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Benefits of integrating complementarity into priority threat management

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Abstract: *Conservation decision tools based on cost-effectiveness analysis are used to assess threat management strategies for improving species persistence. These approaches rank alternative strategies by their benefit to cost ratio but may fail to identify the optimal sets of strategies to implement under limited budgets because they do not account for redundancies. We devised a multiobjective optimization approach in which the complementarity principle is applied to identify the sets of threat management strategies that protect the most species for any budget. We used our approach to prioritize threat management strategies for 53 species of conservation concern in the Pilbara, Australia. We followed a structured elicitation approach to collect information on the benefits and costs of implementing 17 different conservation strategies during a 3-day workshop with 49 stakeholders and experts in the biodiversity, conservation, and management of the Pilbara. We compared the performance of our complementarity priority threat management approach with a current cost-effectiveness ranking approach. A complementary set of 3 strategies: domestic herbivore management, fire management and research, and sanctuaries provided all species with >50% chance of persistence for $4.7 million/year over 20 years. Achieving the same result cost almost twice as much ($9.71 million/year) when strategies were selected by their cost-effectiveness ranks alone. Our results show that complementarity of management benefits has the potential to double the impact of priority threat management approaches.*

Keywords: Australia, conservation, cost-effectiveness, multiobjective optimization, Pareto, Pilbara

Los Beneficios de Integrar la Complementariedad al Manejo de Amenazas Prioritarias

Resumen: *Las herramientas de decisión de conservación basadas en los análisis de rentabilidad se usan para evaluar las estrategias de manejo de amenazas para mejorar la persistencia de las especies. Estos métodos clasifican a las estrategias alternativas por su beneficio al índice de costos pero pueden fallar en la identificación el conjunto óptimo de estrategias a implementar bajo un presupuesto limitado ya que no consideran las redundancias. Diseñamos una estrategia de optimización multi-objetivo en la que el principio de complementariedad es aplicado para identificar los conjuntos de estrategias de manejo de amenazas que protegen al mayor número de especies bajo cualquier presupuesto. Usamos nuestra estrategia para priorizar estrategias de manejo de amenazas para 53 especies de interés de conservación en el Pilbara, Australia. Seguimos una estrategia de obtención estructurada para colectar información sobre los costos y beneficios de implementar 17 estrategias diferentes de conservación durante un taller de tres días con 49 accionistas y expertos en biodiversidad, conservación y manejo del Pilbara. Comparamos el desempeño de nuestro método de amenazas con prioridad en lo complementario con una estrategia actual de clasificación de rentabilidad. Un conjunto complementario de tres estrategias (manejo de herbívoros domésticos, manejo de incendios e investigación, y santuarios) le proporcionó a todas las especies una oportunidad de persistencia del 50% por $4.7 millones al año durante 20 años. Obtener el mismo resultado costó casi el doble ($9.71 millones*

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al año) cuando las estrategias fueron seleccionadas sólo por su categoría de rentabilidad. Nuestros resultados muestran que la complementariedad de los beneficios del manejo tiene el potencial para duplicar el impacto de las estrategias de manejo de amenazas prioritarias.

Palabras Clave: Australia, conservación, optimización multi-objetivo, Pareto, Pilbara, rentabilidad

Introduction

There is an urgent need for cost-effective solutions to the biodiversity loss crisis (Balmford et al. 2002; Ehrlich & Pringle 2008). Although protected areas remain a cornerstone of conservation practice, many species rely on habitat outside protected areas for their persistence. Threats to biodiversity are widespread and threat management across land tenure boundaries is required to maintain functioning populations of native species throughout their range. Threat management prioritization is an emerging approach in conservation science that assists in conservation decision making (Wilson et al. 2007; Joseph et al. 2009; Carwardine et al. 2012). The approach typically applies cost-effectiveness analysis to rank alternative management options by their expected benefits per unit cost (Hughey et al. 2003). Benefits can be measured by an estimated improvement in the persistence of native species (Joseph et al. 2009; Carwardine et al. 2012) or by an estimated reduction in the extent of a threat (Firn et al. 2013). These approaches rely on the expertise of stakeholders and scientists to estimate the cost, benefit, and feasibility of alternative management options in the absence of more formal data (Martin et al. 2012; McBride et al. 2012). Whether prioritizing at the level of species (Joseph et al. 2009), phylogenetic diversity (Bennett et al. 2014), species groups (Carwardine et al. 2011), or locations of actions (Auerbach et al. 2014), threat management approaches identify the highest ranked investment options and thus allow informed and justifiable decisions for prioritizing threat management for biodiversity.

Although previous threat management prioritization approaches have been successful in ranking alternative strategies by their benefit-to-cost ratio (Carwardine et al. 2012; Firn et al. 2013; Auerbach et al. 2014), they have not adequately considered the effects of implementing combinations of strategies simultaneously. If more than one strategy is likely to be implemented, cost-effectiveness assessments of individual strategies will be at best incomplete and at worst misleading if there are complementarities between strategies. For example, a set of strategies that exhibit the highest individually ranked cost-effectiveness may benefit similar species and hence may be less desirable than a combination of strategies that target different species. Managers risk allocating scarce resources to species that already benefit from management, to the detriment of species that do not receive any protection because they rely on less cost-effective strategies. The ideal suite of strategies is complementary; that is, it protects as many species as possible, without unnecessary overlap or redundancy in the benefits generated by management strategies (Justus & Sarkar 2002; Tulloch et al. 2013). Further, some strategies may lead to a decline in expected persistence for some species, such as when the control of one threat leads to the intensification of other threats (Rayner et al. 2007).

The principle of complementarity has been applied in conservation planning for identifying new protected areas as an alternative to ranking or scoring approaches (Kirkpatrick 1983). Although ranking methods select the top sites that have been evaluated individually and independently from each other, complementarity-based approaches select a set of sites that have been evaluated jointly to maximize the representation of conservation targets across a region (Moilanen et al. 2009). Complementarity-based approaches increase the number of species that can be secured in protected areas relative to selecting areas based on species richness ranks (Vane-Wright et al. 1991; Margules & Pressey 2000; Justus & Sarkar 2002). Similar efficiency gains may be possible for threat management prioritization approaches.

Assuming that budgetary constraints prevent implementing all threat management strategies, identifying sets of complementary strategies over a range of budgets is a multiobjective problem (Figueira et al. 2005). The objectives are to maximize the number of species persisting in the landscape and minimize the cost. Because the problem has 2 objectives the solutions must be a trade-off between objectives—reducing the investment in conservation strategies will result in fewer species persisting in the landscape. Finding the best set of strategies is difficult because there are an exponential number of combinations of candidate strategies, and evaluating all possible combinations of strategies becomes more challenging as the number of strategies increases. We devised a multiobjective approach to prioritize optimal sets of threat management strategies that represent a trade-off between species saved and the cost incurred. We demonstrate the efficiency gained when accounting for the combined benefits of multiple threat management strategies with a case study of the Pilbara in Australia (Fig. 11).

Methods

The Pilbara

The Pilbara bioregion of northwestern Australia is home to many endemic plants and animals, including

Leeuwen's wattle (*Acacia leeuweniana*), the Pilbara barking gecko (*Underwoodisaurus seorsus*), and the Pilbara Ningaui (*Ningaui timealeyi*) (Maslin & van Leeuwen 2008; Gibson & McKenzie 2009; Doughty & Oliver 2011; Fig. 1). Overgrazing, increasing frequency of wildfires, exotic species introductions promoting predation and competition, and changed hydrological regimes have degraded the Pilbara (McKenzie et al. 2009). Pastoral use and mining, as well as changed fire frequency and intensity, have altered vegetation cover and soil profiles (Woinarksi et al. 2000). Extraction of water to fuel the growing demands of the mining industry is a more recent and less well understood threat (Charles et al. 2013; Department of Water 2013).

The Pilbara is developing rapidly, driven by mineral extraction industries estimated to be worth over \$100 billion (Briggs & McHugh 2013). (All monetary units are in Australian dollars.) The remoteness of the region means that few studies of the threats to its biota have been carried out. The rapid development of the Pilbara brings new pressures that may negatively impact biota and opportunities for increased survey effort, public and government scrutiny, and increased investment in land management in the region. We conducted the first regionwide assessment of which management strategies provide the best investments for mitigating the effects of multiple threats on the Pilbara's biodiversity (for further details see Carwardine et al. 2014).

Data Collection

We engaged 49 experts and stakeholders in the biodiversity, conservation, and management for the Pilbara. In consultation with ecological experts, we selected a list of 53 species, including 12 species classified as threatened under the Environment Protection and Biodiversity Conservation (EPBC) Act, and 41 species that experts considered likely to be threatened and added to the EPBC list in the next 20 years (Supporting Information). We used a structured elicitation approach to collect information during a 3-day workshop with stakeholders and experts (hereafter participants). Participants agreed upon a list of 17 management strategies, each comprising a management goal and a list of actions required to implement the strategy and achieve the management goal (Table 1). At the group level, participants then estimated the costs and feasibilities of each of the individual actions, drawing on existing information where available. Fixed and variable cost estimates over 20 years were converted to present day values on the basis of a discount rate of 7% (Council of Australian Governments 2007). Two elements of feasibility were collected: probability of uptake (likelihood the action would be implemented, taking into account economic, social, and political factors) and probability of success of the action (likelihood the action would be implemented successfully, if taken up). Feasibility for each action was calculated as the product of the likelihoods of uptake and success. The feasibility of each strategy was calculated by averaging feasibility values across all actions in each strategy. An alternative approach could be to use the lowest feasibility value. For example, use of an herbicide for weed control may have a high probability of success but very low social acceptance. Averaging these 2 feasibility values may therefore fail to adequately capture the reality for an action that meets strong social–political resistance. Another alternative is to take the product of all the feasibilities for each action assuming that all actions are essential to a strategy (Joseph et al. 2009). In our case, individual actions were generally not essential to the feasibility of strategies, so taking average values was an appropriate approach.

To estimate the benefits of each strategy, biodiversity experts estimated the probability of functional persistence of each species under a baseline scenario in which no management above a minimum duty of care was implemented. The probability of functional persistence was given by the likelihood that a species will persist at levels high enough to achieve their ecological function in 20 years (Carwardine et al. 2011). Then, experts estimated the probability of species persistence under each of the 17 strategies. Participants estimated benefits individually following a modified Delphi approach (Speirs-Bridge et al. 2010). The summarized estimates were provided to experts anonymously, with an opportunity to revise their estimates via emails and an online forum (McBride et al. 2012).

Cost-Effectiveness Ranking Approach

Cost-effectiveness analysis provides an independent ranking of strategies based on their cost to benefit ratio, where the benefit is not measured in dollar terms (Levin & McEwan 2001). We estimated the cost-effectiveness of a strategy i (CE_i) as the total expected benefit of the strategy divided by the expected cost (C_i). The expected benefit for each strategy was estimated by multiplying the potential benefit (B_i) by the feasibility (F_i), providing an indication of the likely improvement in persistence across all species in the region if that strategy was implemented:

$$CE_i = \frac{B_i F_i}{C_i}. \qquad (1)$$

The potential benefit B_i of implementing strategy i in the Pilbara was defined by the cumulative difference in persistence probability of all threatened species in the region with and without implementation of that strategy

Table 1. Management strategies and goals and actions (expected costs over 20 years) defined by the experts (participants in the workshop and follow up discussions).

Management strategy	*Management goal*	*Actions and costs (AU$)*
1. Feral ungulate management	Eradicate where possible or maintain at low numbers feral donkeys, camels, horses, unmanaged cattle and pigs.	Management plan for control measures (599,000); monitoring and evaluation program for eradication effectiveness (1,059,000) coordinated consistent aerial shooting of all unmanaged introduced herbivores (use of collar telemetry) (2,605,000); exclusion fencing on all tenures (3,523,000).
2. Domestic herbivore management	Use sustainable grazing practices on pastoral leases (domestic cattle and other livestock) and conduct additional efforts for threatened species.	Develop a management plan for the region and each pastoral property (8,331,000); implement plan (strategic fencing to control stock, spell grazing [removal of grazing at critical times], control access to watering points, manage access to watering points) (7,907,000); exclusion fencing on pastoral leases (2,043,000); monitor and evaluate and share knowledge (5,826,000).
3. Combined feral ungulate and domestic herbivore management		Strategies 1 and 2 combined.
4. Fire management	Manage fire based on current knowledge with the interim goal of managing fire frequency, intensity, and extent for maximum habitat variety (pyrodiversity) for a suite of fire regimes (i.e., create a mosaic of different age-since-burn areas across all tenures).	Develop a central management plan for the region, with overarching fire management goals (2,120,000); develop a fire management operational plan for each tenure to be implemented by land managers (638,000); collect key information for planning, monitoring, and evaluation (3,072,000); share knowledge about fire behavior and management across stakeholders, including traditional ecological knowledge where appropriate (3,072,000); community awareness through education programs (1,059,000); implement burning regime: broad-scale aerial burning in summer and winter (38,880,000).
5. Fire management and research	Implement strategy 4 and improve knowledge of fire behavior.	Improve knowledge of fire behavior and threatened species responses (53,609,000); identify vital attributes (fire ecology) of threatened species, determine fire behavior in different regions, land units, and systems (4,766,000).
6. Combined domestic herbivore, feral ungulate, and fire management		Strategies 1, 2, and 4 combined.
7. Cat management	Develop a landscape scale predator control program (e.g., education, get approval for wide scale application of cat baiting, shooting, trapping, and sterilization).	Baiting (6,262,000); ground shooting localized on conservation estates and pastoral lands (529,000); leg-hold trapping (233,000); sterilize domestic cats (641,000); education programs for sterilization of cats, keeping cats indoors, cat registration laws (788,000).
8. Cat management and research	Implement strategy 7 and conduct research.	Research into grooming traps (726,000); determine impact of predators on threatened species in the Pilbara (135,000); identify spatial distribution and densities of predators and develop tools to be able collection of this information (13,419,000); investigate interactions between dogs, dingos, and cats (1,942,000).

Continued

Table 1. Continued.

Management strategy	*Management goal*	*Actions and costs (AU$)*
9. Sanctuaries	Protect vulnerable species in enclosures on the mainland and on islands.	Establish, manage, and monitor mainland sanctuary of adequate size for species persistence, including species reintroduction and translocation (4,733,000); eradicate black rats and increase biosecurity on islands (12,120,000).
10. Cane toads	Research and monitor cane toads and educate native species.	Research on biological control (4,100,000); surveillance and biosecurity to prevent spread (25,459,000); research impacts and predictions of likely distribution of cane toads (1,525,000); sub-lethal doses of toxin to train threatened native species (1,259,000).
11. Weed management around key assets	Remove all weeds around key assets.	Remove all weeds and follow up removals around key assets (refuge site for threatened species) (40,343,000).
12. Weed biosecurity team	Monitor for and eradicate new weed species.	Surveillance, detection, and eradication of all new weed species (34,078,000).
13. Targeted exotic pasture grasses	Manage non-native pasture grasses and restore non-pastoral land after removal of non-native species.	Manage (contain, control, eradicate) exotic pasture grasses (including buffel grass) and restore nonpastoral land after removal (11,625,000).
14. Combined weed and pasture grasses strategy		Strategies 11, 12, and 13 combined.
15. Hydrology management	Manage changes to surface and groundwater systems to mitigate threats to threatened species in the Pilbara.	Research impact on threatened species (262,000); determine distribution and ecology of cave eel, fortescue grunter, and millstream palm (4,103,000); determine and control discharge frequency on ephemeral streams or replicate the natural system (1,312,000); develop and implement an integrated water management plan for mines to share water (365,000); understand and control drainage treatment so that natural flows are maintained (365,000).
16. Habitat identification, protection, and restoration	Manage habitat modification that impacts threatened species in the Pilbara.	No destruction of habitat beyond fixed percentage representation criteria (72,051,000); create vegetation map (GIS) for predictive modeling (1:50 scale veg map + ground surveys) (424,000); where critical resources must be removed, replicate features of removed areas nearby (2,736,000); proactive protocol development (develop understanding of what restoration works to inform impact assessment and approvals for projects proposing removal of landscape structures or reconstruction of rocky areas) (1,325,000); reconnect fragmented vegetation patches to restore landscape connectivity (424,000); determine impacts of dust, vehicles (off road impacts and collisions), fences, noise, and light on threatened species (156,000); collect existing data to identify critical habitat (2,511,000).
17. Total combined strategy		Strategies 1, 2, 5, 8–13, 15, 16 combined.

averaged over the experts who made predictions for the species:

$$B_i = \sum_{j=1}^{N} \frac{\sum_{k=1}^{M_j}(P_{ijk} - P_{0jk})}{M_j}, \quad (2)$$

where P_{ijk} is the probability of persistence of species j if strategy i is implemented (as estimated by expert k); P_{0jk} is the probability of persistence of species j if no strategy is implemented (baseline scenario) (as estimated by expert k); N is the number of threatened species; and M_j is the number of experts who made predictions for species j.

Complementarity Approach

Because the cost-effectiveness approach evaluates strategies individually, there is a possibility that strategies that are highly cost-effective would benefit the same species. If funding were available to implement several strategies at once, they would be selected from the top of a ranked list based on their cost-effectiveness. In contrast, using complementarity approaches, strategies are evaluated jointly so that strategies selected cover as many different species as possible (Moilanen et al. 2009). In our case, we sought to identify optimal sets of strategies that could achieve target levels of species security at minimal cost or maximize the number of species saved for a given budget. This is useful when decision makers have the dual objectives of maximizing the number of species secured at a minimum cost. We investigated 3 thresholds of species security (i.e., probability of functional persistence) >90%, >75%, and >50% over 20 years.

Finding the optimal sets of strategies that secure as many species as possible above any one of these thresholds for any given budget requires solving a multiobjective optimization problem:

$$\max \sum_{i \in S} \sum_{j \in N} p_{ij} x_i \text{ and } \min \sum_{i} C_i x_i, \quad (3)$$

where x_i is a binary decision variable that denotes whether ($x_i = 1$) or not ($x_i = 0$) a strategy is included in the optimal set of strategies. A vector $\mathbf{x} \in \{x_1, x_2, \ldots, x_S\}$ represents a combination of selected strategies. The S represents the set of strategies listed in Table 1; p_{ij} identifies whether species j is expected to reach a given persistence threshold if strategy i is implemented; $p_{ij} = 1$ if the expected benefit of applying strategy i for species j is above the persistence threshold (i.e., $B_{ij}F_i + B_{0j} > \tau$ with $B_{ij} = \frac{\sum_{k=1}^{M_j}(p_{ijk}-p_{0jk})}{M_j}$); and $p_{ij} = 0$ if this threshold is not exceeded. The persistence p_{ijk} of each strategy, including combined strategies, was elicited independently from the individual strategies allowing participants to provide the benefits of combining management strategies explicitly (Supporting Information).

Because multiobjective problems rarely have a unique solution that maximizes all objectives simultaneously, Pareto optimal solutions are sought. Pareto optimal solutions are solutions that cannot be improved in one objective without degrading at least one other objective (Nemhauser & Ullmann 1969; Ruzika & Wiecek 2005). We found Pareto optimal solutions by iteratively removing the dominated decisions identifying suboptimal sets of strategies. Formally, a decision $\mathbf{x}'$ is dominated by a decision $\mathbf{x}$ if it secures fewer species per unit cost of implementation. We first determined the candidate individual strategies that were not dominated by any other individual strategies. Using this smaller selection of nondominated candidate strategies, we can then iteratively built the set of strategies that were not dominated. The algorithm of our approach is in Supporting Information.

Results

Cost-Effectiveness Ranking of Individual Strategies

The top 3 most cost-effective strategies for improving persistence of conservation significant Pilbara species were feral ungulate management, followed by sanctuaries and cat management (Table 2). All 3 of these strategies had average expected costs of under $1 million/year over 20 years. Feral ungulate management was ranked highest because it was comparatively cheap with a high probability of uptake and likelihood of success. Sanctuaries (including islands) offer high expected benefits and were considered feasible but are comparatively expensive and would only offer protection over a small area relative to other strategies. Cat management offers a high expected benefit, but it had the lowest probability of success of all the strategies (49% over 20 years).

The highest overall expected benefits from any individual strategy were attributed to habitat identification, protection, and restoration, but this strategy was also estimated to be costly (Table 2).

None of the weed management strategies had high expected benefits or cost-effectiveness. Many participants believed that weeds impact biodiversity but that this relationship is poorly understood and difficult to directly relate to the likelihood of extinction of many threatened species (Levine et al. 2003; Grice 2006; Firn & Buckley 2010).

Complementary Sets of Strategies

When aiming for a minimum persistence level for securing species (i.e., >50% likelihood of persistence), all species were secured by implementing 3 management strategies: domestic herbivore management, fire

Table 2. Costs, benefits, feasibility, and cost-effectiveness ranks for the 17 management strategies to address declines in conservation of threatened species.

Strategy	*Benefit*	*Uptake (%)*	*Probability of success (%)*	*Expected benefit after 20 years*	*Rank expected benefit*	*Expected cost after 20 years (AU$ million)*	*Average annual expected cost ($AU millions)*	*Cost-effectiveness score*	*Cost-effectiveness rank*
Feral ungulate management	200.9	98	88	172	10	7.8	0.39	0.2209	1*
Domestic herbivore management	407.1	93	93	351	6	24.1	1.2	0.1457	4*
Combined feral ungulate and domestic herbivore management	423.8	95	91	366	5	29.8	1.49	0.1224	5
Fire management	340.2	96	91	299	8	48.8	2.44	0.0611	10*
Fire management and research	506.6	97	91	447	4	53.6	2.68	0.0833	8*
Combined feral ungulate, domestic herbivore and fire management	806.3	96	91	701	2	83.4	4.17	0.0839	7
Cat management	315.9	100	49	155	12	8.4	0.42	0.1831	3*
Cat management and research	403.4	100	53	214	9	43.6	2.18	0.0490	11*
Sanctuaries (enclosure or island)	365.3	100	85	311	7	16.8	0.84	0.1842	2
Cane toad research and biosecurity	64.3	100	85	55	15	32.3	1.62	0.0168	16*
Weed management around key assets	125.7	100	63	79	13	40.3	2.01	0.0194	14*
Weed biosecurity team	43.2	100	60	26	17	34.0	1.70	0.0076	17*
Targeted exotic pasture grasses management	132.1	34	84	37	16	11.6	0.58	0.0322	12*
Combined weed and pasture grasses strategy	296.7	84	67	166	11	86.0	4.30	0.0192	15
Hydrology management	101.4	100	63	63	14	6.4	0.32	0.0988	6*
Habitat identification, protection and restoration	861.2	94	67	540	3	79.6	3.98	0.0678	9*
Total combined strategy	1352.7	93	74	929	1	348.3	17.4	0.0266	13

Individual strategies that are part of a combined strategy.

Table 3. Set of management strategies and their costs based on the ranked cost-effectiveness approach.

Symbol used in Fig. 2	*Strategy or set of strategies**	*Cost ($AU million/year)*
*t*1	1	0.39
*t*2	1, 9	1.19
*t*3	1, 9, 7	1.58
*t*4	3, 9, 7	2.68
*t*5	3, 9, 7, 15	3.0
*t*6	9, 7, 15, 6	5.68
*t*7	9, 7, 15, 6, 16	9.71
*t*8	9, 8, 15, 6, 16	11.46
*t*9	9, 8, 15, 6, 16, 13	12.04
*t*10	9, 8, 15, 6, 16, 13, 11	14.06
*t*11	9, 8, 15, 6, 16, 14	15.76
*t*12	9, 8, 15, 6, 16, 14, 10	17.38

**Strategies defined in Table 1. Individual strategies that were identified by the participants as having interacting benefits were replaced by the corresponding combined strategies.*

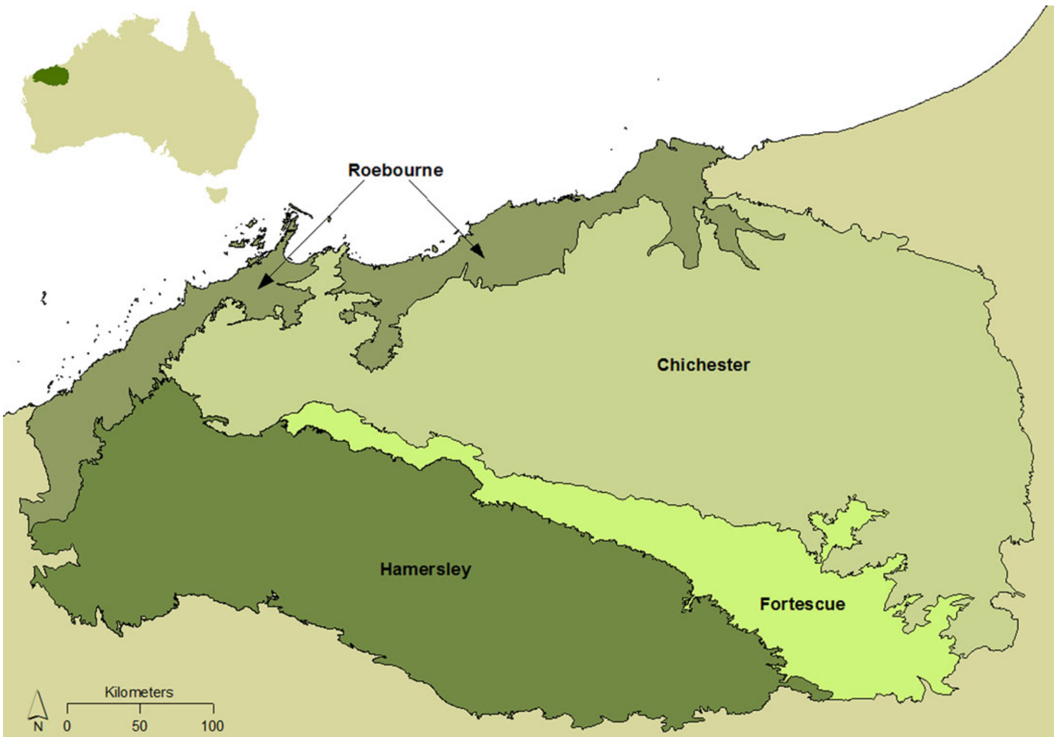
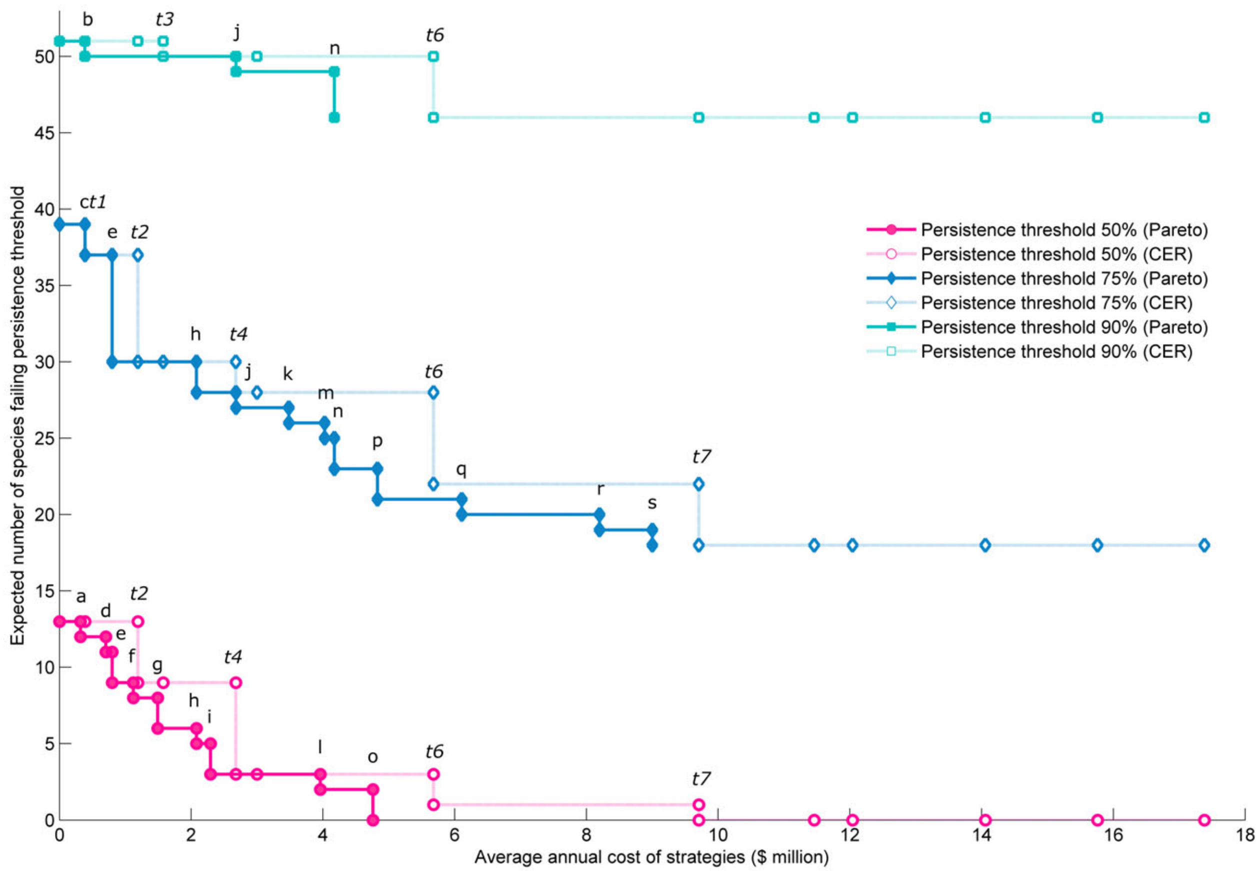


Figure 1. The 4 subregions of the Pilbara bioregion of Western Australia: Chichester, Fortescue, Hamersley, and Roebourne (total >178,000 km^2).

management and research, and sanctuaries at an annual estimated cost of $4.76 million (Fig. 2, o). Sanctuaries were required in this set to secure the black-flanked rock wallaby (*Petrogale lateralis*) and pale field-rat (*Rattus tunneyi*) (Supporting Information). When aiming for a higher and more certain persistence threshold of 75%, the most species (35) were secured by combining the strategies of ungulate, domestic herbivore, and fire management; sanctuaries; and habitat identification, protection, and restoration ($9 million/year, Fig. 2, s). Sanctuaries were required to secure the spectacled hare-wallaby (*Lagorchestes conspicillatus*) (Supporting Information). Feral ungulate management secured the maximum number of species for an investment of <$0.5 million/year (Fig. 2, c).

When aiming to achieve a secure persistence threshold for all species of above 90%, the most species (7; the 2 species secured without management plus Gane's blindsnake [*Ramphotyphlops ganei*], mountain thryptomene [*Thryptomene wittweri*], Hamersley peppercress [*Lepidium catapycnon*], Bush Stone-Curlew [*Burhinus grallarius*], and Pilbara barking gecko [*Underwoodisaurus seorsus*]) were secured by combining ungulate, domestic herbivore, and fire management at a cost of



a	Hydrology management	l	Domestic herbivore and Fire management and research
b	Cat management	m	Habitat identification, protection and restoration
c	Feral ungulate management	n	Combined feral ungulate, domestic herbivore and Fire management
d	Cat and Hydrology management	o	Domestic herbivore and Fire management and research and Sanctuaries
e	Sanctuaries	p	Sanctuaries and Habitat identification, protection and restoration
f	Sanctuaries and Hydrology	q	Domestic herbivore and sanctuaries and Habitat identification, protection and restoration
g	Combined feral ungulate and domestic herbivore	r	Combined feral ungulate, domestic herbivore and fire and Habitat identification, protection and restoration
h	Domestic herbivore and Sanctuaries	s	Combined feral ungulate, domestic herbivore and fire and Habitat identification, protection and restoration and Sanctuaries
i	Combined feral ungulate and domestic herbivore and Sanctuaries	*tx*	Top cost effectiveness strategies (see Table 3)
j	Fire management and research		
k	Fire management and research and Sanctuaries		

Figure 2. Performance of the cost-effectiveness ranking approach (CER) relative to the optimal complementarity solutions (Pareto) for different persistence thresholds (50%, 75%, and 90%) (letters, optimal set of strategies to maximize the number of species secured for a given level of investment). For example, for $3 million, the optimal set of strategies at 50% persistence threshold is i (combined ungulate and domestic herbivore) or j (fire management and research) at 75% and 90% persistence threshold. The complementarity optimal solutions (listed in Fig. 2) always dominate the CER strategies (listed in Table 3). The area between the CER and the Pareto curves identifies how many species are not secured due to suboptimal spending of the CER approach.

$4.17 million/year (Fig. 2, n; Supporting Information). No other species were secured at the 90% persistence threshold even if additional strategies were implemented. If the budget was insufficient to invest in the best strategy to protect species above the 90% threshold, then the strategy fire management and research secured 2 species (Gane's blindsnake and mountain thryptomene) for an estimated $2.68 million/year (Fig. 2, j). Cat management would secure Gane's blindsnake for $0.38 million/year (Fig. 2, b; Supporting Information).

Comparison of Approaches

We compared the performance of the complementarity optimal solutions with the most cost-effective individually ranked strategies listed in Table 2 and 3 (Fig. 2, Supporting Information). For all persistence thresholds, the complementarity solutions always outperformed the set of highest ranked cost-effectiveness strategies at securing the maximum species possible at each investment level (Fig. 2). At a 90% persistence threshold, the complementarity solution secured 7 species for $4.17 million/year, although the same investment secured 3 species when implementing the highest ranked individual strategies. Securing the missing species (Hamersley peppercress, mountain thryptomene, Bush Stone-Curlew, and the Pilbara barking gecko) required an additional $1.5 million/year (Supporting Information). At the 75% persistence threshold, implementing the complementarity solution secured 35 species for $9 million/year. Implementing the highest ranked individual strategies with the same budget secured 31 species; securing the remaining 4 species required spending an additional $0.71 million/year (Supporting Information). At the 50% persistence threshold, the cost-effectiveness ranking approach underperformed dramatically, requiring double the amount of funding to secure all species (Fig. 2, Supporting information).

Discussion

We found that a complementarity approach to selecting sets of threat management strategies has the potential to save twice as many species per unit cost as a cost-effectiveness ranking approach. Our approach provides a rational way of selecting complementary sets of strategies; that is, 2 strategies that secure the same species will not both be selected even if they are both ranked as highly cost-effective. Our comparison showed that using the ranking of the most cost-effective strategies without considering complementarity led to inefficient spending of conservation funds when the goal was to maximize the number of species conserved. We also found that the amount of funds available had an important impact on which strategies were optimal to maximize the species saved.

Typically, there are insufficient funds to implement all possible threat management strategies in a region (Balmford et al. 2002; MacKenzie 2009). In the Pilbara, the most cost-effective strategies ranked independently were not necessarily the optimal set of strategies for any given budget. The result of this discrepancy is in many cases substantial. In the Pilbara, the complementarity solutions could save as much as $5 million/year, a total of $100 million over the 20-year planning period.

Our results provide an insight into which combinations of strategies are optimal for maximizing the number of species above a persistence threshold and minimizing cost. Decision makers may choose to include additional factors outside those we accounted for, such as the preferences of landholders and managers and cobenefits of management strategies for sectors outside biodiversity (Ban et al. 2013). As in many regions of biodiversity importance, empirical data on threatened species responses to threats and strategies are lacking in the Pilbara. Hence, our analysis draws heavily on the knowledge of experts and may include bias and inaccuracies (Martin et al. 2012). We tested the robustness of expert elicited information by running a sensitivity analysis in which we changed the benefit estimates up to approximately 30%. The highest and lowest strategies were relatively robust to changes in the benefit estimates (Supporting Information). Further, the definition of a *secure species* influenced the results; some strategies may have a benefit but fail to push the species probability of persistence above the persistence thresholds. It is possible to remove the persistence threshold assumption and use our method to compute strategies that maximize the overall benefit rather than the number of species saved above a persistence threshold. However, doing so risks allocating resources that incrementally improve the persistence of many species without securing any species. In our case study we chose to use persistence thresholds to ensure that species were adequately protected.

The project prioritization protocol (PPP) (Joseph et al. 2009) differs from our threat management prioritization approach, most notably because PPP strategies (or projects) are designed to improve the persistence of one individual species over 50 years to above 95%. Hence each strategy is expected to secure a species but is not evaluated against multiple species. The PPP prioritizes between projects using an efficiency measure where efficiency is calculated by the weighted product of the benefits and likelihood of success of the project divided by its cost. Similar to previous ranking approaches, PPP selects the top strategies until funding runs out. Because the projects in PPP are assumed to only contribute to one species, accounting for the complementarity in benefits between strategies is not relevant.

Complementarity is not a new concept in conservation decision making (Kirkpatrick 1983; Margules & Pressey 2000; Justus & Sarkar 2002). Recently, Tulloch et al. (2013) used complementarity to select the best set of indicator species to monitor management success of threatened species in Western Australia under budget constraints, a method that improved accuracy and cost-efficiency. In conservation planning, complementarity is now a central property that reserve design software must achieve (Moilanen 2008; Ball et al. 2009). Our complementarity approach does not include a spatial component, but this extension is possible if data are available and computational challenges can be tackled. Priority threat management requires accounting for larger sets of possible combinations of strategies, actions, or zones than spatial conservation planning approaches currently address. In conservation planning, multiple objectives are often aggregated to provide one objective function (i.e., an approximation of the real multi-objective problem [Moilanen et al. 2009]). In doing so, one risks exploring only part of the optimal solution sets (Figueira et al. 2005). In our case, we did not need to aggregate our 2 objectives because we found the optimal set of solutions by using our pruning algorithm (Supporting Information). However, as the number of possible choices grow, multiobjective problems and their solutions (Pareto optimal frontiers) become notoriously difficult to calculate opt-imally but can be estimated by means of approximate methods, such as simulation and aggregation methods (Ruzika & Wiecek 2005; Pichancourt et al. 2014).

Ours is the first priority threat management approach that recommends optimal combinations of strategies that secure the highest number of species for any given cost. With an increasing number of priority threat management projects being funded, we encourage decision makers to investigate complementarity and potential redundancies when implementing the most cost-effective strategies. Significant cost-savings are likely to be achieved.

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Supporting Information

A list of species considered in our study and their conservation status under different legislations (Appendix S1), the multiobjective pruning algorithm (Appendix S2), details of the step-by-step complementarity solutions and cost-effectiveness ranking approaches for persistence thresholds (Appendices S3–S8), results of sensitivity analyses (Appendices S9–S10), and a depiction of the benefits of combined strategies (Appendix S11) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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