Integrating local social-ecological knowledge to prioritise invasive species management

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Abstract

There is a lot of uncertainty about how we pick the best invasive species management strategies to improve the environment, local economy, and human well-being, as invasive species management involves complex and multidimensional challenges. Invasive species management on inhabited islands is especially challenging, often due to perceived socio-political risks and unexpected technical difficulties. Failing to incorporate local knowledge and local perspectives in the early stages of planning can compromise the ability of decision-makers to achieve long-lasting conservation outcomes. Hence, including local knowledge and accounting for subjective stakeholder perceptions is essential for invasive species management, yet this often remains unaddressed. To address this gap, we present an application of invasive species management based on structured decision-making, and the resource allocation tool INFFER, on Minjerribah-North Stradbroke Island (Australia). We assessed the cost-effectiveness of six management scenarios, co-developed with local land managers and community groups, aimed at preserving the environmental and cultural significance of the island by controlling the impacts of European red foxes and feral cats. We further conducted a survey eliciting local stakeholders' perspectives regarding the significance of the Island, their perception of the benefits of the proposed management scenarios, funding requirements, technical feasibility of implementation, and socio-political risk. We found that the best decisions when the budget is low are less cost-effective than when the budget is high. The best strategy focusses on control of European red fox on Minjerribah. However, our results also highlight the need for more research on feral cat management. This work demonstrates how to use a structured decision support tool, like INFFER, to assess contesting management strategies; this is particularly important when stakeholder's perceptions regarding management outcomes are heterogeneous and uncertain.

1. Introduction

Rates of species extinction and decline are increasing, and are likely to continue to increase worldwide unless we address the main threats to biodiversity (Barnosky et al. 2011; De Vos et al. 2015; Jones et al. 2016). Invasive species are one of the main causes of species decline and extinctions (Clavero & García-Berthou 2005; Bellard et al. 2016; Doherty et al. 2016). Approximately 75% of recorded terrestrial extinctions have occurred on islands (Tershy et al. 2015), and invasive species have been identified as the leading factor (Courchamp et al. 2003; Clavero & García-Berthou 2005; Doherty et al. 2016). This has concerning implications for global biodiversity, as a disproportionately high percentage of global biodiversity is found on islands (Aguirre-Muñoz et al. 2008), despite them only occupying a 3.5% of the Earth's total land area (Whittaker et al. 2017).

Islands are particularly susceptible to invasive species and their impacts (Simberloff 1995, 2009). In response to the threat posed by invasive species, more than 1,000 eradication programmes have been implemented on islands around the world (Simberloff et al. 2011). Most of these programmes have resulted in positive outcomes for native species (Zavaleta et al. 2001; Innes & Saunders 2011; Jones et al. 2016). However, most invasive species eradication programmes have been implemented on uninhabited islands, mostly due to operational difficulties, such as perceived health hazards or financial burdens on the local community (Oppel et al. 2011b). A global challenge is to shift the focus of invasive species control from uninhabited islands to populated islands (Oppel et al. 2011b; Glen et al. 2013), since many of the highest priority islands for eradications are inhabited (Brooke et al. 2007). Inhabited islands pose particular difficulties due to the presence of companion animals and livestock species, which hamper eradication actions (Glen et al. 2013). At the same time, commonly used eradication methods cannot be employed close to communities, or the existing methods can be substantially more expensive to implement than on uninhabited islands, mostly due to logistic difficulties and implementation restrictions around populated areas (Glen et al. 2013). Thus, eradication programmes on inhabited islands need to account for local environmental, social and economic conditions, as well as the biological and technical expertise required to remove invasive species (Oppel et al. 2011a).

Community engagement has a major role to play in determining the outcomes of future efforts to improve invasive species management programmes on inhabited islands (Aguirre-Muñoz et al. 2008; Campbell et al. 2011; Ford-Thompson et al. 2012). Calling for engagement of local stakeholders is not new (Aguirre-Muñoz et al. 2008; Campbell et al. 2011), because the preferences and opinions of all people affected by conservation actions should be integrated in any environmental decision-making process that might affect them and the surrounding environment (Reed 2008; Estévez et al. 2015; Crowley et al. 2016). Public opposition can hinder the success of eradication programmes (Bremner & Park 2007) and is common where the target species is valued by people (e.g. pets, livestock) (Glen et al. 2013). Consequently, lack of involvement and communication with the local community has been linked to the failure of previous eradication efforts (Campbell & Donlan 2005). Hence, to halt biodiversity decline caused by invasive species, it is imperative we advance not only with eradication protocols (Saunders et al. 1995) and reporting strategies (Iacona et al. 2018), but also with techniques to engage with local stakeholders when eradication plans are undertaken (Braysher 2017; Toomey et al. 2017).

Incorporating local values and preferences into early planning stages can be challenging (Oppel et al. 2011b; Ford-Thompson et al. 2012). Through engagement it is possible to clarify and diminish any safety or social concerns (Glen et al. 2013), mitigating possible opposition to the implementation of eradication projects, and thus recognising the importance of informing the local community about all the socio-economic, health, and ecological benefits (and costs) (Vane & Runhaar 2016) that could arise through implementation of eradication plans. This is particularly important in invasive species management, given that the survival of a few —invasive— individuals can undermine the whole project (Glen et al. 2013)

Existing approaches to incorporate the preferences and values of local communities and practitioners have often targeted a single-stage of the eradication planning process (Ford-Thompson et al. 2012; Novoa et al. 2018) for example: engagement (Luyet et al. 2012), eliciting information (Larson et al. 2011), or informing perceptions (Bardsley & Edwards-Jones 2006). In this work, we present a novel, systematic approach to address the multiple challenges of incorporating local knowledge and preferences throughout the eradication planning process. We engaged with multiple stakeholder, elicited local knowledge, and included natural resource managers' perceptions to compare contesting management scenarios by using a cost-benefit analysis. Our approach is based on adaptive management principles (Holling 1978) and the Investment Framework for Environmental Resources (INFFER) (Pannell et al. 2012), and it can be implemented by decision-makers to: (i) assess the perceptions and preferences of stakeholders regarding invasive species management; (ii) assess the feasibility, impacts and expected benefits of alternative projects; and (iii) incorporate stakeholders' expertise and perceptions to better inform invasive species management plans.

We applied the proposed approach on Minjerribah – North Stradbroke Island, located in Queensland, Australia (hereafter Minjerribah), where we co-developed and evaluated six management scenarios, with different investment levels, each designed to control the impacts of

European red foxes (*Vulpes vulpes*, Linnaeus, 1758) and feral cats (*Felis catus*, Linnaeus, 1758). We elicited stakeholder data through a semi-structured online survey (eSurvey) (Appendix A). The objective of this study was to aid decision-makers to select management scenarios that would deliver the most cost-effective benefits to threatened and culturally relevant species (Appendix B), and to the local community on Minjerribah.

2. Methodological analysis and context

The objective of this study was to aid decision-makers to select the best alternatives to control the impacts of invasive species on native terrestrial populations by implementing INFFER (Pannell et al. 2012). In this section, we provide details about our case study, Minjerribah, the stakeholder-engagement process, application of INFFER (Pannell et al. 2012), data collection, and development and analysis to select the best strategies to control invasive species impacts on native and culturally relevant species. This wider process is described in Figure 1.

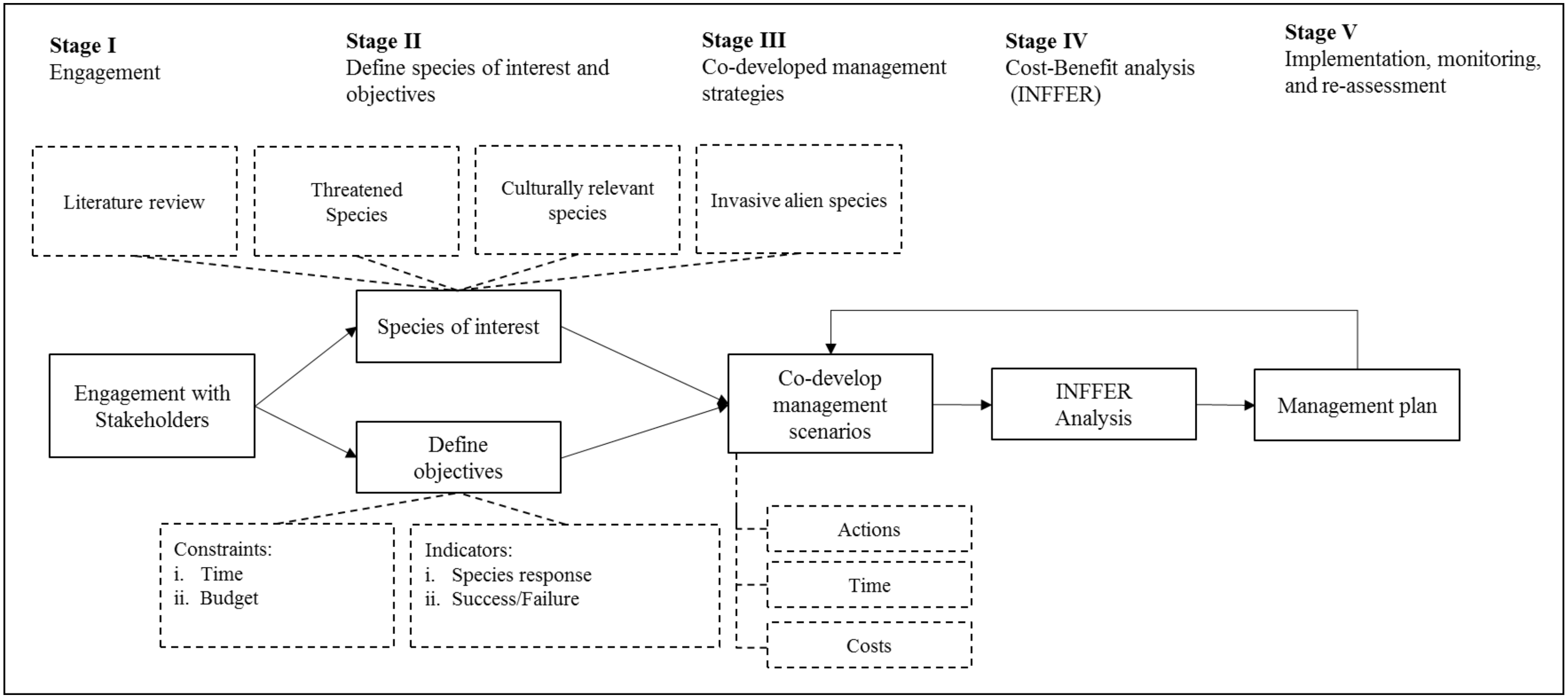

Fig. 1. Stages of our proposed framework to develop, assess, and select invasive species management strategies. The dot outlined boxes represent complementary actions that need to be undertaken to complete the main goal in every stage, which is represented by solid outlined boxes.

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2.1. Study area: Minjerribah – North Stradbroke Island (Queensland, Australia)

Minjerribah has unique ecological, economic, and culturally relevant values for the local and national Australian population. These values are currently being impacted, directly or indirectly, by invasive species. Minjerribah's ecological uniqueness and internationally important cultural heritage make it one of the top 50 offshore islands prioritised for protection in Australia (Kramer & Whelan 2009). The Island is located approximately 40 km east of Brisbane (Queensland, Australia) (Figure 2). It is the second largest sand island in the world (approximately 285 km^2) (Laycock 1978), and the largest of the Moreton Bay Islands (Queensland, Australia) (27°30'S, 153°28'E). Minjerribah hosts a wide variety of habitats (Queensland Herbarium 2009) that support many native sedentary and migratory species. The island is a stepping stone along the East Asian-Australian Flyway and is a "Wetland of International Importance" (Ramsar Convention 1971) marking it an important site for Australian bird resident species as well as for intercontinental migrants (Wilson et al. 2011).

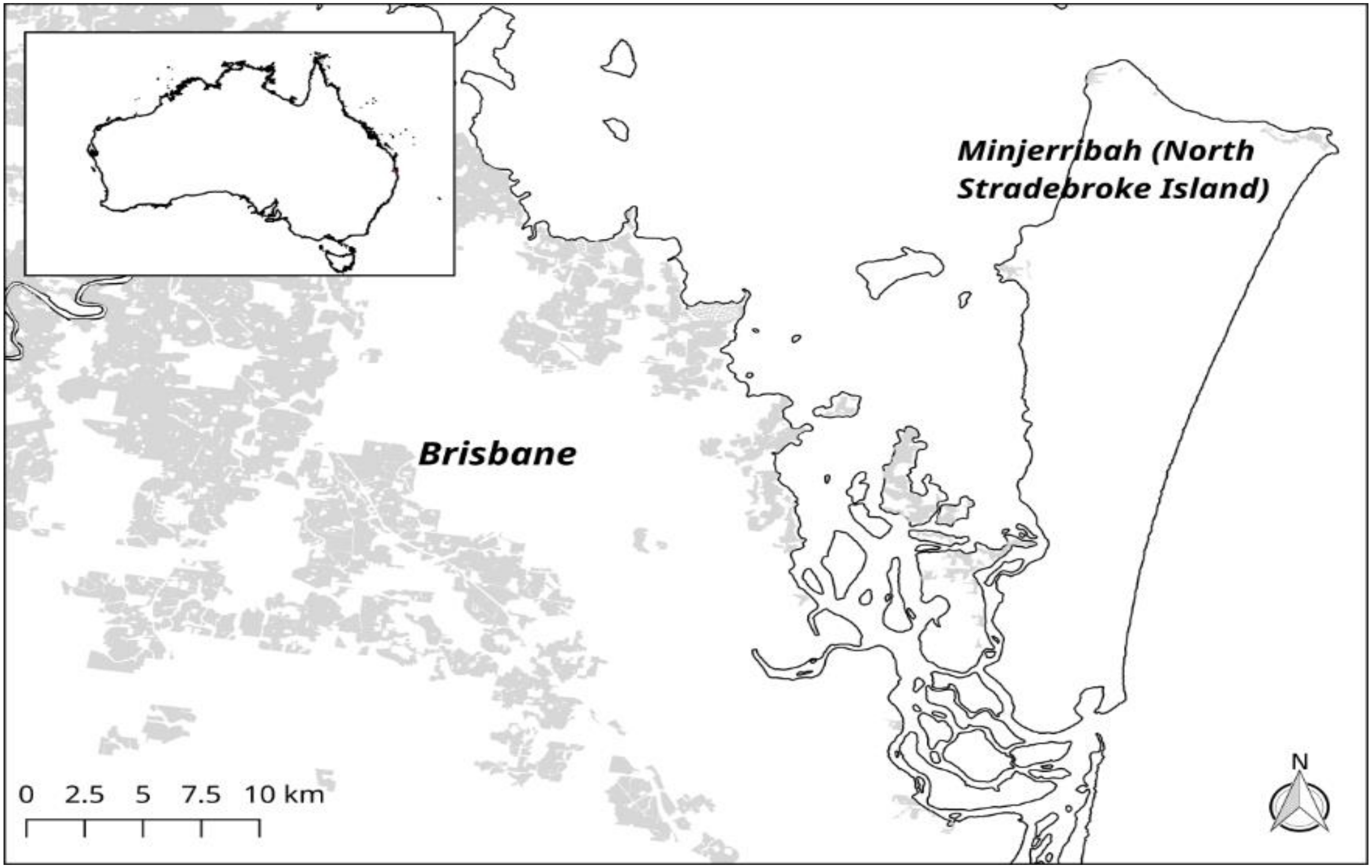
139 

Fig. 2. Location of Minjerribah (North Stradbroke Island) in Queensland, Australia).
Light grey areas indicate urban development

The Island has been inhabited by the Quandamooka people for at least 21,000 years (Barram et al. 2016). The Quandamooka people are the historical custodians of Moreton Bay. In 2011 this was recognised by the Federal Court of Australia (National Native Title Tribunal 2011), highlighting the cultural significance of the area. Since the 1940s, the Island has also been the source of extensive sand mining operations. The mining activities are scheduled to end by late 2019; a period which marks the end of an industrial era on Minjerribah, and the prospect of major change and potential economic growth for local businesses, tourism, and the local community.

Fifteen vertebrate invasive species have been recorded on the island, including red foxes and cats (Appendix B) (Threatened Island Biodiversity Database Partners 2014). Red foxes and feral cats are two of the most damaging invasive species in the world (Lowe et al. 2000; Courchamp et al. 2003; Doherty et al. 2016), and on Australian islands they are a main driver of native species decline (Glen & Dickman 2005; Saunders et al. 2010; Doherty et al. 2015; Legge et al. 2016). Red foxes and feral cats species not only have direct and indirect impacts on the threatened and culturally relevant species of the Island, but also affect its cultural heritage, and economically valuable local industries, such as tourism (Jones et al. 2006; Gong et al. 2009). In response to this threat, the local pest management authorities formed the *Straddie Pest Management Group* (SPMG*)*. The aim of this group is to manage the impacts of invasive species on the Island. The diversity of local stakeholders, including indigenous and non-indigenous residents, and economic activities, as well as its biological uniqueness make Minjerribah the perfect location to assess optimal invasive species management approaches.

2.2. Stakeholder engagement

The first step of this study was to engage with senior managers from a wide range of federal and local government authorities who were involved in invasive species management on Minjerribah (see Figure 1 for more details). After a process known as *Snowballing Sampling* (Atkinson & Flint 2004), we were able to engage with the broader group of local stakeholders involved in the *SPMG* (Stage I in Figure 1). The *SPMG* members have been working on invasive species management for almost 10 years. Collectively their members have extensive experience managing invasive species on the Island and are familiar with the views of the local community regarding invasive species management. In consultation with the *SPMG* we co-developed a *Species of Interest* list, comprising not only invasive and threatened species that are found on the Island, but also species that have some cultural or local significance (Appendix B). We used the *Species of Interest* list to co-develop a set of management scenarios to control the impacts of red foxes and feral cats on Minjerribah's *Species of Interest* (Table 1).

2.3. Scenario development

Over a two-year period (2015 – 2017), we met biannually with members of the *SPMG,* and attended the group's annual general meeting. During this period, we co-developed six scenarios to manage invasive species by reviewing relevant literature, and drawing on the experience of the *SPMG* members (Stage III in Figure 1). The scenarios were based on different investment levels, defining the *management intensity* with which different actions would be implemented throughout the year over a three-year implementation window (a summary of the scenarios can be found in Table 1). The goal of the different scenarios was to diminish the impacts caused by red foxes and feral cats, by controlling these species from the Island, hence increasing the probability of survival of culturally relevant and threatened species

Table 1

Summarised proposed scenario of actions. A detailed description of the six portfolios can be found in Appendix C.

Target species	Scenario #	Investment level	Management intensity
Only red fox (*Vulpes vulpes*)	1	Low	Low
	2	Medium	Medium
	3	High	High
Red foxes (*Vulpes vulpes*) and feral cats (*Felis catus)*	4	Low	Low
	5	Medium	Medium
	6	High	High

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Each scenario varied in its management intensity (i.e. number of traps deployed, number of baits/km^2, number of stations/km^2, and number of baiting campaigns per annum), and length of implementation of the different control methods throughout the year (i.e. baiting, trapping, hunting, and den fumigation; see Appendix C for a detailed description, including overall cost information). The cost of each scenario was constructed by using a combination of data provided by members of the *SPMG*, scientific and grey literature, and quotes by private distributors of the consumables goods and capital assets (Mcleod & Saunders 2010; Auerbach et al. 2014; Holmes et al. 2015, 2016). We report in detail the cost of the different stages in Appendix D, following the recommendations made by Iacona et al. (2018). We assessed the present value of each scenario over a 25 year period. The scenario costs included planning, implementation, and monitoring costs over ten years; and fifteen years of maintenance costs. We applied a discount rate of 5%.

2.4. Data collection

To identify which of the scenario would offer the greatest return on investment, we used INFFER (described below). We elicited the input parameters for INFFER (stage IV) by sending out an online, semi-structured questionnaire (eSurvey, found in Appendix A), following the requirements of the Human Research Ethics Committee (HREC) of The University of Queensland (Approval number: 2016001001). This questionnaire was based on INFFER's Project Assessment Form (*PAF*) (Pannell et al. 2012). The data collected from the eSurvey recorded basic information about respondents (e.g. sector, invasive species' knowledge, years of experience working on invasive species management, and quality available information, and probability of eradication of different scenarios), and collected the input parameters for the *PAF*.

2.5. Analysis framework: INFFER analysis

We then used the PAF from the Investment Framework for Environmental Resources (INFFER^{TM}) (http://inffer.org/, verified 01 April 2018; Pannell *et al.* 2012) to evaluate the six proposed scenarios. INFFER was primarily designed to help managers evaluate and prioritise competing projects. It provides a structured approach based on a benefit-cost ratio (BCR) to identify management actions that will achieve the best environmental outcome (Pannell et al. 2012), the steps of the INFFER approach are shown on Table 2.

Table 2.
Steps of INFFER (Investment Framework for Environmental Resources) (Pannell et al. 2012)

1. Asset identification
2. Asset filtering and/or refine list of assets using pre-set criteria
3. Definition and assessment of projects
3.1. Asset significance (value)
3.2. Threats
3.3. Activities
3.3. Effectiveness
3.4. Costs
4. Selection of priority projects
5. Develop investment plans and/or funding bids
6. Implement funded projects
7. Monitoring, evaluation, adaptive management

By defining SMART (Specific, Measureable, Achievable, Relevant and, Time-Bound) projects, INFFER helps people to clarify what is required to achieve the proposed outcomes (Bottrill et al. 2008). This assessment process is the core of *INFFER*, and provides the basis to assess whether a project is cost-effective, as calculated by the *BCR* (Equation 1):

$$BCR = \frac{V \times W \times A \times B \times F \times P \times G \times DFb(L) \times 20}{C + PV(M) \times G} \quad \textbf{(Eq. 1)}$$

where:

V is the value that users assign to the asset on a scale of 0 – 100 (where a score of one equates to a monetary value of 20 million of currency, in this case Australian Dollars). *W* represents the effectiveness of management works; *A* is the adoption rate by private land managers (if required); *B* represents the risk of adoption of adverse practices; *F* is the multiplier for technical feasibility risk; *P* is the probability that socio-political factors will not derail the project, and that the required changes take place; *G* is the probability of obtaining long-term funding; *DFb* is the discount factor; *C* is the short-term project cost ($ million in total, over the life-span of the project); *M* is the total cost of maintaining the outcomes ($ million per year, beyond the immediate project); *PV(M)* is the present value to convert a stream of future annual maintenance costs (assumed constant in real terms) to their present-day value (in $ millions) (Pannell et al. 2012). Further information about the rationale for the BCR algorithm and the underpinning theoretical background can be found in Pannell et al. (2012, 2013). Subsequently, the results from the INFFER analysis were sent out to the *SPMG* members for review, and to assess whether the scenarios could be implemented (Stage V).

It is worth noting that obtaining estimates regarding *V* —the value of environmental assets (e.g. species or habitats) — can be very difficult in practice. There can be a lack of relevant studies for benefit transfer (Bateman et al. 2011), and in the case where primary values are sought, these can be highly influenced by individual preferences, and are often overestimated by local stakeholders (Portney 1994; Jakobsson & Dragun 2001). Heterogeneous responses can also confound the proper interpretation of this parameter. Hence, standard practice advocates adopting a conservative —risk-adverse— approach (McDonald-Madden et al. 2008).

We used a ranking-based assessment for the six proposed scenarios. We obtained an *Overall ranking* for the six scenarios; and two, more detailed, *Internal rankings*: One for fox-only control, and a second for joint-management. By using a structured decision-making approach based on INFFER, we were able to account for intrinsic biases, information-gaps, and respondents' valuation heterogeneity, thereby facilitating the overall analysis and increasing the robustness of policy recommendations.

3. Results

3.1. Respondents summary

All sectors involved in invasive species management on the Island were represented in the surveyed respondents: 46% were representatives of government agencies; 39% were from community or non-government organisations; and 15% were from private organisations. A key aspect of the INFFER assessment is to define the significance of the environmental asset that a project will affect. Respondents held varied views about the significance of Minjerribah (asset valuation–*V*): 31% indicated it has "International" significance, 38% said "National" significance, 8% noted a "Very High State", and 23% gave a mark of "High State" significance. Respondents justified their choices with a wide range of reasons, including: (i) Minjerribah is a RAMSAR site (international significance), (ii) it is part of the East Asian-Australian Flyway (international significance), (iii) the island has a genetically distinctive and healthy koala (*Phascolarctos cinereus*) population (national significance), and (iv) provides habitat for threatened species and culturally relevant species (national significance), (v) Minjerribah is the second largest sand island in the world (international significance), and (vi) historical indigenous heritage (international significance). Around one third of the respondents (31%) said they would have estimated a higher value if it was not for the disturbances caused by mining on the Island.

All respondents scored their knowledge regarding invasive species management as medium or better (5-point scale from "comprehensive" to "uncomprehensive"). A majority of respondents (84%) stated that the most important reason to be involved in invasive species management is to protect biodiversity, while 16% stated statutory or legal obligations (8%), while 8% held Traditional Owners values as most important.

The respondents also assessed the *Quality of the available information* regarding fox management, feral cat management, and joint-management of these species. For European fox management, approximately 38% of respondents scored the information as *good or sufficient*, 31% as *medium*, and 31% as *low or insufficient*. For feral cat management, approximately 23% scored the information as *good or sufficient*, and 77% as *low or insufficient*. Approximately 31% scored information regarding joint-management as *good or sufficient*, 15% as *medium*, and 54% as *low or insufficient*.

Respondents scored the probability of eradication of European red foxes under Scenario 1 as *low*–77% (*medium*–23%*)*, Scenario 2 as *medium*–46% (*low*–23% and *high*–31%), and Scenario 3 as *high*–85% (*medium*–15%). The probability of joint-eradication (European red foxes and feral cats) under Scenario 4 was scored as *low*–77% (*medium*–23%), Scenario 5 as *medium*–54% (*low–23%* and *high*–23%), and Scenario 6 was scored as *high*–77% (*low*–15% and *medium*-8%).

3.2. INFFER analysis

We present the results of the INFFER parameters in Table 3. We found that respondents' asset valuation–*V* was highly heterogeneous. Hence, we assessed the BCR of each scenario under three different assumptions regarding the value of this parameter, the (i) mode ($V = 50$), (ii) minimum ($V = 15$), and (iii) lower-bound ($V = 1$). When *V* is equal to 1, the BCRs are less than one for all scenarios, except for Scenario 3. When the BCR value is higher than one, it represents the "break even" point of the project, meaning that the ratio between benefits to costs is greater (i.e. benefits exceed the costs of the project). When $V = 15$ and $V = 50$, all scenarios have BCRs higher than 1. Despite the changes in the BCR according to changes of the asset value, the rankings do not change.

By comparing the scenarios under different perspectives of the asset value (*V*) we were able to assess the robustness of our results to different stakeholders' values. Table 3 shows the INFFER cost-benefit analysis of the six proposed invasive species' management scenarios at all values of *V*. We found that the *Overall* and *Internal Rankings* of actions were constant across the values of *V*. In what follows, we describe results for the lower bound of *V* (most conservative assumption). A complete table with the parameters used in the INFFER BCR can be found in Appendix E.

Table 3.

Results of benefit-cost ratios and correspondent parameters calculated in INFFER

Scenarios	Intensity	Cost	Impacts of the works	Socio-political risk	Lag-time	Benefit:Cost Ratio (BCR)			Overall ranking	Internal ranking
		(AU$m)	(W)	(P)	(L)	[b] (V=1)	[c] (V=15)	[d] (V=50)		
1 – Only fox management	Low	$3.48	0.21	0.85	7	0.52	7.79	25.96	3	3
2 – Only fox management	Medium	$4.08	0.41	0.88	7	0.88	13.18	43.94	2	2
3 – Only fox management*	High	$5.33	0.61	0.85	3	**1.15**	17.19	57.28	1	*1
4 – Joint management	Low	$4.03	0.21	0.85	30	0.08	1.13	3.77	6	3
5 – Joint management*	Medium	$5.84	0.61	0.85	10	**0.39**	5.83	19.44	4	*1
6 – Joint management	High	$7.76	0.61	0.85	10	0.29	4.31	14.37	5	2

[a] Expected present value (AU$million) of costs over 25 years

[b] INFFER lower bound for V

[c] Minimum value for Asset Valuation–*V* by respondents

[d] Mode value for Asset Valuation–*V* by respondents

* Selected scenarios

Across all six scenarios, the highest-ranking strategy was Scenario 3 (BCR = 1.15), as shown in *Overall* and *Internal ranking* for fox-only management in Table 3, which was the fox-only "High" management intensity Scenario. For fox-only management scenarios, Scenario 3 was also the most expensive approach (AU$m 5.33). Scenario 1 (AU$m 3.48) was approximately 35% cheaper than Scenario 3; whereas Scenario 2 (AU$m 4.08) was 24% cheaper than Scenario 3. Across all three scenarios targeting only foxes there was little variability in socio-political risk (*P*) however, the Impact of works–*W* varies considerably. For the 'Low' intensity scenario (Scenario 1), *W* was 0.21, and this increased to 0.61 in the "High" intensity scenario (Scenario 3), with the "Medium" intensity scenario having a *W* = 0.41. The estimated Lag time (*L*) was lower for High-intensity–Scenario 3 (*L* = 3 years), whereas for Scenarios 1 and 2 it was estimated as seven years.

For joint-management (eradication of both red foxes and feral cats), Scenario 5 (BCR = 0.39) — i.e. "Medium" intensity— was the highest ranking alternative. The cost of joint-management increased almost linearly, from AU$4.03 million (Scenario 4) to AU$7.76 million (Scenario 6– "High" intensity). Scenario 4 (*W* = 0.21) had the lowest Impacts of the works–*W*, while Scenarios 5 and 6 were the same (*W* = 0.61). The socio-political risk (*P* = 0.85) did not vary across the 3 alternatives for joint-management, however the Lag time (*L*) for scenarios 5 and 6 (*L* = 10 years) were both considerably shorter than for scenario 4 (*L* = 30 years).

Adoption of the proposed actions by private landholders and citizens (*A*) was described as *highly attractive* for fox-only management, and *neutral* for joint-management scenarios, so this parameter was set at 1, as none of the proposed actions requires behavioural changes by local private landholders and citizens. The chance of private landholders or citizens *not* adopting adverse practices *(B*) was 0.95 in the scenarios that target fox-only management (Scenarios 1–3), and 0.7 for those scenarios that aimed at joint-management (Scenarios 4-6).

3.3. Sensitivity analysis (SA)

We conducted a sensitivity analysis to determine the sensitivity of management recommendations to changes in three of the INFFER parameters: (i) Impact of works–*W*, (ii) Socio-political risk–*P*, (iii) and Lag time–*L*. We chose these parameters because they demonstrated the greatest heterogeneity or are identified in the literature (Glen et al. 2013) as having a large impact on the success of invasive species management. We assessed changes in the three parameters across the *Best Performing Scenarios* (Scenarios 3 and 5), and calculated a Sensitivity Index (SI) (Alexander 1989) for each parameter, as well as a *BCR Difference* (%) (see Table 4). A high SI score indicates a high sensitivity of the BCR to changes in that parameter. Across the three parameters, the BCR was most sensitive to changes in Socio-political risk–*P* (SI = 0.88 and 0.87 in Scenarios 3 and 5 respectively). After socio-political risk, Scenario 3 was more sensitive to changes in Impacts of the works–*W* (SI = 0.69), than to variation in Lag time–*L* (SI = 0.60); whereas Scenario 5 was more sensitive to changes in Lag time–*L* (SI = 0.77), than to changes in Impacts of the works–*W*.

Table 4. Sensitivity Analysis indices calculated for *initial*, *best*, and *worst* values of INFFER's parameters Impacts of the works–*W*, Socio-political risk–*P*, and Lag time–*L*. *Initial Benefit-cost ratio* (BCR), indicates the resulting BCR score when we use the *best* and *worst* values for each INFFER parameter (i.e. *W*, *P*, and *L*). *Difference in Benefit-cost ratio* (ΔBCR) shows the percentual change of the BCR once we recalculated it with the *best* and *worst* values for *W*, *P*, and *L*. The *Sensitivity index* (SI) shows how much the BCR changes according to the *best* and *worst* values for the INFFER parameters, a higher SI value indicates greater sensitivity of the BCR to changes of *W*, *P*, and *L*. The *Sensitivity Index Ranking* (SI rank) orders the *Sensitivity index* from 1^{st} to 3^{rd}, according to the SI values.

	Sensitivity Analysis indices									
	Scenario 3					**Scenario 5**				
INFFER Parameter	**Value**	**BCR**	**ΔBCR(%)**	**SI**	**SI rank**	**Value**	**BCRi**	**ΔBCR(%)**	**SI**	**SI rank**
W - Impacts of the works										
initial	0.61	1.15	n.c.			0.61	0.41	n.c.		
best	1	1.88	63.48%	0.69	2^{nd}	0.81	0.54	31.71%	0.61	3^{rd}
worst	0.31	0.58	-49.57%			0.31	0.21	-48.78%		
P - Socio-political risk										
initial	0.85	1.15	n.c.			0.85	0.41	n.c.		
best	0.97	1.31	13.91%	0.88	1^{st}	0.97	0.47	14.63%	0.87	1^{st}
worst	0.12	0.16	-86.09%			0.12	0.06	-85.37%		
L - Lag time										
initial	3	1.15	n.c.			10	0.41	n.c.		
best	1	1.26	9.57%	0.60	3^{rd}	1	0.64	56.10%	0.77	2^{nd}
worst	20	0.5	-56.52%			30	0.15	63.41%		

n.c. = not calculated

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4. Discussion

We assessed the Benefit-Cost Ratio (BCR) of six invasive species management scenarios on Minjerribah by including the perspectives of local government and community members into a cost-benefit analysis —INFFER—. The analysis showed that fox-only control with 'high' intensity (Scenario 3) was the best strategy, as well as the only strategy under a conservative estimate of asset value ($V = 1$) that had a BCR greater than 1 (1.15), implying that the benefits of implementing this action exceeded the costs.

Among the fox-only Scenarios, Scenario 3 had a shorter time lag (3 years versus 7). This result suggests that higher investment levels will lead to quicker outcomes, relative to lower investment levels. The dominance of this strategy can be explained by the perceived greater knowledge of fox ecology among respondents, the current understanding of eradication measures, and wider political and community support to control a species that is not considered a companion animal (like cats). Among the scenarios aimed at joint-management of feral cats and red foxes, scenario 5 ("Medium" investment levels) had the highest BCR (BCR = 1.15). Invasive species managers on the island judged that Scenarios 5 and 6 (high investment levels) would have equivalent impact of works, socio-political risk and lag times. However, the higher cost of Scenario 6 resulted in a lower BCR relative to Scenario 5. It is important to note that Scenario 5 corresponds to current, recommended feral cat management strategies (Department of the Environment 2015).

The perceived risk of management failure due to technical failure is low across all scenarios; this is consistent with the experience and on-ground expertise of Minjerribah's land managers who have already undertaken trial eradication campaigns over the last four years. At the same time, the risk of failure due to socio-political factors is considered low; this shows that the existing stakeholder network between government agencies, private organisations, and community groups provides a suitable socio-political environment to develop and implement management actions aimed at these invasive species. However, on Minjerribah Island there is a risk that the local community could adopt adverse practices (*B*), e.g. by not participating on identification or neutering programmes. This risk is evident in the value of *B*: 0.95 in the case of foxes, and 0.7 for cats, as management works under all scenarios are expected to encounter some opposition from community groups, especially when it comes to island-wide baiting programmes and companion animals' legislation. Maintaining open communication between invasive species managers and local community members, particularly pet owners, is identified as an important requirement for all future invasive species management on the island (Crowley et al. 2016).

Overall, the impacts of feral cats on native species are well documented (Dickman 1996; Denny & Dickman 2010; Campbell et al. 2011; Medina et al. 2011; Doherty et al. 2015). What is not well understood is how to operationalise invasive management activities, such as baiting and banning companion animals on Islands, without incurring significant community resistance. Existing management actions (i.e. hunting, trapping, and baiting), which target feral cats are unlikely to be effective on inhabited islands in the long-term, as pet cats can be a source for re-establishment of feral cat populations (Denny & Dickman 2010). This is captured by the *Lag time* (*L*) for joint-management scenarios, which was 30 years (Scenario 4) compared to 10 years for Scenarios 5 and 6. In this project, none of the scenarios required behavioural changes (*A*) by the community —which we know is needed— which is why the perceived *Impacts of the Works–W* value for joint-management scenarios might not have been higher. Notwithstanding the lack of a standard procedure to tackle these species (Parkes et al. 2014), management plans ought to be adapted to local environmental, socio-political conditions, and use reporting protocols (Iacona et al. 2018). The implementation of complementary actions, such as: legislation that regulates existing and future companion animals, mandatory identification, control of the existing pet population by mandatory spay and neuter programmes, predation deterrents, cat curfews by nigh time, and the prohibition —or control of— new pet cats are needed to secure long-term effects (Denny & Dickman 2010; Nogales et al. 2013). These complementary actions can prevent —in the long term—the spillover of pet cats to establish new feral populations, but as shown by Ratcliffe et al. (2010) it is possible to encounter public opposition and adoption of adverse practices (*B* = 0.7), reflected by lower values of the joint-management scenarios, despite the high adoption by private landholders and citizens (*A* = 1).

We would have expected a joint-management scenario to be the O*ptimal Strategy* – as Ballari et al. (2016) found, the removal of a single invasive species is not enough to have a positive, or even neutral effect on native species' performance or survival. The reasons joint-management was not the *Optimal Strategy* in our study were because of: (i) lower than expected values for Impacts of the work–*W* for joint-management scenarios, therefore resulting in lower *BCRs* for scenarios 4, 5, and 6; (ii) higher perceived uncertainty on the long-term benefits from the implementation of more expensive, combined actions; (iii) longer expected Lag times (*L*) as management of feral cats require the implementation of complementary actions and behavioural changes; (iv) and the possibility of public opposition and adoption of adverse practices. Gaps in information will result in higher uncertainty, and prevent robust comparison between proposed actions. We highly recommend further research on this topic, methods such as *Ensemble Ecosystem Modelling* by (Baker et al. 2016), *Optimal eradication schedules* (Bode et al. 2015), and *Optimal surveillance* (Holden et al. 2016; Rout et al. 2017), have proven to be valuable techniques to identify potential ecosystem impacts from single-species management, and to optimise the invasive species eradication.

Eliciting values for environmental goods is a difficult and complex process. Stakeholder valuation of local assets, like Minjerribah, can overestimate the intrinsic significance of the asset, and be sensitive to personal bias (Portney 1994). The result is a high level of subjectivity and heterogeneity in provided answers (Marsh et al. 2010). In this analysis we have demonstrated a structured approach to track the *change* in asset value as a result of management works. Nevertheless, we need approaches that account for cultural values, management preferences, and contesting plans aimed at protecting biodiversity, to later compare them with alternatives that may adversely affect their future survival (Jakobsson & Dragun 2001). Using INFFER allowed us to incorporate these subjective perspectives and preferences explicitly to support a transparent decision-making process (Marsh et al. 2010).

The environmental uniqueness of Minjerribah is a key determinant of the island's environmental and cultural significance. However, native species on the island are threatened by European red foxes and feral cats. Involving stakeholders in invasive species management is a critical but difficult aspect of management (Ford-Thompson et al. 2012). We have overcome barriers to incorporate local stakeholder knowledge into invasive species management by following a multi-stakeholder engagement process based on adaptive management principles (Holling 1978) and INFFER (Pannell et al. 2012). Our approach allowed us to identify that a medium level of investment targeting foxes on Minjerribah would provide greater benefits relative to its costs. This result is a timely example of how invasive species management can be approached on inhabited islands, but outlines the need for more research directed at feral cat management protocols.

We believe that, provided the right pre-assessment, implementation, and monitoring tools, Minjerribah is a suitable candidate location to pursue eradication of feral cats and European red foxes. It is important to consider the existing socio-political environment, the technical experience of local natural resource managers, as well as community cohesiveness, engagement and overall support. Implementing these actions will ultimately protect the Island's unique biodiversity, future economic wellbeing, and its unique cultural heritage.

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