix of aerial shooting of buffalos and pigs, riparian fencing and chemical spraying of weeds, applied at varying levels of management effort in key areas of the catchment.
4. Uncertainty in experts' estimation of species responses to threats causes 60% of the species to achieve 80% of their conservation targets, which was consistent across target levels.
5. *Synthesis and applications*. Our prioritization approach facilitates the planning of conservation management at fine spatial scales and is applicable to terrestrial, freshwater and marine realms. Plan implementation may require policy instruments ranging from landowner stewardship agreements, market-based mechanisms and low-intensity land use management schemes, to regulation of commercial activities within portions of marine protected areas. However, assessing plan sensitivity to uncertainty in species response to management and finding

ways of dealing with it in the prioritization rather than ignoring it, as often done, remains vital for effective achievement of conservation objectives.

KEYWORDS
conservation management, conservation planning, freshwaters, northern Australia, optimal resource allocation, priority threat management, spatial conservation prioritization

1 | INTRODUCTION

Spatial conservation prioritization aims to identify optimal sets of sites, and conservation management actions to prescribe at those sites, to achieve a conservation objective for multiple species, within some defined constraints (e.g. cost of actions) (Possingham, Ball, & Andelman, 2000). This is achieved by accounting for the contribution of management at individual sites to the overall conservation objective (i.e. complementarity) (Moilanen, Wilson, & Possingham, 2009). Originally, spatial conservation prioritization problems aimed to select a set of sites for establishment of protected areas (Possingham et al., 2000). However, recently, the attention has shifted towards real-world prioritization problems, with multiple actions and levels of within-site management effort (Moilanen, Leathwick, & Quinn, 2011; Pouzols & Moilanen, 2013; Watts et al., 2009). Species responses to actions and to their levels of effort are uncertain and the effectiveness of any prioritization solution must be assessed against variability in input information, to avoid allocating insufficient effort or wasting limited resources (McCarthy, Thompson, Moore, & Possingham, 2011; McDonald-Madden, Baxter, & Possingham, 2008; Moilanen et al., 2006; Rondinini, Wilson, Boitani, Grantham, & Possingham, 2006). Yet, a unifying approach capable of addressing simultaneously different real-world complexities (e.g. multiple actions and levels of effort) and quantifying the impact of information uncertainty on prioritization solutions is still missing.

The level of management effort to be allocated to an action refers to a site-specific factor, such as the time frame over which to conduct a certain management action (e.g. surveillance/monitoring, patrolling to reduce poaching, active control of an invasive species), or the budget to invest in the action (Auerbach, Tulloch, & Possingham, 2014; Chades et al., 2008; Chauvenet, Baxter, McDonald-Madden, & Possingham, 2010; Hauser & McCarthy, 2009). Identifying the optimal level of management effort to allocate to an action within a site maximizes the biodiversity benefits for a given dollar invested (i.e. cost-effectiveness) (Hauser & McCarthy, 2009; McCarthy et al., 2010). However, considering multiple levels of management effort represents a main challenge in conservation prioritization, as it increases rapidly the number of management options available for a site (e.g. multiple combinations of actions and levels at each site). Recently, Cattarino et al. (2016) showed the improvement in cost-effectiveness generated from prioritizing continuous levels of management effort to multiple actions. However, in order to isolate the effect of continuous responses, Cattarino et al. (2016) made several simplifying assumptions (e.g. constant costs and theoretical species responses), which reduced the degree to which the study results can be extrapolated to other settings. A generalizable, spatial conservation prioritization scheme which captures a range of real-world complexities (i.e. multiple actions and levels of management effort, real costs and species responses) could improve prioritization of conservation management effort but has yet to be developed and tested.

Prioritizing conservation actions and levels of effort requires information on the responses of species to the actions or the threats addressed by the actions. However, data on species responses to actions are often incomplete or have associated uncertainty (i.e. epistemic uncertainty) (Regan, Colyvan, & Burgman, 2002). Uncertainty can be expressed in the form of empirical error measurements around a nominal estimate (Moilanen et al., 2006), or as a range of plausible values around an expert's best answer, as estimated through an elicitation process (Burgman, Lindenmayer, & Elith, 2005; Martin et al., 2012). Despite the pervasiveness of uncertainty in conservation decision problems, prioritization studies often consider a single value (nominal or most likely) as true species response (Carwardine et al., 2012; Chades et al., 2015; Mills, Adams, Pressey, Ban, & Jupiter, 2012). However, if the true benefit a species accrued following the implementation of a management action is lower than the species benefit used in the prioritization, the management decision may fail to achieve conservation objectives (McDonald-Madden et al., 2010). Conversely, if the true benefit is higher than the benefit used in the prioritization, the prescribed effort might be higher than needed to achieve objectives, resulting in low cost-effectiveness. Therefore, assessing how uncertainty in species responses affects achievement of conservation objectives is crucial for effective allocation of conservation management effort.

Here, we developed a conservation prioritization approach which considers multiple actions and multiple levels of effort to allocate to each action. Our study addresses two main questions. What is the spatial location and overall cost of priority management actions, and their level of allocated management effort, to achieve specific conservation objectives, when we assume that species responses are known with complete certainty? What is the impact of uncertainty in species response estimates, here parameterized using expert knowledge, on achievement of conservation objectives? We answered those questions using a case study from northern Australia where we prioritized spatial allocation of four management actions, at varying levels of effort, to address threats to freshwater-dependent fauna.

2 | MATERIALS AND METHODS

2.1 | Conceptual framework

We built on the problem addressed by Cattarino et al. (2016), who prioritized the allocation of alternative levels of management effort to multiple conservation actions, across multiple sites (planning units), to remediate threats to multiple species for the least cost, based on the ecological responses of species to actions (see Supporting Information). We expanded this problem to account for the varying intensity (i.e. magnitude) of a threat in a planning unit (e.g. spatial extent of a conflicting land use), which influences the level of management effort required to remediate the threat (Adams & Setterfield, 2015). We collated information on species and threat intensity distribution and assumed that the intensity of a threat in a planning unit falls into one of three categories ("Low," "Medium" and "High") (Figure 1a,b). Species responses represent how the probability of persistence of the species varies under increasing threat intensity (Figure 1c). We quantified species responses and uncertainty around response information using expert elicitation. Information uncertainty was expressed as a range of values (*lower bound and upper bound*) around a most likely answer (*best guess*) (Figure 1c). Action costs were sourced from previously published studies (Figure 1d).

We developed a prioritization framework in which three potential levels of effort ("Low," "Medium" and "High") could be allocated to each action. Low level maintains (i.e. avoid increasing) the initial threat intensity, while medium and high levels reduce threat category by one and two categories respectively (Figure 1e).

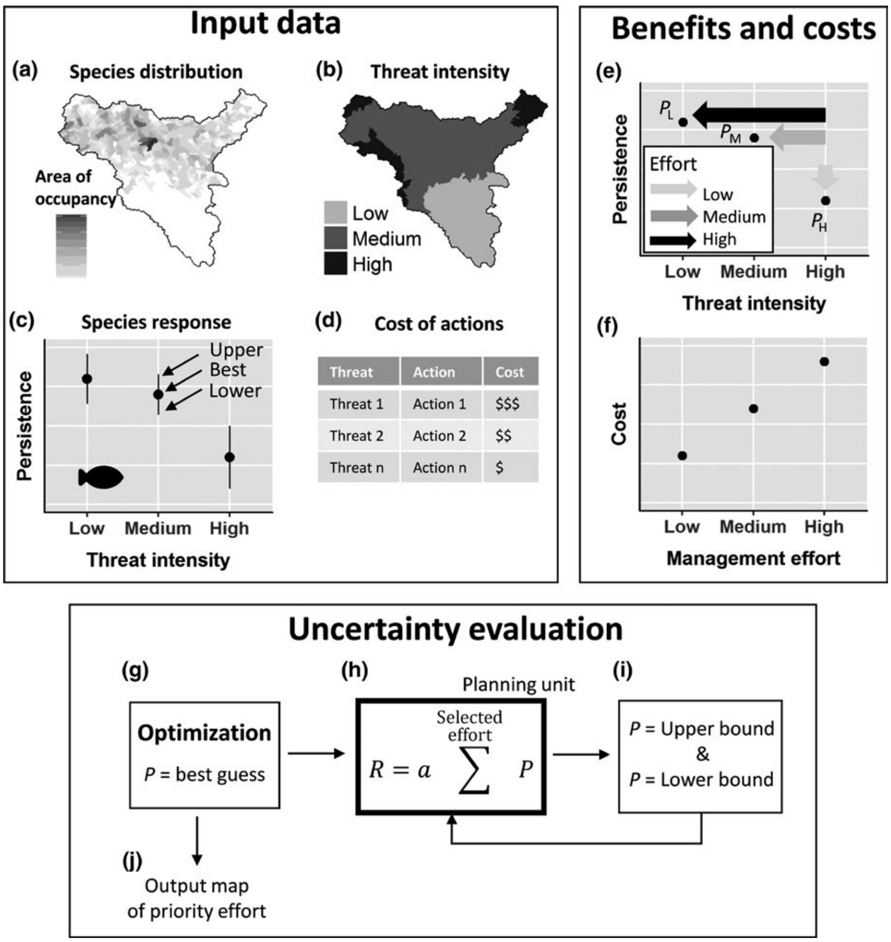

FIGURE 1 Conceptual framework of the study. We assembled input data on spatial distribution of species (a), intensity of different threats (b), species responses (c) and cost of different remediating actions (d). Species responses were estimated using expert elicitation as a best guess and an upper–lower bound interval, which represented uncertainty in an expert's answer. We assume that different levels of management effort could be allocated to each remediating action to reduce threat intensity and improve species persistence (P_H, P_M and P_L) (e). The cost of implementing management effort to an action in a planning unit increases as a linear function of the level of allocated effort (f). To evaluate the effect of information uncertainty on target achievement, we first assumed that species responses were known without uncertainty and used the experts' best guesses (averaged across experts) as estimates of species responses to achieve representation targets in the prioritization (g and j). We then quantified the impact of uncertainty around species response estimates on target achievement, by recalculating species representation in the prioritization solution using the experts' lower and upper bounds estimates of species responses (averaged across experts) (h and i). Representation, R, of a species in a planning unit equals the sum of the probability of persistence (P) achieved through implementation of different actions, multiplied by the area of occupancy (a) of the species in the planning unit

We assumed that the cost of actions increased linearly with the level of management effort (Figure 1f). The aim of the framework is to identify a set of priority areas, the type of management action and the level of effort prescribed within those areas, to achieve a minimum representation for each species, while minimizing management costs (Figure 1g, j). The minimum representation, or *target*, is the area of occupancy of each species, which is expressed as the product of the probability of persistence, achieved through selected actions and effort, and the area of occupancy of a species in the planning units where actions and effort are selected (Figure 1h).

To evaluate the effect of information uncertainty on achievement of conservation objectives, we first generated a prioritization solution using expert best guesses, which is analogous to assuming no uncertainty around experts' most likely answers (Figure 1g). This reflects a common assumption in conservation planning. Then, in post hoc analysis, we quantified species representation (in the prioritization solution) by assuming that experts' answers were uncertain. We simulated the effect of experts' uncertainty using the lower and upper bounds of the experts' answers (averaged across all experts) as estimates of species responses (Figure 1i). This reflects the extent to which the implementation of a conservation plan may result in target shortfalls (in the case that the true species response is the lower bound) or in an unexpected windfall (in the case that the true response is the upper bound).

2.2 | Study area and species

The Daly River catchment is in tropical northern Australia and extends over 53,000 km^2 of tropical savanna woodland (Chan et al., 2012). Despite low levels of clearing (*c*. 5%) and existing conservation areas (*c*. 10%), long-term persistence of freshwater-dependent fauna in the Daly River catchment is affected by major threatening processes, including invasive animals, agricultural land use (particularly grazing, which is the dominant land use) and proliferation of aquatic weeds (Adams et al., 2014).

We defined a spatial framework consisting of 865 hydrologically defined sub-catchments, which represent the planning units of analysis (see Supporting Information, Section 1). We considered a suite of freshwater-dependent taxa (44 fishes, 8 freshwater turtles and 86 water birds) and four major threats to freshwater biodiversity: (1) introduced water buffalos *Bubalus bubalis*; (2) feral pigs *Sus scrofa*; (3) grazing land use; and (4) para grass *Brachiaria mutica*—a highly invasive weed.

2.3 | Management actions and costs

For each threat, we considered a remediating management action: aerial shooting of water buffalo and feral pigs, building cattle-proof fences along riparian zones to reduce cattle trampling and other damages to freshwater ecosystems and chemical spraying of para grass (Bayliss & Yeomans, 1989; Carwardine et al., 2011; Setterfield et al., 2013). The management costs of implementing different levels of effort of each action (AU\$ ha^{-1} year^{-1}) were sourced from peer-reviewed studies in other river–floodplain ecosystems of northern Australia (see Supporting Information, Section 3.4). Cost estimates were calculated as the net present value of the sum of set-up costs (long-term capital, materials, supplies and labour) in the first year and the ongoing annual maintenance costs, assuming an ongoing investment in the action over 20 years and a 5% discount rate (Carwardine et al., 2012). We assumed that the cost of implementing increasing levels of management effort to an action in each planning unit increased as a linear function of the level of allocated effort (Santika, McAlpine, Lunney, Wilson, & Rhodes, 2015). When costing the actions, we assumed that: (1) aerial shooting was conducted over the area of the entire planning unit; (2) riparian fencing was implemented along the stream network within each planning unit; and (3) para grass spraying occurred over the estimated extent of para grass infestation in each planning unit.

2.4 | Species' ecological responses to threats

We asked experts to estimate the ecological responses of species to threats using a structured, email-based elicitation approach (McBride et al., 2012) (see Supporting Information, Section 2). We categorized species from all faunal groups into 18 different ecological groups, based on similarities in ecological requirements and behaviour (see Table S1.1). We then engaged 13 experts in the ecology and conservation of freshwater fishes, turtles and/or water birds via email and asked them to estimate probabilities of persistence of species in different ecological groups, given exposure to three intensities of each threat (Carwardine et al., 2012). Following a four-point elicitation procedure, we asked the experts to provide the most likely value (best guess), lowest and highest plausible values and level of confidence they had that the true value of persistence lay within the lowest–highest value bound (Speirs-Bridge et al., 2010). This interval represents the uncertainty of one expert in the actual response value exhibited by a taxon. We collected a total of 72 ecological responses (18 ecological groups × 4 threats) (Figure S3), which were then used in the prioritization.

2.5 | Benefits of actions

The benefit of a particular level of effort was equal to the increase in probability of persistence following action implementation. For example, given initial "High" threat intensity, implementing a "Medium" level of effort for an action reduces the threat to "Medium" intensity, and therefore, the benefit corresponded to the species persistence under "Medium" intensity of that threat (the persistence value is averaged across experts) (see Supporting Information, Section 3.3). The benefit of the "Low" effort corresponded to the probability of persistence under the initial intensity of the threat.

2.6 | Optimization approach

We used the optimization approach described in Cattarino et al. (2016), which is based on simulated annealing, to find a near-optimal solution to the action prioritization problem (see Supporting Information, Sections 3.2 and 3.5). This approach is similar to the one adopted by the spatial conservation prioritization software, Marxan (Ball, Possingham, & Watts, 2009). However, while Marxan focuses on planning unit selection, our optimization algorithm iteratively removes from, or adds to, the solution, one level of management effort for one action in one planning unit, at a time.

2.7 | Quantifying the effect of information uncertainty

To assess the effect of expert uncertainty on achievement of conservation targets, we adopted a two-stage procedure. We first identified the set of priorities (sites, actions and levels of effort) to assess a conservation target for each species, using the expert best guesses (averaged across experts) as the "true" response. These spatial priorities reflect real-world cases in which managers use best available information to set priorities, ignoring uncertainty around species response. We then estimated the extent to which implementing these sets of priorities may result in either over- or under-achievement of species targets, when the true species responses deviate from expert best guesses. Upper and lower estimates of species representation were calculated by assuming that the true response corresponded to either the lower bound or the upper bound of the experts' answers (averaged across experts) respectively.

We calculated the percentage change in the representation of species j under different assumptions of true response (*observed* representation), relative to the representation level achieved in the original prioritization (*expected* representation). Percentage changes were calculated as:

$$\Delta_j = \frac{O(R)_j - E(R)_j}{E(R)_j} \times 100 \tag{1}$$

where $E(R)_j$ and $O(R)_j$ are the expected and observed representation for species j respectively. A positive change occurs when a species is less sensitive to the threat than expected, because for a given action–effort combination, the true species probability of persistence is higher than what was assumed in the prioritization. The consequence of this is that, when a manager uses the results obtained using the best guess prioritisation, the effort selected in the prioritization is higher than what is actually needed. This means that the solution is less cost-effective, but will assure achievement of targets.

A negative change occurs when a species is more sensitive to the threat than expected, because for a given action–effort combination, the species probability of persistence is lower than what was assumed in the prioritization. Therefore, the effort selected in the prioritization is lower than the effort needed to achieve the targets. Consequently, we might fail to achieve species targets.

2.8 | Analysis

We applied species targets proportional to each species area of occupancy to ensure representing the whole distribution of rare species and avoid over representing common ones (Rodrigues et al., 2004). We set a fixed target corresponding to 100% of the range of species with an area of occupancy smaller than 500 km^2

TABLE 1 Average cost per year, over 20 years and spatial extent of prescription application, of different levels of management effort, for different actions prescribed in the Daly River catchment

Action	Management effort	Annual cost	20-year cost	Treated area*
Aerial shooting of buffalos	Low	1.10	21.96	17,713
Aerial shooting of buffalos	Medium	0.17	3.42	2,762
Aerial shooting of buffalos	High	–	–	–
Aerial shooting of pigs	Low	1.49	29.80	9,142
Aerial shooting of pigs	Medium	1.16	23.10	7,086
Aerial shooting of pigs	High	–	–	–
Riparian fencing	Low	2.74	54.82	142
Riparian fencing	Medium	2.10	42.08	13
Riparian fencing	High	–	–	–
Chemical spraying	Low	0.19	3.72	207
Chemical spraying	Medium	0.17	3.40	225
Chemical spraying	High	0.32	6.35	562
Total		9.43	188.66	37,853

*Area (km^2) of the planning units where each level of effort (for different actions) is prescribed. For aerial shooting of buffalos and pigs, treated area is the area of the planning units; (2) for riparian fencing, treated area is the stream area (assuming a 100 m river width) in the planning units; (3) for chemical spraying of para grass, treated area is area of the planning units infested with Para grass.

(20% of species). We also set a fixed target of 10% of the range of species with an area of occupancy larger than 10,000 km^2 (24% of species). The target for species with area of occupancy of intermediate size (57% of species) was calculated using linear interpolation (see Supporting Information, Section 1). We investigated how sensitive our results were to species targets and repeated the analysis for a range of target level (see Supporting Information, Section 5.3).

3 | RESULTS

3.1 | Cost and spatial priorities of conservation management effort in the Daly River catchment

Ensuring ecological persistence of freshwater-dependent fauna in the Daly River catchment would cost approximately 9.4 million AU$ per year, for a total of just below 189 million AU$ investment over 20 years (Table 1). This requires, for example, conducting low levels of aerial shooting of water buffalos over around 17,700 km^2, and medium levels of aerial shooting of feral pigs over 7,000 km^2, per year (Table 1). Long-term persistence of freshwater-dependent fauna in the Daly also requires riparian fencing at low and medium levels of management effort, over 142 and 13 km^2 of stream area, respectively, and low, medium and high levels of chemical spraying over 207, 225 and 562 km^2, respectively, of para grass infestation, per year (Table 1). Priority areas selected for allocation of conservation management effort are mainly located on the floodplain and tributary streams of the lower Daly River catchment, along the main stem of the Daly River, and in the headwaters in the north-eastern part of the catchment (Figure 2).

3.2 | Effect of an expert's own confidence level on target achievement

When the lower bounds of experts' answers were assumed to be the true species responses, average species representation was 20% lower than when the experts' best guesses were used as true responses (Figure 3). This pattern was consistent across different target levels (Figure S7). The observed drop in species representation was due to almost 60% of the species achieving approximately 80% of their conservation targets (Figure S5 and S6).

When the upper bounds of experts' answers were assumed to be the true species responses, average species representation was 2.5% higher than when the experts' best guesses were used as true responses (Figure 3). Positive change in species representation did not translate into an increasing number of species represented above target levels. This is because most of the species were already represented at or above target level when using the experts' best guesses (Figure S5).

4 | DISCUSSION

We have developed a novel approach for optimizing the spatial allocation of priority threat management effort (Carwardine et al., 2012; Chades et al., 2015; Moilanen et al., 2009). We demonstrated the efficacy of our approach using a case study from northern Australia and identified priority areas where a mix of aerial shooting of water buffalos and feral pigs, riparian fencing and chemical spraying of para grass, applied at varying degrees of management effort, are needed to conserve freshwater biodiversity. We also showed that, in a consistent fashion across a range of conservation objectives,

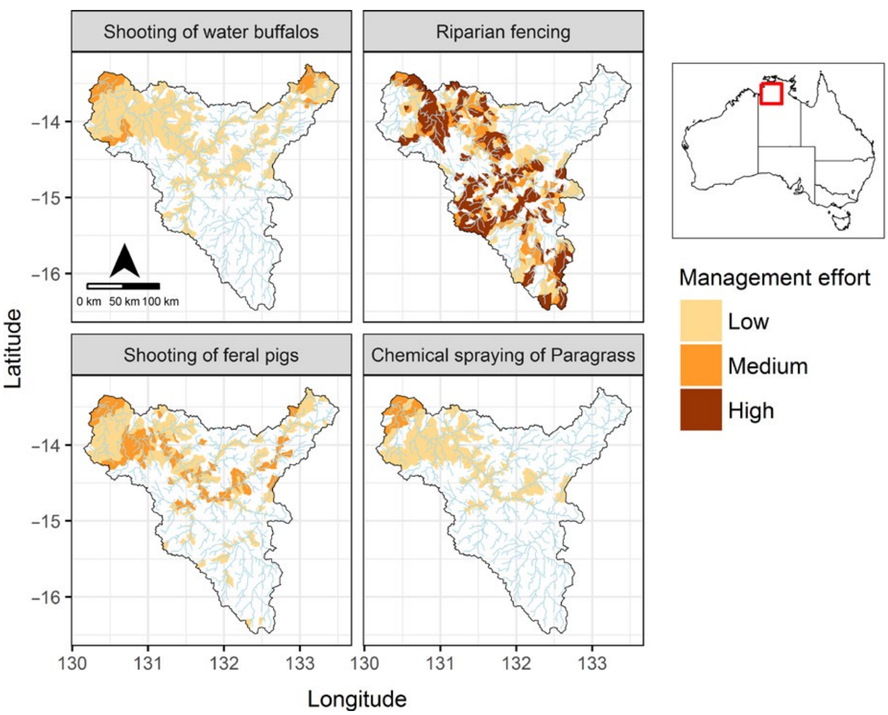

FIGURE 2 Spatial distribution of management effort allocated to four different actions in the Daly River catchment. Results are shown for the best solution of 10 replicates and best guess expert estimate (averaged across experts) [Colour figure can be viewed at wileyonlinelibrary.com]

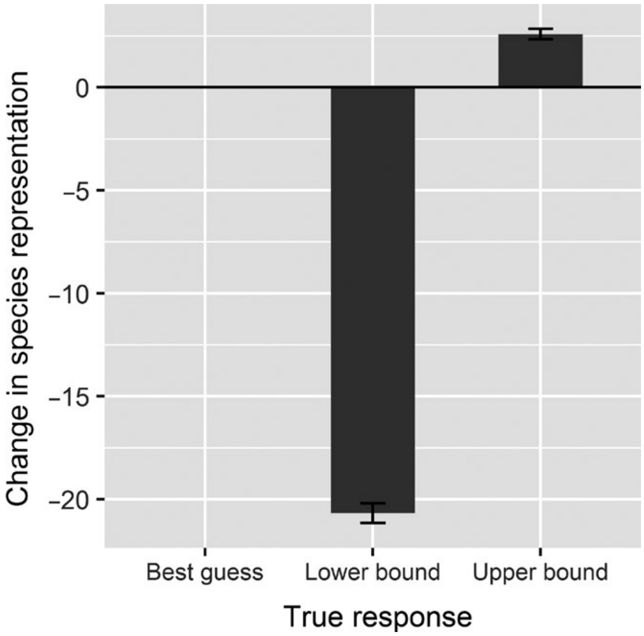

FIGURE 3 Percentage change in species representation, relative to the best guess scenario, when the true species responses deviate from an expert best guess, due to an expert's own confidence level. The value on the *y* axis is the percentage change value averaged across species (± 1 *SE*). Best guess scenario refers to when the best guesses of individual experts (averaged across experts) were assumed to be the true species responses (continuous 0 line). The effect of an expert's own confidence level refers to when the lower and upper bounds of individual experts (averaged across experts) were assumed to be the true species responses. Displayed values are from the run with the lowest objective function, among a set of 10 replicate runs

uncertainty in estimates of species response to actions undermines the capacity to achieve conservation objectives. This suggests that using experts' best answers for conservation decisions may increase the risk of misallocating limited conservation resources or lead to overoptimistic assessment of conservation progresses, as species are considered able to persist in the face of threats, when in reality, they are not. Our approach can aid planning conservation management strategies at fine-spatial scales. Our findings call for improving accuracy of experts' answers to be used in prioritization and highlight the importance of assessing the performance of prioritization plans based on experts' best answers.

We identified key areas for allocation of threat-specific management efforts in the Daly River catchment, with the Anson Bay floodplain (north-east), the Daly River Middle Reaches (central) and the Arnhem Land Plateau/Katherine River headwaters (north-west) being top priorities (Figure 2). These areas have been identified by the Northern Territory government as sites of conservation significance and feature among the top conservation priorities of previous freshwater prioritization studies in the region (Linke et al., 2012; Northern Territory Government, 2017). However, previous studies assumed that priority areas were converted into protected areas by acquiring their land, which is often not a viable conservation strategy due to the pressure imposed by other human activities (e.g. agriculture). In contrast, we identified the specific management actions (and the required level of management effort) to undertake in priority areas. While invasive herbivore and aquatic weed control are priority actions in the coastal floodplain and Arnhem plateau, riparian fencing was selected for most of the Daly middle reaches. Furthermore, these areas should be allocated a higher level of management effort (e.g. spatial extent or hours of management) relative to other areas, according to our analysis. This information provides much more operational detail for protected area managers and land owners confronted with threat management.

Our study highlights the importance of the spatial distribution of threats and species responses to the associated actions in driving spatial allocation of conservation management effort (Tulloch et al., 2015). Among the spatial priorities, we identified the south-western portion of the catchment (Katherine River's main channel) as a key area where to undertake riparian fencing. This area overlaps with the spatial distribution of cattle grazing, a threat to which the species considered here (e.g. fishes) are particularly vulnerable (Figure S3). The Kathrine River's main channel, however, was missing from the priority areas identified by previous study in the region, which was largely based on the same set of species considered here, but did not account for the spatial distribution of threats and the responses of species to the remediating actions (Linke et al., 2012).

The cost of threat-specific conservation actions (e.g. invasive species management) is comparable to those estimated by other studies in the Daly and in other parts of northern Australia (Kimberley) (Adams, Pressey, & Stoeckl, 2012; Carwardine et al., 2012). However, our total cost estimates differ from those of other similar studies. This is unsurprising given the differences in threats and management actions considered. In addition, we assume that prescribed management occurred in the portion of the planning units where the threats occurred, as opposed to managing the entire planning unit, as assumed in other studies. This means that it is hard to make meaningful cost comparisons across studies. Furthermore, our cost estimates should be interpreted conservatively, as we extrapolated them from studies conducted at different spatial scales and did not account for the cost reduction obtained by managing large areas of land. Accounting for such economies of scale would have likely resulted in generating even lower cost estimates, thus increasing cost-efficiency of our approach (Armsworth, Cantu-Salazar, Parnell, Davies, & Stoneman, 2011).

Our findings suggest that considering variability in species responses to actions when prioritizing conservation management effort should become best practice, if we want to minimize the risk of undermine conservation objectives. Unfortunately, current approaches often do not quantify the effect of response uncertainty, but rather tend to make use of best (most likely) responses estimates, which might not represent true species responses (Carwardine et al., 2012; Chades et al., 2015; Mills et al., 2012). We showed that ignoring the variability in an expert's own range of potential answers (the confidence level) might lead to failure to achieve conservation targets. Our result highlights the importance of considering uncertainty from the onset of the planning stage. Doing so might reduce the risk of generating solutions highly susceptible to uncertainty in expert knowledge.

This is particularly relevant when specific conservation objectives must be met, as we have demonstrated in our analysis. One way to properly account for uncertainty in species responses when prioritization actions is to create "robust" spatial prioritization solutions, which can tolerate large variations in the expected response values, without compromising the achievement of conservation targets (Burgman et al., 2010; Moilanen et al., 2006). Previous studies have addressed this in the context of conservation problems with only site reservation action and could be expanded by incorporating multiple actions.

4.1 | Study limitations

We assumed categorical levels of threats and management effort as well as a linear relationship between level of management effort and amount of threat reduced. However, the use of continuous response curves or varying shapes is likely to provide the greatest cost-efficiency (Cattarino et al., 2016). Nevertheless, for the current applied study, we decided to use categorical responses, which facilitated experts' task of estimating species responses, by providing a benchmark, when available, for each individual threat intensity (e.g. estimated number of buffalos/km^2). Moreover, defining more detailed categories would have required more precise threat distribution information, particularly on the intensity of individual threats, which was unavailable. Our framework can be easily expanded to incorporate continuous responses of different shapes. Where and when finer scale information on threat intensity are available, an infinitesimal (continuous) number of threat and effort categories can be implemented. Moreover, if the relationship between amount of effort and threat intensity is known or can be easily elicited from experts, the present framework can be broadened to incorporate different relationships between threat and effort categories or curves of varying shapes.

Effective on ground management is not purely a matter of mathematical optimization—there are other social and human factors which have not been considered here. For example, we did not consider landowners' willingness to engage in conservation practices, such as aquatic weed control, river bank restoration and improved invasive herbivore management (Honig, Petersen, Shearing, Pinter, & Kotze, 2015). Given most of the Daly River catchment is privately owned or managed, failing to account for landowners' willingness to participate into conservation programmes, or more generally their attitudes towards conservation, is likely to represent a barrier to achievement of conservation objectives.

4.2 | Management implications

Our approach can aid local and regional government agencies to plan and implement priority threat management at fine-spatial scales (Carwardine et al., 2012; Game, Kareiva, & Possingham, 2013; Wilson et al., 2011). This may require putting in place policy instruments which target individual properties, such as landowner stewardship agreements, where portions of the property are set aside for conservation or where best farming management practices are adopted (Claassen, Cattaneo, & Johansson, 2008; Moon & Cocklin, 2011). Such agreements might be directed at implementing specific actions at specific levels of effort, such as removing a number of invasive herbivores per km^2, setting up cattle fences of specific length along a river to keep cattle away or applying chemical spraying to a portion of weed-infested floodplain. Alternative policy tools include market-based mechanisms, such as labelling or certification of products (e.g. beef) produced on land where conservation practices are adopted, and land use management schemes promoting sharing land between conservation and agricultural production, through adoption of less intensive farming practices (e.g. rotational grazing) (Fischer et al., 2008; Higgins, Dibden, & Cocklin, 2008). Our approach may help prioritizing fine-scale management in settings different from freshwater/terrestrial ones. In marine settings, for example, management regimes which can be prioritized with our approach include exclusion of fishing and other economic activities around sensitive sites (e.g. coral reef), restoration of specific tracts of coastal habitat (e.g. mangroves) and regulation of fishing pressure within portions of a marine protected area (Adame, Hermoso, Perhans, Lovelock, & Herrera-Silveira, 2015; Costello et al., 2016; Foley et al., 2010).

The marked effect of information uncertainty on achievement of conservation objectives highlights the importance of improving accuracy of species response estimates to management. This may require to refine the expert elicitation process by, for instance, giving experts opportunities to discuss their answers in person and testing the experts beforehand with similar questions to the ones they will be required to answer (Burgman et al., 2011; Hemming, Burgman, Hanea, McBride, & Wintle, 2018). However, insufficient resources (time and money) often require managers to make quick decisions with the best available information, that is, experts' best guesses. In this case, we recommend to carefully assess the performance of the conservation plan developed using the best response estimates (Sarkar et al., 2006). If the plan turns out to perform poorly (some species in decline), a manager might need to calibrate management effort in selected priority areas. Our approach represents a flexible tool which may aid managers with effort calibration, as it prioritizes variable levels of management effort at individual sites. Varying the level of effort to apply to actions in existing priority areas might be more cost-effective than finding new priority areas given resources (e.g. personnel and vehicles) are already deployed on site.

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AUTHORS' CONTRIBUTIONS

L.C. performed the analysis and drafted the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

DATA ACCESSIBILITY

Data and R code are available from the Zenodo Digital Repository https://doi.org/10.5281/zenodo.1184586 (Cattarino et al., 2018).

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