The costs of abating threats to Australia's biodiversity

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Abstract

1. Budgeting for biodiversity conservation requires realistic estimates of the costs of threat abatement. However, data on the costs of managing threats to biodiversity is often unavailable or unable to be extrapolated across relevant locations and scales due to a lack of transparency and consistency in how it was collated. Conservation expenditure largely occurs without a priori estimates costs across broad scales and is not recorded in ways that can inform future budgets nor the comparison of action cost-effectiveness.
2. We provide transparent, broadly applicable cost models for 18 Threat Abatement Strategies aimed at managing the processes threatening biodiversity across the Australian continent. We define the actions required to implement each strategy and use a consistent structure to classify costs into components of labour, travel, consumables and equipment. We drew upon expert knowledge and literature to parameterise and apply each model, estimating the implementation cost of each strategy across Australia, accounting for spatial variables such as threats, terrain, and travel distance.
3. The baseline cost estimates generated by the models for threat abatement strategies varied considerably between strategies and across Australia, ranging from \$24 - \$0.88m per km^2/year (\$0.24 - \$8.8k per ha/year). Across all strategies, Labour made up most of the action costs (49%), followed by Consumables (37%), Travel (13%) and Equipment (2%). A Monte Carlo simulation indicated that threat abatement strategy costs had on average an upper and lower bound of +44% and -33% of the baseline cost.
4. **Policy Implications -** We provide a consistent and transparent approach to budgeting for threat abatement strategies, aiming to improve conservation planning processes, outcomes and reporting requirements across Australia. Understanding the budget required to achieve threat management outcomes can aid revenue-raising and target setting. The models, cost layers and estimates we generate

provide the basis for a nationally consistent approach for estimating and recording the cost of biodiversity management strategies, which should be continually improved and updated over time.

Keywords: Cost model, threat management, biodiversity conservation, budget

Introduction

Understanding the financial resources required to manage threats and achieve conservation goals is important for budgeting, investigating value of alternative actions, target-setting and prioritising limited conservation resources (Cook *et al.* 2017; Iacona *et al.* 2018). However, the costs of implementing a conservation action are often challenging to estimate, and most conservation investments occur without reliable estimates of their return on investment (Auerbach, Tulloch & Possingham 2014). This is, in part, due to the lack of readily applicable cost data available to the conservation sector (Iacona *et al.* 2018). Where conservation cost data are available it often lacks critical information on how estimates are produced, and what is included and excluded (Armsworth 2014). The influence of a cost layer in prioritisation can be as high as the joint influence of thousands of species layers (Kujala *et al.* 2018), and absence of high quality cost data can be sub-optimal (Naidoo *et al.* 2007; Carwardine *et al.* 2008) driving up to 35% loss of environmental value benefits (Pannell & Gibson 2016).

Local and regional scale conservation budgeting tools (Iacona *et al.* 2018; Wenger *et al.* 2018; Thomson *et al.* 2020) can contribute to more accurate project cost predictions (Cook *et al.* 2017), improve cost data collection processes (Iacona *et al.* 2018) and estimate the efficiency of delivering conservation outcomes at the scale that the models have been applied (Margoluis *et al.* 2009). However, estimates generated by these tools are not generalisable for larger scale strategic planning that must occur across vast areas and land tenures. Hence, cost estimates cannot easily be compared across studies and applications, nor confidently extrapolated to other locations (Cook *et al.* 2017; Iacona *et al.* 2018). For example, while it is possible to find one or more locations with accurate cost information for managing weeds, we lack information on larger scale to strategically budget at a regional or continental scale (Kearney *et al.* 2019). The knowledge gap in the budget required to achieve a conservation outcome at the broad-scale cannot easily be filled by combining multiple sources of local scale cost estimates that have been derived using different approaches or delivery agents. Further effort is needed to build cost models and budgets applicable across broad landscapes, with adjustable assumptions to enable transparent comparisons of costs across different regions, actions and contexts.

Here we address this knowledge gap by developing and implementing a systematic approach to model the costs of conservation threat abatement strategies across Australia. Australia is a mega-biodiverse nation whose biodiversity faces significant threatening processes over vast landscapes, tenures and ecosystem types (Jackson 2016; Kearney *et al.* 2019). Building on previous efforts (Wenger *et al.* 2018; Thomson *et al.* 2020), we developed models that include a comprehensive range of actions, with underlying assumptions assigned to the cost components of labour, travel, consumables and equipment. We model generic and scalable actions, rather than attempting to piece together cost information collected using different approaches and locations. In doing so, we provide estimates of the costs of abating 18 major threats to Australia's biodiversity, and a set of transferable, transparent cost models and spatial cost layers that can used for planning and prioritisation efforts at national and other broad scales. These estimates are reflective of average efforts across broad landscape and assumptions should be modified for finer resolution analyses where improved local scale information exists.

Methodology

Our approach applies the best available national scale knowledge on threat abatement for the benefit of biodiversity and builds upon existing approaches for estimating the costs of threat abatement actions. We collated information and methods on threat abatement actions and costs from the scientific and grey literature, including Australian threat abatement plans (TAP), Australian threat abatement advices and action plans, and available data and approaches from two existing programs: the Saving our Species program in NSW (DPIE 2021) and DELWP's Strategic Management Prospects in

Victoria (Thomson *et al.* 2020). We established a working group of 47 experts, with whom we developed strategies, actions and cost estimates at two online workshops and discussions. Six of the experts are co-authors in this paper and the complete list is provided in the acknowledgements.

We applied this knowledge and information to estimate the costs of threat abatement strategies following three steps (Fig. 1). First, we described each threat abatement strategy (hereafter, TAS), the actions involved to complete each strategy over a 30-year time frame. Within each action (e.g. pre-action office planning, aerial baiting, post-action valuation), we defined four cost components: labour (L), travel within site (T), consumables (C) and equipment (E) (Table 1) (see Supp. Material 4 for details). Second, we structured generic models to estimate the cost of each strategy, as a function of the contributing action costs (spatial and non-spatial) and travel to site costs for all actions included in the strategy. Third, we extrapolated the estimated action and travel costs across Australia to create spatial cost layers at 1km^2 resolution, using information on the locations of threats, landscape resistance levels and travel time. We created spatial cost models for each TAS separately for areas across Australia where the strategy is likely to be relevant, based on available information about the spatial extent of threats.

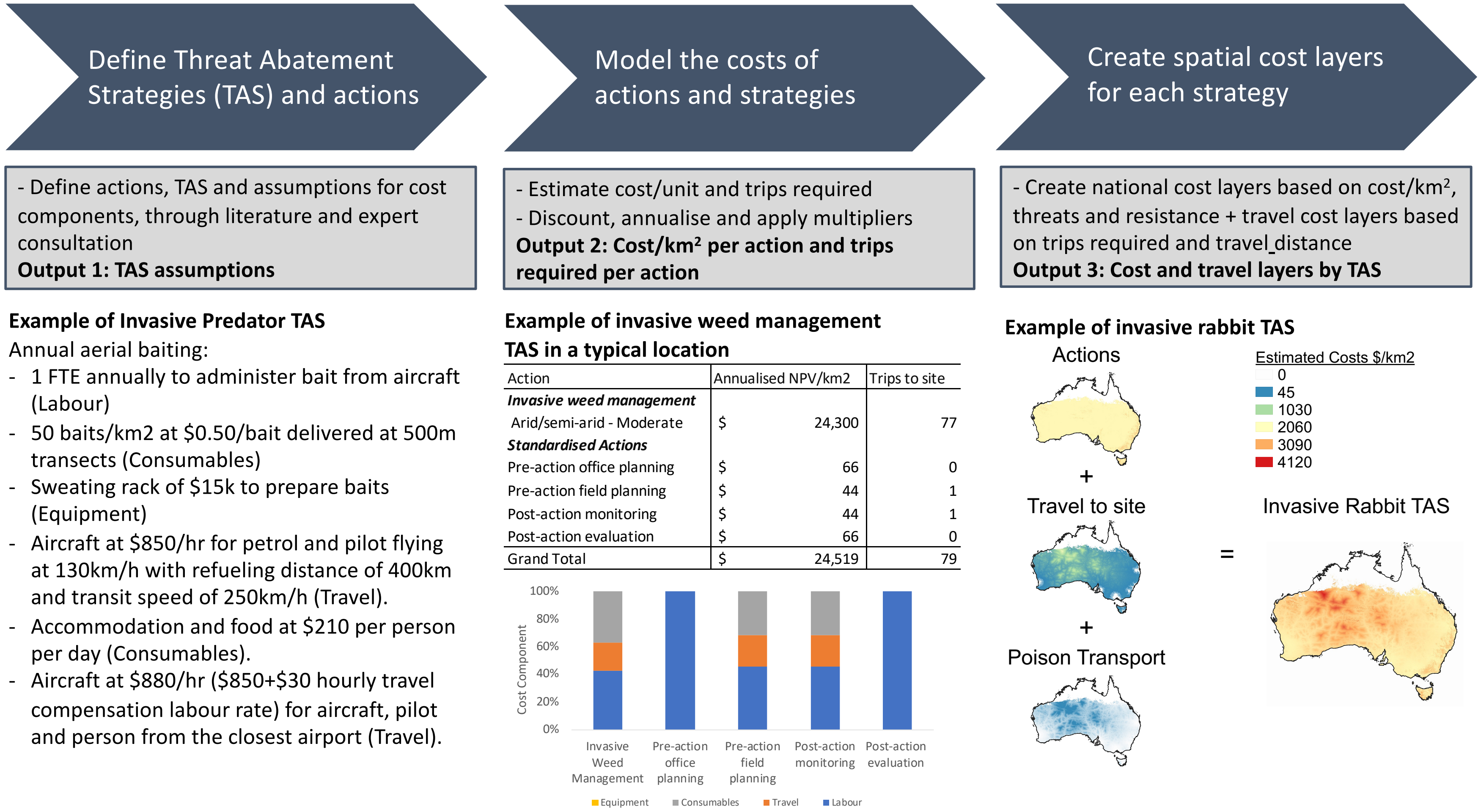

Figure 1. The three-step methodology overview to estimate costs for Threat Abatement Strategies (TASs). The broad steps are shown at the top row, the middle row summarises the generic methodology that applies to each TAS, and in the bottom row we demonstrate the output of each step with an example.

Defining Threat Abatement Strategies and actions

We defined 18 strategies to abate the key threats to Australia's terrestrial and freshwater biodiversity, using the current literature on the threats to Australia's biodiversity and existing and future potential threat management strategies. We worked with experts in biodiversity conservation and management (see Acknowledgements) to define a Threat Abatement Strategy (TAS) to abate each threat presented by Ward *et al.* (2021), who define threats impacting Australia's EPBC listed threatened species (1,796 species). We assumed the threats impacting threatened species would be relevant to the range of Australia's biodiversity. Where possible we grouped threats of similar nature that could be abated under the same TAS (see Supp. Material 1 for the assignment of TAS to the threats compiled by Ward *et al.* (2021)).

For each strategy (detailed in Supp. Material 2) we defined the set of actions involved throughout the planning, implementation, and evaluation process of carrying out the strategy (adapted from (Iacona *et al.* 2018; Wenger *et al.* 2018; Carwardine *et al.* 2019). The implementation actions were specific to each strategy, however we defined four standardised actions that covered the planning and evaluation stages for all threat abatement strategies: pre-action office planning, pre-action field planning, post-action monitoring and post-action evaluation, and made general assumptions on the level of effort required for each (Table 1).

We defined implementation actions generically, rather than attempting to prescribe site-specific details of actions, which would require more detailed local scale information. However, actions and their costs vary based on spatial variables like terrain ruggedness, vegetation type and human population density (see Supp. Material 3). All actions and strategies were considered over a 30-year time period, and we assigned a frequency of re-occurrence for each action (e.g. every "X" years over 30 years). We assumed all actions are performed humanely, are undertaken by competent/skilled practitioners that follow best practices, and that landholders and stakeholders are willing to participate.

Table 1. Standardised planning and evaluation actions that are included in each Threat Abatement Strategy, the general description of each, and the assumed effort required for each action and finally, the cost components relevant to each action. These standardised actions are additional to the on-ground implementation efforts involved with each strategy. The assumptions regarding amount of effort used was based on expert knowledge and grey and published literature (see Supp. Material 2).

Action	Description	Effort	Cost components
Pre-action office planning	Office-based planning to coordinate action logistics	3 weeks of off-site labour per standardised management area (see Section 2.2)	Labour only
Pre-action field planning	Evaluation of site context, threat status and habitat condition.	On-site survey of 30% of the management area	Labour, travel, consumables and equipment.
Post-action monitoring	Monitor the threat abatement impact within management area	On-site survey of 30% of the management area	Labour, travel, consumables and equipment.
Post-action evaluation	Reporting requirements, data analysis and integrating insights into management	3 weeks of off-site labour per standardised management area	Labour only

Model the costs of actions and strategies

We designed a generic cost model structure that can be applied to each threat abatement strategy and used it to estimate the costs of each strategy. The process of applying the cost models included estimating the action costs and travel to site costs associated with each strategy and conducting an uncertainty analysis on the cost inputs to test their robustness.

Generic Cost Model

The total cost of a strategy within a management area is a function of its spatial action costs, travel to site costs, and non-spatial costs (Equation 1), with the action costs per km^2 calculated as the sum of the cost components (Equation 2), and the travel to site cost per km^2 determined by the cost of the return trips required for each action (Equation 3). To account for efficiencies of scale we typically assumed actions were carried out over a management area window of 100 km^2 (Table 2). The time horizon for each action, and hence the cost models, is 30 years from 31st of December 2020 to 31st of December 2050. We present all final cost estimates as an annualized cost of the 30-year Present Value (PV) as at 31st of December 2020 accounting for the frequency of actions and using a real discount rate of 4% and assuming constant real costs into the future (see Supp. Material 3 for detail). The description of model parameters is shown in Table 2.

$$TAS\ cost = \sum_{actions} (Action\ cost\ per\ km^2 \times Action\ area) + \sum_{actions} (Travel\ to\ site\ cost\ per\ km^2\ per\ km\ distance \times Action\ area \times Distance\ to\ site \times 2) + \sum_{actions} Non\ spatial\ costs \quad (1)$$

where

$$Action\ cost\ per\ km2 = \sum_{L,T,C,E} Annualised\ Cost\ components\ \times multipliers \times (management\ grid\ window\ size)^{-1} \quad (2)$$

and

$$Travel\ to\ site\ cost\ per\ km2\ per\ km\ distance = Annualised\ Travel\ cost\ per\ hour \times (transit\ speed)^{-1} \times Number\ of\ trips\ required \times multipliers \times (management\ grid\ window\ size)^{-1} \quad (3)$$

Table 2. Cost model parameter description from Eq. 1, 2 and 3.

Equation	Cost Model Parameter	Description
1	Action Cost unit	Per km^2 unless specified otherwise, e.g. per km of river length or per in-stream structure.
1	Action area	Spatial extent of action, based on relevant threat layers
1	Distance to site	Distance to closest city/airport to each grid-cell, multiplied by 2 for return trip
1	Non-spatial costs (if any)	High level efforts that do not vary spatially, e.g. policy and education
2	Annualised Cost components	A Present Value (PV) was calculated for the costs accounting for different payment frequencies, then the PV was annualised over 30 years. The components included Labour (L), travel within site (T), consumables (C) and equipment (E)
2,3	Multipliers	30% for on-costs that are only applied to labour and 10% for on-site contingencies that only apply

		to costs that are incurred on-site. These can be adjusted by the end-user.
1,2,3	Management grid window size	Standard management area of 100km^2 unless specified otherwise e.g. per 100km waterway or per instream structure
3	Number of trips	Visits required for onsite action to be completed in multiples of 21-day periods of field work
3	Annualised Travel cost	Cost per hour includes vehicle cost and time compensation cost for personnel. A PV was calculated for the costs accounting for different payment frequencies, then the PV was annualised over 30 years.

For each action we calculated the aggregate present value of costs over 30 years and converted the result to an equivalent annual value (an annuity). Using the standard annuity due formula (Chan & Tse 2017) (Equation 4), cash flows were first calculated as a PV across the time horizon adapted for the differing payment frequencies (Equation 5), then the PV values were annualised using the standard annuity due formula (Equation 4). This allowed cash flows to be consistent and additive across all actions and strategies.

$$\ddot{a}_n = P\ x\ \frac{1-\ (1+i)^{-n}}{i}\ x\ (1+i) \tag{4}$$

Where $\ddot{a}_n$ is the annuity due at time zero for n payments, *P* is the regular cash flow incurred from period 0 to period $n-1$, and i is the real discount rate.

$$\ddot{a}_{rk} = P\ x\ \frac{1-\ (1+I)^{-rk}}{I}\ x\ (1+I) \tag{5}$$

Where $\ddot{a}_{rk}$ is the annuity due at time zero for r repayments that occur at the start of every k periods such that $n = rk$, and the adapted real discount rate I across the k periods such that $(1 + I) = (1 + i)^k$

We included two cost multipliers, which were combined multiplicatively to each relevant cost component. For labour on-costs, we applied a 30% multiplier to Labour costs based on the on-cost percentages used for professional staff at the University of New South Wales in NSW and ACT (HR 2018b; HR 2018a) and on-costs applied to action costs in South Africa (van Wilgen *et al.* 2016). On-costs account for employee support, office space and IT equipment, insurance, superannuation and leave, etc. For on-site contingencies, a 10% multiplier was applied to Labour, Travel and Consumable cost components for on-site based work, to account for unforeseen circumstances like bad weather and logistical and operational challenges. The 10% was chosen based on the collective advice of the expert group.

Action and travel to site costs

Based on the model assumptions (see Supp. Material 3) and cost component assumptions (see Supp. Material 4), we modelled the action costs within each TAS at the relevant unit of measurement (Eq. 2) (see Supp. Material 5). The relevant unit of measurement was typically per km^2, with management actions that occurred along a waterway estimated per km of waterway length (e.g. waterway fencing in Grazing Management TAS, Trout Barrier Installation in Invasive fish management TAS), and management actions that occurred for Hydrology TAS were estimated per in-stream structure (see Supp. Material 2 & 5). We converted the PV costs for each action to an equivalent annual value (see annuity calculation above). We then divided all the costs by the standardised area to calculate a per unit of measurement and applied the corresponding cost multipliers for the relevant cost components. We estimated the Travel to site costs per km^2 per unit area (Eq. 3) driven by the mode of transport, travel distance and the number of trips required (for detail see Supp. Material 3 for cost models see Supp. Material 5).

Uncertainty in Costs

We conducted a Monte Carlo analysis to represent the uncertainty around the cost inputs. We created probability distributions for global variables that were common across the TASs and these were often labour related, and uncertainty of action-specific variables were not included i.e. bait costs, bullet costs etc. We assume that the cost estimates generated from our cost inputs represent our baseline estimates that correspond to the median value (50^{th} percentile), we then subjectively set values for the lower bound and upper bound values that correspond to the 10^{th} and 90^{th} percentile. We created individual probability distributions for 18 parameter values that were common across the TASs, with a 25% probability for the lower bound, 50% for the baseline values and 25% for the upper bound (see Supp. Material 6 Table 1).

We also explored the effect of adding an uncertainty buffer to account for budget deviance from the baseline, following analyses on mega industry project management that highlights a 33% over-run cost for the majority of projects (Merrow 2013) (see Supp. Material 6 for detail).

Cost estimate validation

We conducted cost estimate validations for specific actions within TASs when cost data was available, by checking these estimates against information available in the scientific and grey literature, and/or through verifying with experts in threat management of the action being costed (see Supp. Material 7).

Applying cost models to create spatial cost layers

We created spatial layers at $1km^2$ grid cells of the estimated costs of each TAS over its potential management area across Australia, a summation of the spatially variable action and travel to site costs, excluding any continent-wide costs (Eq. 1 excluding non-spatial costs). All analyses were carried out in ArcGIS version 10.4 (Redlands 2016).

We accounted for spatial variation in actions in two ways: (i) the type of action suitable to the landscape (e.g. human population density, major vegetation type and occurrence of other threatened species) and (ii) the level of effort required to conduct the action (e.g. vegetation type and terrain ruggedness) (see Supp. Material 3 for detail).

To create the spatial cost layers for each action, we intersected the models with spatial information that determined the cost estimates to capture the spatial variation in efforts and costs over the potential management area. The action cost layers reflect the approximate effort that is needed in each $1km^2$ grid cell, rather than prescribing detailed local scale actions. For each grid cell, we summed of the number of annualized trips required for the corresponding actions within a strategy, forming a spatial travel cost layer. These travel cost layers differed by land, air, and poison transport (see Supp. Material 3) that were calculated using a time to city map and the closest airport (see Supp. Material 8).

All spatial action cost and travel layers were clipped to the extent of the relevant threat (see Supp. Material 8), and for actions with no available or relevant threat layer, we presented the layers at the national scale (e.g. Invasive/Problematic Bird Management). The cost of each TAS was then calculated by adding the cost layers for each action involved in the TAS, including the relevant modes of transport (see Supp. Material 8).

Results

Cost estimates for Threat Abatement Strategies

We defined a total of 18 strategies that aimed to address key threats to Australia's biodiversity and estimated the action costs split by Labour, Travel within site, Consumables and Equipment (detailed estimates in Supp. Material 9, summarised at the TAS level in Table 3).

More complex TASs required a higher number of actions (Table 3) due to addressing multiple threats (e.g., Invasive Fish Management has Tilapia and Trout across different river types) and multiple management requirements (e.g., Grazing Management required liaison with landowners, land and waterway fencing). There were 52 actions across the TASs, with some actions that were common across the TASs. Policy was the most common continent-wide action across 6 TASs, with other non-spatial actions including refugia mapping in Map Refugia, liaison in Grazing Management, extent mapping in Forestry Management, and Biosecurity. The remaining actions were largely unique to each TAS, except for the ground shooting action that applied to Invasive Predator Management, Large Invasive Herbivore Management, Native Herbivore Management and Invasive Rabbit Management, and the key habitat fencing action that applied to Native Herbivore management and Grazing Management (see Supp. Material 9).

The annualised spatial cost estimates of Threat Abatement Strategies ranged from \$25/km^2 (\$0.25/ha) for the cheapest strategy of Map Refugia to \$0.88m/km^2 (\$8.8k/ha) for the most expensive strategy of Habitat Restoration in Rainforests (Table 3, see Supp. Material 11 for more detail). Cost estimates of TASs varied depending on the underlying action type and effort required, influenced by characteristics like action suitability, environment type, vegetation type and human population density (see Supp. Material 3).

The continent-wide costs were estimated for efforts that pertained across Australia but were centrally carried out and independent of specific areas. The highest non-spatial costs were estimated for Biosecurity was $932m (Table 3) that was largely adapted from the reported and recommended spending from the Australian biosecurity enquiry (Craik, Palmer & Sheldrake 2017) (see Supp. Material 2). Map Refugia was costed non-spatially but applied per species, and the total cost of this strategy when applied can be multiplied by number of species that need this TAS (i.e. 10 species would require 10*$13,899).

Table 3. The range of annualised PV cost per unit estimated for each Threat Abatement Strategy summed across the management actions ("number of actions"), compared across all possible cost variation scenarios ("# cost variation scenarios"), where costs could vary by topographic resistance level (low, medium and high) and the spatially varying types and costs of management actions (i.e. aerial vs ground, vegetation type, intactness, etc.). We show the median, minimum, and maximum cost, and the mode, or the most common cost of each TAS across Australia ("most common across Australia"), determined from the highest proportion of projected threat management area at a national level. Hydrology management was costed per instream structure, invasive fish management and fencing for riparian zones in Grazing management was costed per km of waterway, and when not specified the remaining were costed per km^2 area. Any non-spatial estimated costs were also displayed separately as "continent-wide", these were either entire Threat Abatement Strategies (i.e. Biosecurity) or the non-spatial component associated with the Threat Abatement Strategy (i.e. policy component within Habitat Restoration). There was a non-spatial component for Map Refugia that was costed per species.

					Cost across cost variation scenarios			
#	**Threat Abatement Strategy**	**Unit for costing**	**Number of actions**	**# cost variation scenarios**	**Median**	**Minimum**	**Maximum**	**Most Common Across Australia**
1	Biosecurity	Continent-wide	1	1	$931,770,000	-	-	-
2	Critical Sites Access Management	Per km^2	5	3	$297	$286	$329	$286
		Continent-wide	1	1	$1,205,100	-	-	-

3	Disease Management – General	Per km^2	4	3	$196	$192	$202	$192
4	Disease Management – Phytophthora	Per km^2	6	3	$139,948	$139,877	$140,089	$139,877
5	Ecological Fire Regime Management	Per km^2	8	54	$1,505	$1,461	$2,403	$1,464
6	Forestry Management	Per km^2	6	3	$334	$328	$346	$328
		Continent-wide	1	1	$1,230,371	-	-	-
7	Grazing Management	Per km^2	19	3	$1,392	$1,380	$1,424	$1,380
		Continent-wide	1	1	$1,205,100	-	-	-
		Per km waterway	2	1	$4,549	-	-	$4,549
8	Habitat Restoration	Per km^2	5	21	$440,080	$176,164	$879,985	$176,164
		Continent-wide	1	1	$1,205,100	-	-	-
9	Hydrology Management	Continent-wide	10	1	$1,205,100	-	-	-
		Per structure	1	1	$42,235	-	-	$42,235
10	Invasive Fish Management	Continent-wide	13	1	$1,205,100	-	-	-
	Invasive Fish Management	Per km waterway	1	3	$59,022	$52,053	$77,525	$77,525
11	Invasive Large Herbivore Management	Per km^2	10	6	$719	$498	$1,201	$498
12	Invasive Predator Management	Per km^2	6	6	$750	$296	$1,289	$296
13	Invasive Rabbit Management	Per km^2	8	3	$1,535	$1,426	$1,761	$1,426
14	Invasive Weed Management	Per km^2	4	18	$36,690	$219	$146,060	$24,519

15	Invasive/Problematic Bird Management	Per km^2	8	3	$727	$664	$868	$664
16	Map Refugia	Per km^2 per species	2	3	$25	$24	$28	$24
		Continent-wide per species	1	1	$13,899	-	-	-
17	Native Herbivore Management	Per km^2	9	9	$814	$483	$1,532	$716
18	Policy & Education	Continent-wide	1	1	$2,960,100	-	-	-

The proportion of budget for each cost component

The proportion of TAS budgets that were estimated to be required for each cost component were, on average, Labour (49%), Travel within site (13%), Consumables (37%) and Equipment (2%). However, these proportions differed across TASs (Fig. 2). Actions such as Hydrology management, Map Refugia, Critical Sites Access Management, Forestry management were very labour intensive and required relatively minimal consumables apart from accommodation and meals. Others were more evenly balanced between labour and consumables such as Native Herbivore Management (bullets), Invasive Predator Management (baits), Invasive/Problematic Bird Management (bullets and nest-boxes), Ecological Fire Management (petrol for burning and water refills), and Invasive Rabbit Management (viral and bait supplies) (Fig. 2). Some TASs required consumables that outweighed other cost components, like materials for Habitat Restoration, fencing for Grazing Management, and the phosphide application for Phytophthora management (Fig. 2).

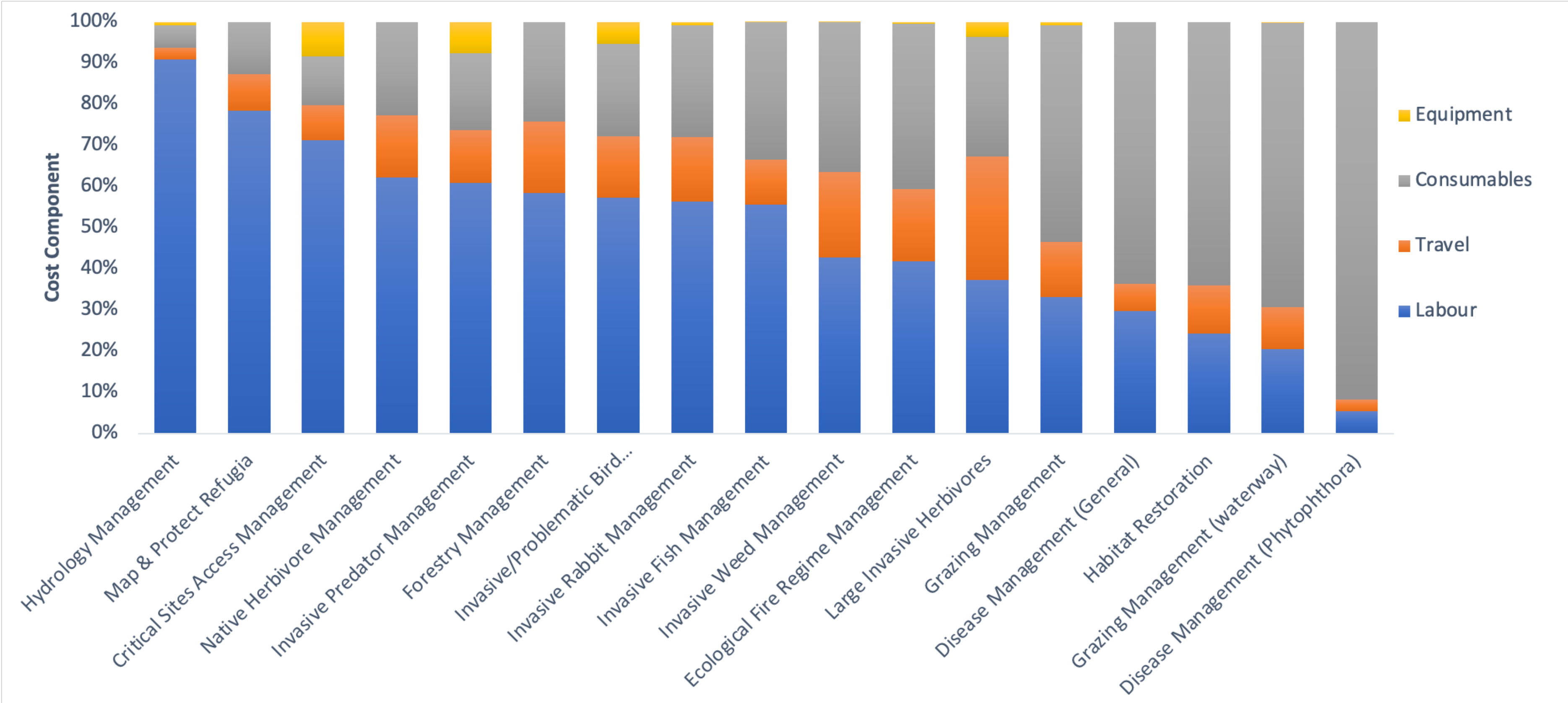

Figure 2. The cost component composition of each Threat Abatement Strategy displayed for the most common management option (determined from the highest proportion of projected threat management area at a national level), sorted by decreasing proportion of labour. We include spatial costs (any non-spatial costs were excluded).

Uncertainty in Cost estimates

We estimated the impact of uncertainty for the TAS cost estimates by investigating how costs changed over 17 global input variables and including an uncertainty multiplier (Fig. 3). The overall relative distance of the lower and upper bound of TAS estimates from the baseline were -34% and 55% (Supp. Material 6 Table 2). Labour intensive TASs demonstrated higher relative uncertainty, as the global variables in the analysis mostly related to labour. The three most uncertain TAS cost estimates were for Map Refugia (-62%, +116%), Critical Sites Access (-51%,+84%) and Invasive Predator Management (-50%,+77%) (Supp. Material 6 Table 2).

Threat Abatement Strategies with higher cost/km^2 had a higher absolute variation in cost estimates under uncertain global parameters. For example, the cost estimate for Habitat Restoration ranged from $122k to $259k per km^2 (a difference of $137k) with % variation from the baseline (-31%,+46%), and Phytophthora Management had the second highest absolute range in values from $115k to $195k per km^2 (a difference of $80k) with relative distance from baseline (-21%,+34%) (Fig. 3 and Supp. Material 6 Table 2

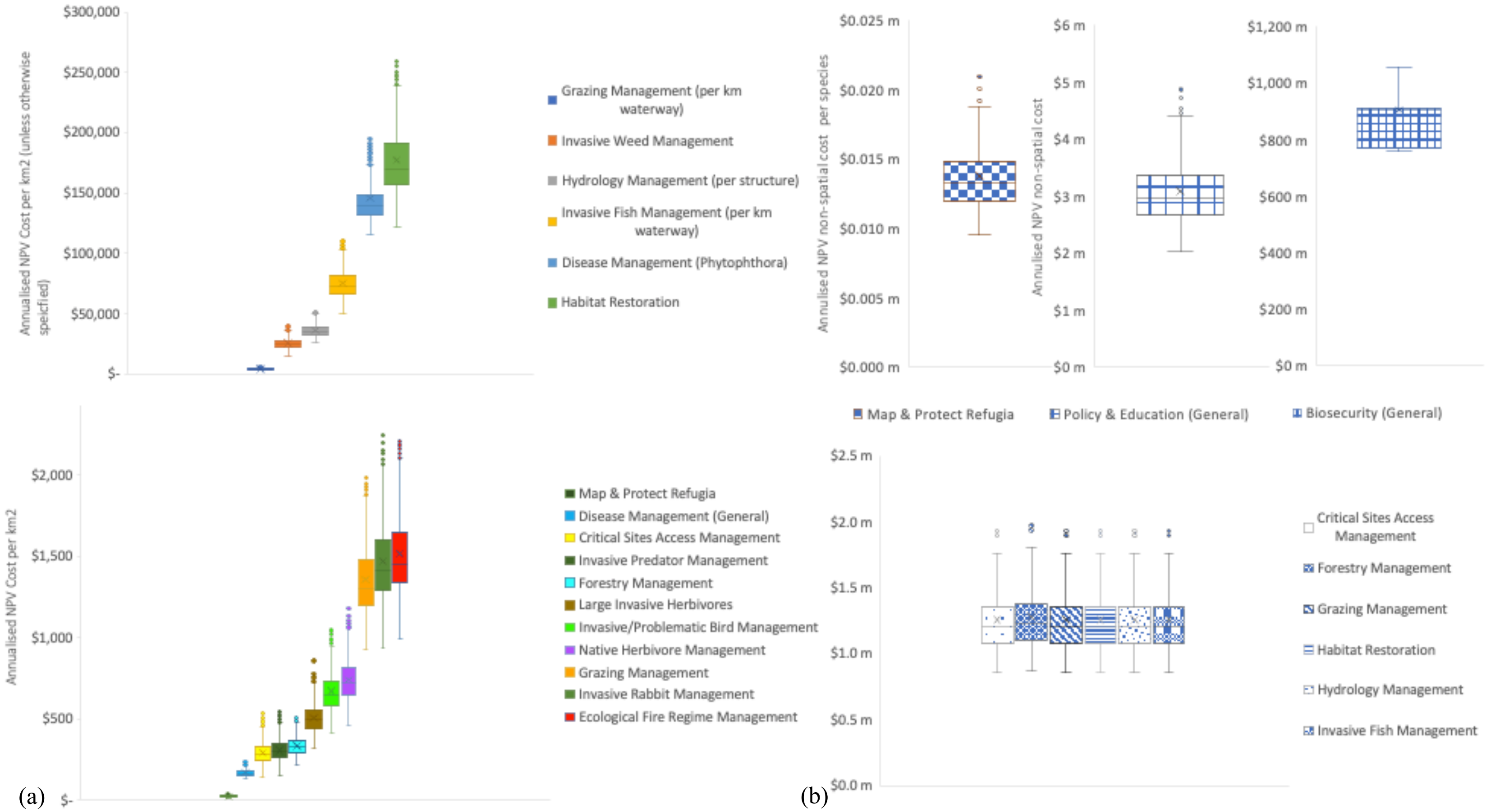

Figure 3 (a) and (b). An uncertainty analysis (N=1000) performed on discrete probability distributions of 18 global variables (Supp. Material 6) reveals the range of annualised NPV costs for each Threat Abatement Strategy (TAS), including: (a) spatially variable costs using the baseline (mode) cost value, determined from the highest proportion of projected threat management area at a national level), and b) the baseline total Australia-wide cost for strategies without spatial variation. Box plots show the median, the quartiles and interquartile ranges, with the mean marked with an X and the outliers with dots. The chart groupings were determined by the axis range of costs of each TAS.

Spatial variation in the costs of actions

The cost of implementing a TAS at a location was a summation of the contributing action costs, accounting for spatial variables at the location (vegetation type, terrain ruggedness, action suitability, etc.) and including the travel to site cost (distance from the closest city or airport) (see Supp. Material 3 for detail). Excluding continent-wide non-spatial actions and TASs (Biosecurity and Policy and liaison only had continent-wide actions), we projected 16 TAS costs across the threat range or Australia-wide if there was no specific threat range, with the cost estimates including travel to site costs being \$24 - \$1.02m /km^2 (Fig. 4, see Supp. Material 10 for individual spatial cost maps).

The costs of Threat Abatement Strategies with fewer or less impactful spatial variables were relatively consistent throughout Australia, such as Map Refugia (\$24 - \$72/km^2) where the only spatially variable action was ground surveys that varied by terrain ruggedness and travel to site costs. In contrast Large Invasive herbivore management (\$0 - \$255/km^2) included divergent cost estimates for aerial and on-ground actions that were prescribed at a location depending upon the suitability of each action, and Grazing management (\$0- \$7460/km^2), which includes different fencing costs at each location depending upon whether riparian zones fencing was prescribed (Fig. 4).

TASs with higher management costs per unit were often associated with smaller management areas or limited threat ranges. For example, Habitat Restoration has high costs (mode of \$176k/km^2) driven by the relatively large labour effort required for the regeneration of an area, but only projected across a smaller management area (1.6% of Australia) (Fig. 4). Similarly, Phytophthora management has a high cost/km^2 (mode of \$140k/km^2) and a small range of 9.3% of Australia. In contrast, Ecological Fire Regimes and Invasive Rabbit management have lower associated management costs (mode of \$1,464/km^2 and \$1,426/km^2) but are projected over a large extent of Australia (100% and 82%) (Fig. 4). The exception was Invasive Weed Management that had a moderate to high cost per km^2 (mode of \$24.5k/km^2) but was required across a broad range of Australia (64%).

Travel costs were generally higher in the central-west of Australia, and for strategies with the lower labour, consumable and equipment costs, the travel cost in these regions represented a larger proportion of overall costs (TASs on the left half of Fig. 4). For TASs with action costs that had low spatial variation the travel to site costs represented the source of overall cost variation. For example, for Disease management and Invasive Rabbit management, expensive pockets occur in remote areas due to travel to site and viral consumable costs increasing by up to ~2 fold (Supp. Material 12). For higher cost/km^2 TASs, the travel to site costs were not as visible due to the lower contributing proportions. For example, Invasive Weed Management had a labour-intensive weeding action cost that out shadowed the “remoteness” travel to site cost, with the spatial variation instead driven mostly by intactness and aridity (Supp. Material 12).

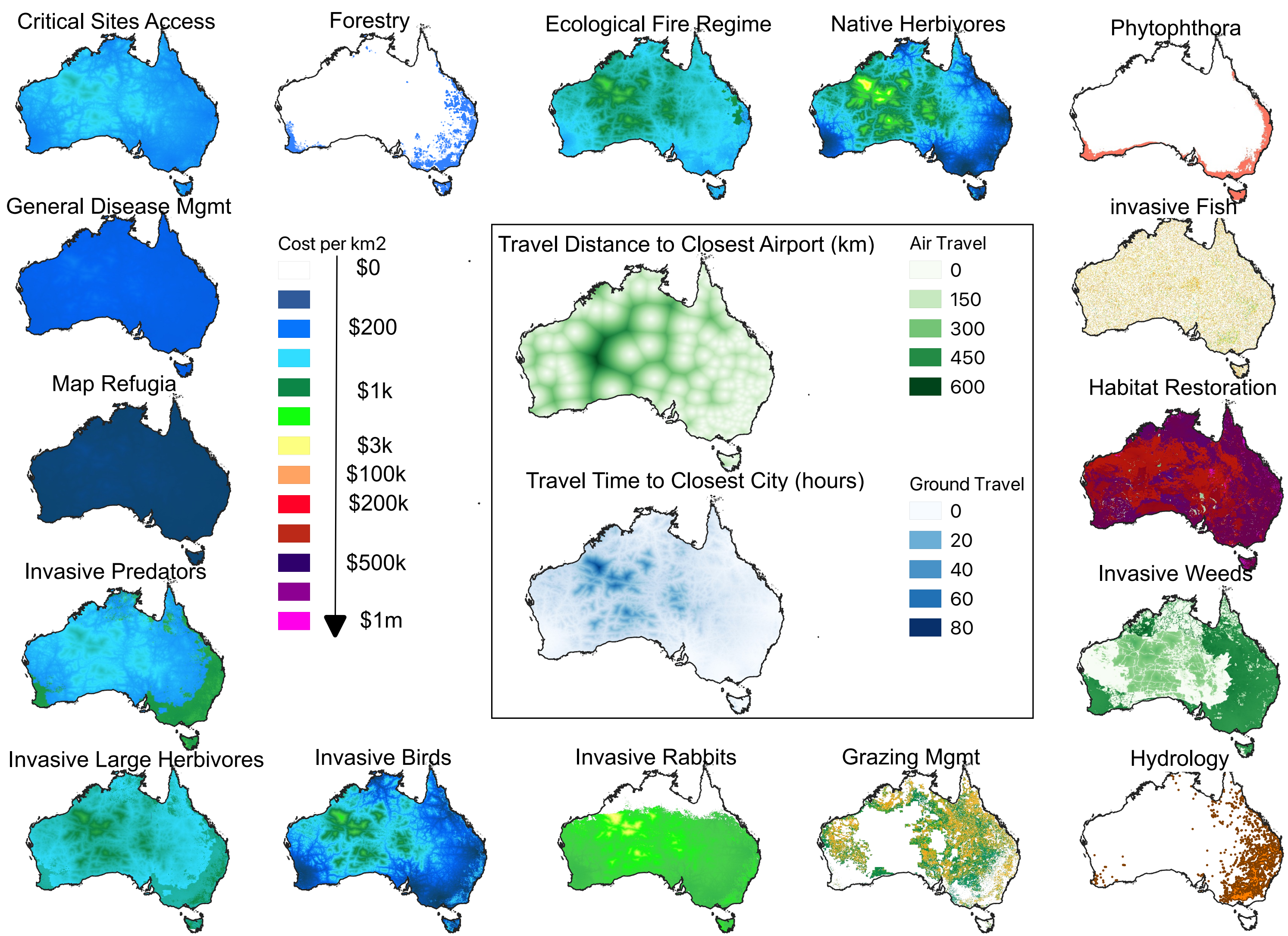

Figure 4. The spatial cost layers for 16 spatially variable Threat Abatement Strategies that include the travel time to site (inset ground travel time and air travel distance) projected to threat range or Australia-wide if there was no pre-determined threat range.

Discussion

We provide a novel threat abatement budgeting tool for estimating the costs of a comprehensive set of generic threat management strategies impacting biodiversity across Australia. The cost estimates and approaches for applying them are transparent and updatable, allowing for continual improvements in conservation planning that is better informed by knowledge of threat management costs. Our approach builds on existing information focussed on the actions and resources required to abate threats to biodiversity (Brazill-Boast *et al.* 2018; DPIE 2021; Ward *et al.* 2021) and costing out threat abatement efforts at smaller spatial scales (Cattarino *et al.* 2018; Wenger *et al.* 2018; Carwardine *et al.* 2019; Thomson *et al.* 2020). The three outputs provided can help plan for on-ground management and inform decision-making across broader scales. First, a set of expert-derived assumptions that define the 18 TASs. Secondly, a mechanistic cost model for each strategy that can be applied or modified to suit the locally determined locations and extent of management. Third, spatially variable TAS cost maps that can estimate management effort across large scales.

Our models show that the cost of managing a threat to biodiversity across Australia are likely to vary from \$24 - \$1.02m /km^2, depending on the TAS required, the travel distance to site and the site characteristics. Our per km^2 cost estimates were similar or higher than cost estimates from previous analyses, which is likely due to the comprehensive inclusion of all cost components in our cost models, including planning, travel to site and labour on-costs (see Supp. Material 7).

Improving the use of consistent standardised financial reporting is important for the effectiveness of the conservation sector (Cook *et al.* 2017; Iacona *et al.* 2018). Current conservation investments largely occur without reliable information on the costs of how the investment will be spent, and conservation expenditure is typically not recorded in ways that can improve current knowledge of conservation costs. The bottom-up costing model structure we provide can inform, and be improved by, the collection of additional cost information. By consistently recording the costs of individualised components of threat abatement activities, it becomes possible to understand the make-up of a total strategy cost and leverage these estimate costs elsewhere.

The collection of improved data on conservation expenditure should be used to improve the accuracy and precision in the presented cost models. Our uncertainty analysis indicated our estimates had a range of (-34%, +55%) for the baseline TAS values, and this variation needs to be accounted for when applying the cost estimates. We modified only global parameters, and further investigation of action specific parameters could reveal other parameters influencing cost estimates. A value of information (VoI) analysis approach estimates the higher expected payoff from better decision making as a result of reducing uncertainty (Raiffa & Schlaifer 1961), and VoI analyses are only just gaining traction in the realm of conservation decision making (Bolam *et al.* 2019). A VoI analysis can help prioritise the collection of improved information for the parameters which influence the cost estimates and subsequent management investment decisions.

Conclusion

Every year billions of dollars are spent on conservation management worldwide (Waldron *et al.* 2013). This expenditure largely occurs without a priori estimates of conservation management costs across broad scales and is not recorded in ways that can inform future conservation management budgets and analyses comparing the relative cost-effectiveness of actions. Our work provides new guidance on consistent approaches for estimating, recording, and informing cost estimates that can be built on or adapted with additional information from local to national scales. We aim to enable the conservation industry to match other sectors in articulating the investment required to achieve its sought goals. By continuing to progress knowledge on the costs of managing threats to biodiversity, more strategic revenue raising and improved use of available resources to achieve conservation outcomes are possible.

Author Contributions

CY, JW, MW, AR, JC conceived the ideas and design methodology; CY collected the data with contribution and direction from SvL, SL, WG, SS, ML, and MK. CY and MW analysed the data; CY, JW and JC led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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