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RESEARCH ARTICLE

The costs of managing key threats to Australia's biodiversity

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Abstract

1. Budgeting for biodiversity conservation requires realistic estimates of threat abatement costs. However, data on threat management costs are often unavailable or unable to be extrapolated across relevant locations and scales. Conservation expenditure largely occurs without a priori cost estimates of management activities and is not recorded in ways that can inform future budgets or cost-effective management decisions.
2. We provided transparent, broadly applicable cost models for 18 Threat Abatement Strategies aimed at managing the processes threatening Australia's biodiversity. We defined the actions required to implement each strategy and used a consistent structure to classify costs of labour, travel, consumables and equipment. We drew upon expert knowledge and published literature to parameterise each model, estimating the implementation cost of each strategy across the Australian continent, accounting for spatial variables such as threat presence, terrain, and travel distance.
3. Estimated annualised costs for the threat abatement strategies varied considerably between strategies and across Australia, ranging from \$24 to \$879,985 per km^2 (\$0.24–\$8880 per ha). On average, labour was the largest cost component (49%), followed by consumables (37%), travel (13%) and equipment (2%). Based on national scale variables and assumptions, cost estimates across Australia for each threat abatement strategy ranged from +44% and −33% of the most common cost estimate.

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 across Australia. In addition, 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 updated and improved with local-scale information over time.

KEYWORDS
bottom-up, conservation budget, cost models, cost per unit, environmental management actions, extinction, realistic costs, threat abatement

1 | INTRODUCTION

Understanding the financial resources required to manage threats and achieve conservation goals is important for budgeting, comparing alternative actions, setting realistic targets and prioritising limited conservation resources (Cook et al., 2017; Iacona et al., 2018). However, most conservation investments occur without a repeatable approach for estimating the costs and the cost-effectiveness of investments (Auerbach et al., 2014). This is, in part, due to the lack of readily available cost data in 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). As 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), the absence of high quality cost data can lead to sub-optimal planning (Carwardine, Wilson, Watts, et al., 2008; Naidoo et al., 2007), driving up to 35% loss of expected benefits due to an inferior project prioritisation (Pannell & Gibson, 2016).

Local and regional scale conservation budgeting tools (Iacona et al., 2018; Thomson et al., 2020; Wenger et al., 2018) can contribute to more accurate project cost predictions (Cook et al., 2017), improve cost reporting processes (Iacona et al., 2018) and estimate the efficiency of delivering conservation outcomes (Margoluis et al., 2009). However, these tools have not yet been applied extensively enough to generate more generalisable cost estimates needed for larger scale strategic planning. 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 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. The different extents and scales of actions, and the lack of consistency in cost collection and reporting in local budgeting efforts, mean new ways to build cost models applicable across broad landscapes, with adjustable assumptions to enable transparent comparisons across regions, actions, and contexts, is now critical for effective regional and national scale conservation planning.

Here, we address this 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 et al., 2016; Kearney et al., 2019). Building on previous efforts (Thomson et al., 2020; Wenger et al., 2018), we develop models that include a comprehensive range of actions, with underlying assumptions on cost components including labour, travel, consumables, and equipment. We model generic and scalable actions, that consider variables such as threat locations, terrain and travel distance. In doing so, we provide cost estimates of managing 18 major threats to Australia's biodiversity, and a set of transferable, transparent cost models and spatial cost layers that can be used for planning and prioritisation across broad scales.

The cost model estimates presented in this paper are reflective of average efforts across the broadest scale in Australia (i.e. the continent), and provide a cost-estimation framework and a decision-support tool for continent-scale actions that apply across Australia. Our cost model framework can also be adapted for use at local scales, although the model assumptions should be modified for a finer resolution analyses (e.g. state-wide or a singular national park) to reflect the cost variation relevant to the application context, as a mismatch could lead to sub-optimal priorities (Armsworth, 2014). For example, broad vegetation groups suffice at the broad scale for invasive weed management, but at a finer scale the knowledge of the locations of specific weeds like Lantana *Lantana camara* or Buffel grass *Cenchrus ciliaris* will improve the accuracy of estimates.

2 | MATERIALS AND METHODS

Our approach applied the best available national scale knowledge on the key threats to Australia's biodiversity and builds upon existing approaches for estimating threat management costs. We collated information on threat abatement actions and costs from scientific and grey literature, including Australian threat abatement plans (TAP), Australian threat abatement advices, action plans, and available data and approaches from two existing programs: the Saving our Species program in New South Wales, Australia (DPIE, 2021) and the Department of Environment, Land, Water and Planning's Strategic Management Prospects in Victoria, Australia (Thomson et al., 2020). We established a working group of 47 experts who provided general advice on this methodology, predominantly at two online workshops. Six of the experts are co-authors in this paper (Supporting Information 13) and provided more detailed information used to parameterise the models and their assumptions. This study did not require ethical approval.

A total of 18 broad strategies were identified. We applied a four-step process to estimate the costs of each strategy (Figure 1). The first step was to define each threat abatement strategy (hereafter, TAS), its assumptions, underlying actions, and cost components. We described each TAS with an objective and the underlying actions involved to achieve the TAS objective over a 30-year period. Within each action we defined four specific cost components: labour (L), travel within site (T), consumables (C) and equipment (E) (Supporting Information 4). The second step was generating structured generic models to estimate the cost of each TAS as a function of actions included in the strategy (spatial and non-spatial) and the respective travel to site costs. The third step was extrapolating the estimated action and travel costs across Australia to create spatial cost layers at 1 km^2 resolution where the strategy is likely to be relevant, using information on available spatial extent of threats, vegetation type, remoteness, terrain ruggedness, rivers, irrigation channels, and travel time. The final step was the incorporation of feedback and improvement of cost estimates when new information arises. We detail each step in the following sections.

2.1 | Step 1: Define threat abatement strategies

We worked with experts in biodiversity conservation and management (Supporting Information 13) to define TASs to abate the threats to Australia's terrestrial and freshwater biodiversity detailed by Ward et al. (2021). We assumed the threats impacting threatened species would be relevant to the full range of Australia's mainland biodiversity. We excluded all threats existing in offshore islands, the marine zone, as well as catastrophic events from the analysis.

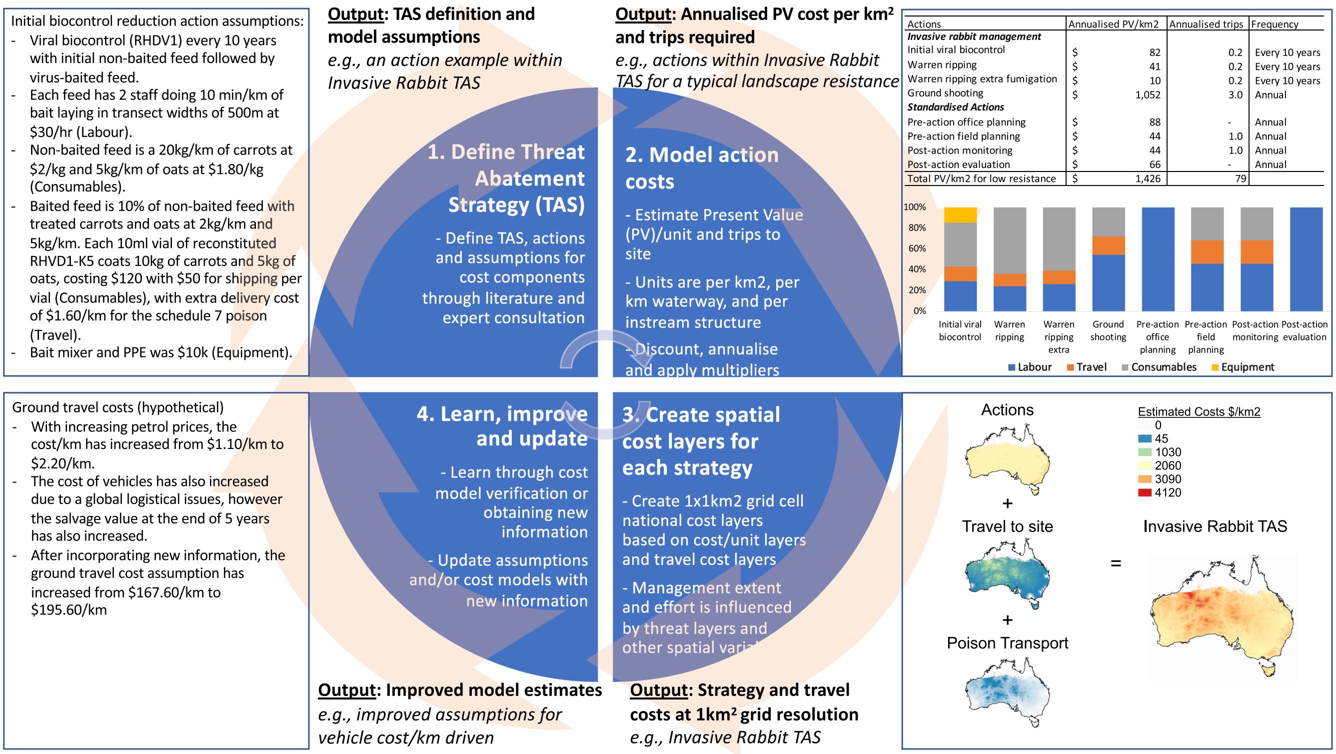


FIGURE 1 The four-step process applied to estimate costs for Threat Abatement Strategies (TASs). Each TAS constitutes multiple actions, and each action is defined by the cost components of labour, travel, consumables and equipment. The broad steps are shown in the middle quadrants, with the output specified for each step and demonstrated with the Invasive Rabbit TAS example. In Step 1 the TASs are described in detail, defining the actions and the corresponding cost components. In Step 2, for each action the Present Value (PV) per management unit and travel to site trips are calculated. In Step 3, the per management unit costs are modelled spatially. In Step 4, the models are updated when new information arises.

We grouped threats compiled by Ward et al. (2021) of similar nature that could be abated under a combined TAS (Supporting Information 1), to create a total of 18 TASs that would address the key threats. Our groupings of the TAS were guided by the first and second level comprehensive actions in the World Conservation Union–Conservation Measures Partnership (IUCN-CMP) classification of direct threats to biodiversity (version 1.1) (Salafsky et al., 2008). However, for the detail needed in modelling management costs we defined TAS at the third level classifications, which were not comprehensively defined by Salafsky et al. (2008) as they involved more specific strategies.

We specified that the objective of each TAS was to manage and reduce the impact of each threat as effectively as possible given current knowledge and management techniques. We then outlined the underlying actions involved to achieve each TAS objective over 30-years, which included defining the assumptions that would be used to estimate the costs of each action (Supporting Information 2). Underlying actions involved the planning, on-ground implementation, and evaluation process of the strategy (adapted from Carwardine et al., 2019; Iacona et al., 2018; Wenger et al., 2018).

Following Salafsky et al. (2008) we defined four general management actions for the planning and evaluation stages that were applied to all TASs (Table 1). Next, we described the on-ground implementation actions that were unique to each TAS, keeping these generic rather than attempting to prescribe context-specific details (Supporting Information 2). We then defined four cost components within each action: labour (L), travel within site (T), consumables (C), e.g. and equipment (E) (For more details see Supporting Information 2). Labour included all personnel hours, travel within site was the cost of on-site vehicle hire, consumables were any items expended (e.g., accommodation, food, herbicide, bait), and equipment included the necessary apparatus needed to achieve the action (Supporting Information 4). Apart from vehicle use intensity that can differ across projects and jurisdictions, the particular vehicle arrangements for a project (e.g. which could vary from lease hire or purchase with salvage value) can mean it shifts between being classified as a consumable (consumed during implementation of the action) or a piece of equipment that is paid for as an outlay and then re-used. Hence, we have included travel within site as a separate cost component allowing modification and/or removal if necessary.

Some actions and costs varied spatially based on land use or tenure, terrain ruggedness, vegetation type and remoteness (Supporting Information 3). Each action was assigned a frequency of re-occurrence over the time period (e.g., occurs every 'X' year over 30 years). We assumed all actions are performed humanely, undertaken by competent/skilled practitioners that follow best practices, and landholders and stakeholders are willing to participate.

We did not attempt to account for all the costs involved with threat abatement. We excluded some elements of costs that were context-specific and advise that end-users add these where relevant. These include unforeseen changes in actions or pricings over time, costs associated with achieving social and political feasibility of a particular effort (e.g. comprehensive Traditional Custodian and Indigenous community engagement, liaising with the relevant stakeholders and community members to gain support for threat management, time and process to get approval for projects/policies), costs related to land rent or purchase that is an enabling action rather than threat abatement action, opportunity costs for land-owners as a result of threat abatement (i.e. changes in grazing management to improve biodiversity outcomes that potentially shifts the undertaken activities on land), research costs to improve threat management outcomes, training costs for personnel performing threat abatement, and the costs involved with industry transitions to changed policies and practices to be less harmful to biodiversity (e.g. costs to transition the state of New South Wales, Australia out of native forest logging; Frontier Economics, 2022).

2.2 | Step 2: Model costs of actions and strategies

We designed a generic cost model structure to estimate the action and travel to site costs for each TAS and evaluated the robustness of the models with a Monte-Carlo analysis

TABLE 1 The general management actions that encompass planning and evaluation included in each Threat Abatement Strategy (TAS), with the assumed effort required and the relevant cost components. These actions are additional to the on-ground actions for TASs. The effort assumptions were based on expert knowledge and grey and published literature (Supporting Information 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	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

*Survey of 30% was chosen based on existing literature and the knowledge of the authors on this paper as the percentage that would be on average sufficiently representative to plan for management actions in the 100 km^2 grid management areas across Australia.

2.2.1 | Generic cost model

The total cost of a TAS within a management area was 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) (see Table 2). We assumed $1 \times 1\,km^2$ grid cell resolution for all analyses, all on-ground actions were carried out over a management area window of $100\,km^2$ or 100 1×1 km grid cells (Table 2), and that the generalised management actions (e.g., planning, valuation, monitoring) only occurred once per standardised grid scale of $100\,km^2$. We assumed managers will only need to do one trip to visit all grid cells within a $100\,km^2$ management window and we calculate the 'average travel to site cost' for all cells within this management window. We first calculate the travel cost to each grid cell, sum up the travel to site costs for all grid cells in the management area, then divide by 100 so that the travel to site costs for the management area equate to 1 trip per 100 grid cells averaged across those cells, or each grid cell contributing 1/100 of the travel to site cost (Equation 3).

The time horizon for the cost models was 30 years from 31 December 2020 to 31 December 2050. We present all final cost estimates as an annualised cost of the 30-year Present Value (PV) as at 31 December 2020 accounting for the frequency of actions, assuming constant real costs into the future and using a real discount rate of 4% (Supporting Information 3). The annualised cost is the PV paid in equal amounts for each year across the time horizon, that allows cash flows to be compared consistently and additively across all actions and strategies.

We calculated the PV of costs accounting for differing payment frequencies by adapting the standard annuity-due formula (Chan & Tse, 2017) (Equation 4) to a complex annuity-due formula (Equation 5) so that there were 'r' repayments that occur at the start

TABLE 2 Cost model parameter descriptions from Equations 1–5.

Equation	Cost model parameter	Description
1	Action Cost per management unit	The three management units for action cost estimation are per km^2 for land-based actions, per km of waterway length and per in-stream structure for waterway-based actions
1	Management unit size	The action spatial extent for the management unit based on relevant threat layers
2	Standardised Management Unit Size	The standardised management unit size that is managed as a standalone unit, for planning, action and travel purposes. This is set at $100\,km^2$ for land-based actions, 100 km of waterways and per instream structure
1	Management area	Used for travel to site cost calculations, this is the number of $1 \times 1\,km^2$ grid cells that the management unit size translates to (i.e., 170 km of river length could be across 130 $1 \times 1\,km^2$ grid cells)
3	Standardised management area	The standardised management area was measured in in $1 \times 1\,km^2$ grid cells and is set as the number of grid cells managed as one area for travel to site purposes. We created a cost-sharing window of 100 neighbouring 1 km^2 grid cells to distribute the travel cost of the distance travelled over the management area, such that each grid cell incurred 1% of the travel cost required for the management area. The exception to this was the Hydrology management TAS with no cost-sharing window as travel to locations was site specific and not spread over a management area
1	Distance to grid cell	Distance to closest city/airport from each grid-cell, multiplied by 2 for return trip
1	Non-spatial costs (if any)	High level efforts that do not vary spatially, for example, policy and education
2	Annualised Cost components	This is a summation of the annualised cost components that are labour (L), travel within site (T), consumables (C) and equipment (E). The annualised value is the equivalent annualised cost of the present v(PV)
2,3	Multipliers	30% for overheads applied to labour and 10% for on-site contingencies only applied to on-site actions
3	Number of trips	The trips required for onsite action to be completed in multiples of 21-day periods of field work
3	Annualised travel cost	Includes vehicle and personnel-time compensation cost. The annualised value is the equivalent annualised cost of the present value (PV).
4	Annuity due formula ($\ddot{a}_n$)	$\ddot{a}_n$ is the PV of an 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
5	Complex annuity due formula $(\ddot{a}_{rk})$	$\ddot{a}_{rk}$ is the PV of a complex annuity due at time zero for r repayments of amount P that occur at the beginning of every k periods such that $n = rk$, and the adapted real discount rate I across the k periods such that $(1+I) = (1+i)^k$, where i is the real discount rate

of every ‘k’ periods (Equation 5) (e.g., over a 30-year period, (r = 30, k = 1) is an annual payment and (r = 3, k = 10) is a payment that occurs every 10 years). We then converted the PV of the complex annuity to an equivalent annualised value using the standard annuity formula (Equation 4; see Table 2).

We included two cost multipliers, a 30% multiplier to labour that employers pay in excess to a person's salary (hereafter, overheads) including employee support, office space and IT equipment, insurance, leave, and superannuation (retirement money set aside by employers in Australia). We also included a 10% multiplier for on-site contingencies that was applied to labour, travel and consumables to account for unforeseen circumstances for on-site based work (for more detail see Supporting Information 3).

The description of model parameters is shown in Table 2.

$$\begin{aligned}\text{TAS cost} = & \sum_{\text{actions}} (\text{Action cost per management unit} \times \text{management unit size}) \\ & + \sum_{\text{actions}} (\text{Travel to site cost pe grid cell per km distance} \\ & \times \text{management area} \times \text{distance to grid cell} \times 2) \\ & + \sum_{\text{actions}} \text{Non spatial costs},\end{aligned} \quad (1)$$

where

$$\begin{aligned}\text{Action cost per management unit} = & \sum_{\text{L,T,C,E}} \text{Annualised Cost components} \\ & \times \text{multipliers} \times (\text{standardised management unit size})^{-1},\end{aligned} \quad (2)$$

and

$$\begin{aligned}\text{Travel to site cost per grid cell per km distance} = & \text{Annualised Travel cost per hour} \\ & \times (\text{transit speed})^{-1} \times \text{Number of trips required} \times \text{multipliers} \times \\ & (\text{standardised management area})^{-1},\end{aligned} \quad (3)$$

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

$$\ddot{a}_{rk} = P \times \frac{1-(1+I)^{-r}}{I} \times (1+I)$$

$$= P \times \frac{1-(1+i)^{-rk}}{(1+i)^k - 1} \times (1+i)^k \quad (5)$$

2.2.2 | Action and travel to site costs

Based on the model assumptions (Supporting Information 3) and cost component assumptions (Supporting Information 4), we modelled the action costs within each TAS at the relevant unit of measurement (Equation 2) (Supporting Information 5). The relevant unit of measurement was typically per km^2, with certain actions estimated per km of waterway length (e.g. waterway fencing in Grazing Management TAS, Trout Barrier Installation in Invasive fish management TAS), and actions for Hydrology TAS estimated per in-stream structure (Supporting Informations 2 and 5). We annualised the PV costs for each action (see annuity calculation above), divided all the costs by the standardised area to calculate a cost 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 (Equation 3) driven by the mode of transport, travel distance and the number of trips required (for more detail see Supporting Information 3).

2.2.3 | Uncertainty in costs

We assumed that the modelled costs represent our baseline estimates that correspond to the median value (50th percentile). We used a Monte Carlo (MC) simulation (Mooney, 1997) to evaluate the impact of cost model input uncertainty on TAS cost estimates, by varying 17 parameter values that were used in the majority of the TAS cost models (hereafter, global parameters) and an extra uncertainty parameter (For more detail see Supporting Information 6). The uncertainty parameter was to account for overall budget deviance from the baseline cost estimates as the majority of projects in mega industry project management had a 33% over-run cost (Merrow, 2013). We applied the McNamee-Celona method of assigned probabilities 0.25, 0.5 and 0.25 for the p10, p50 and p90 parameter values (McNamee & Celona, 1990). We constructed individual probability distributions to capture the range of these parameters with a 75% confidence value across 3 values, with a 25% probability of occurrence for the lower bound value, 50% for the baseline value and 25% for the upper bound value (Supporting Information 6 Table 1), with the range of values set objectively based on the observed data. We then applied the Monte-Carlo simulation with 1000 repetitions for all parameters simultaneously. Uncertainty of action-specific variables (e.g., cost per bait, bullet cost, phosphide costs) were not evaluated.

2.2.4 | Cost estimate validation

We validated cost estimates for certain actions against information in the scientific and grey literature when available, and/or through verifying with experts (for more detail see Supporting Information 7)

2.3 | Step 3: Create spatial cost layers for each strategy

We created spatial cost layers to reflect the approximate effort needed in each 1km^2 grid cell for 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 (Equation 1 without the non-spatial costs). All analyses were carried out in ArcGIS version 10.4 (Redlands, 2016).

We overlayed geographic layers to account for spatial variation (Supporting Information 3) through the type of action suitable to the (e.g., vegetation canopy cover influences whether an action is aerial or ground based) and the level of effort required to conduct the action (e.g., a rugged terrain requires more walking time compared to a smooth terrain) (Supporting Information 3). All action variations were modelled as an annualised PV (Step 2 Figure 1) and applied to the corresponding spatial extent (see sheets with prefix 'GIS – …' in Supporting Information 5).

The spatial travel cost layers were calculated for each action in each grid cell (second term, Equation 1), providing a return trip cost of the number of annualised trips required, weighted by the closest 100 $1 \times 1\,km^2$ grid cells. These travel cost layers differed by land, air and poison transport (Supporting Information 3), the time to travel from each grid cell to the closest city (Weiss et al., 2018) and the distance from each grid cell to the closest airport (Supporting Information 8).

Spatial action and travel layers were cropped to the extent of the relevant threat (Supporting Information 8), and when a relevant threat layer was unavailable, we presented the cost layers at the national scale (e.g. Invasive/Problematic Bird Management). The TAS cost totals were then calculated by adding the cost layers for each action including the relevant travel layers.

2.4 | Step 4: Learn, improve and update

Knowledge of threat abatement actions and cost estimates are likely to change over time. Through the on-going model update step the a priori assumptions used in the models can be improved upon based on new information. In some cases, new information can arise through an additional peer review or consultation with subject matter experts, or cost estimates may change due to dynamic environments and socio-economic systems. Where a priori cost model assumptions were adopted with limited empirical data, a revision could be deemed relevant using cost information that has recently been systematically recorded.

The strategic acquisition of new information on uncertain parameters or better model structures can be guided by value of information analyses, evaluating the trade-offs of the costs and benefits of acquiring new information that have an impact on the decision-making outcome (Raiffa & Schlaifer, 1961). We recommend systematically recording and reporting of actual conservation action costs when possible and reviewing cost model assumptions and estimates at least every 2-years to ensure the models are as current, relevant and accurate as possible.

3 | RESULTS

3.1 | Cost estimates for threat abatement strategies

The 18 strategies identified in our analysis to address key threats to Australia's biodiversity (detailed estimates in Supporting Information 9 summarised at the TAS level in Table 3) were comprised of 52 actions. Some actions, such as pre-action office and field planning, post-action monitoring and evaluation, and some policy and liaison actions were common to multiple TASs. The remaining actions were largely unique to each TAS, except for ground shooting which was applied to invasive predator management, large Invasive herbivore management, native herbivore management and invasive rabbit management, and habitat fencing that applied to native herbivore management and grazing management (Supporting Information 9)

The annualised spatial cost estimates of TAS ranged from the cheapest strategy of $24/km^2 ($0.24/ha) (Map Refugia), to the most expensive strategy of $0.88 m/km^2 ($8800/ha) (habitat restoration in rainforests) (Table 3, for more details see Supporting Informations 2 and 11). Cost estimates of TAS varied depending on the underlying action and effort required, influenced by characteristics like action suitability, environment type, vegetation type and human population density (Supporting Information 3).

Continent-wide costs were estimated for efforts that pertained across Australia and were independent of spatial areas. The highest non-spatial costs was estimated for Biosecurity—at $932 m (Table 3) that was largely adapted from the reported and recommended spending from the Australian biosecurity enquiry (Craik et al., 2017) (Supporting Information 2). Map Refugia also had a non-spatial (desktop) mapping action that was conducted at the national scale and costed per species (Supporting Information 2), with the total cost of this strategy equivalent to the ground survey cost required for the threatened species and the non-spatial cost multiplied by number of species that need this TAS (i.e. 10 species would require a total non-spatial cost of 10 × $13,899). There were multiple TASs that had the same cost for continent wide control as this was a generic communication/liaison cost that involved 11 full-time staff (1 management staff and 10 liaison staff) at the national scale.

3.2 | The proportion of budget for each cost component

The average proportion of TAS budgets split by cost component were labour (49%), travel within site (13%), consumables (37%) and equipment (2%), with these proportions differing across TASs (Figure 2). Certain TASs were labour intensive and required relatively minimal consumables apart from accommodation and meals (e.g. Hydrology management, Map Refugia). Others were more evenly balanced between labour and the necessary consumables such as 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) (Figure 2). Some TASs required consumables that outweighed other cost components, like restoration consumables for Habitat Restoration, fencing materials for Grazing Management, and phosphide application for Phytophthora management (Figure 2). Equipment costs were generally minimal (on average 2% of total costs) as the annualised cost of equipment is minimal due to the low frequency of cost incurrence (e.g. every 10 years).

TABLE 3 The range of annualised present value (PV) cost per unit estimated for each threat abatement strategy (TAS) 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 management action type (e.g., aerial vs ground, intactness, etc.). We show the median, minimum, maximum and the mode or 'most common cost across Australia' determined from the highest proportion of projected threat management area at a national level. Unit of measurement for spatial actions were per instream structure, per km of waterway, and per km^2 area. Any non-spatial estimated costs were displayed separately as 'continent-wide' and were either a TAS (e.g., Biosecurity) or the non-spatial component of the TAS (i.e. policy within Habitat Restoration). There was a 'continent-wide per species' non-spatial component for Map Refugia.

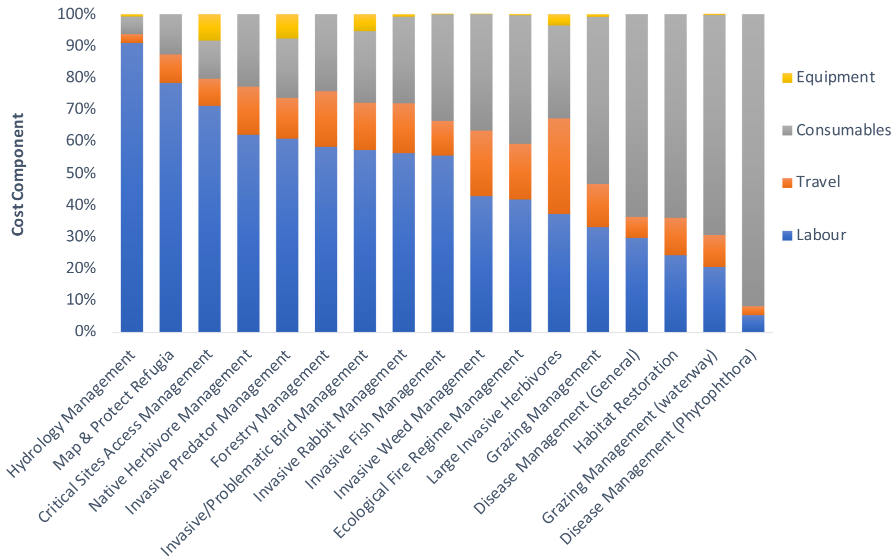
#	Threat abatement strategy	Unit for costing	Number of actions	# cost variation scenarios	Cost across cost variation scenarios			Most common across Australia
					Median	Minimum	Maximum	
1	Biosecurity	Continent-wide	1	1	$931,770,000	—	—	—
2	Critical Sites Access Management	Per km^2	5	3	$297	$286	$329	$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	$1505	$1461	$2403	$1464
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	$1392	$1380	$1424	$1380
		Continent-wide	1	1	$1,205,100	—	—	—
		Per km waterway	2	1	$4549	—	—	$4549
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	—	—	—
		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	$1201	$498
12	Invasive Predator Management	Per km^2	6	6	$750	$296	$1289	$296
13	Invasive Rabbit Management	Per km^2	8	3	$1535	$1426	$1761	$1426
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	$1532	$716
18	Policy & Education	Continent-wide	1	1	$2,960,100	—	—	—

3.3 | Uncertainty in cost estimates

We evaluated TAS cost estimate uncertainty by simulating 17 global parameters and including an uncertainty multiplier across their individual probability distributions (Figure 3). The overall relative distance of the lower and upper bound of TAS estimates from the baseline were −34% and 55% (Supporting Information 6; Table 2). The three most uncertain TAS cost estimates were for Map Refugia (−62%, +116%), Critical Sites Access (−51%, +84%) and Invasive Predator Management (−50%, +77%) (Supporting Information 6; Table 2).

TASs 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 $122,000 to $259,000/km^2 (a difference of $137,000) 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 $80,000) with relative distance from

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 excluded any non-spatial costs.



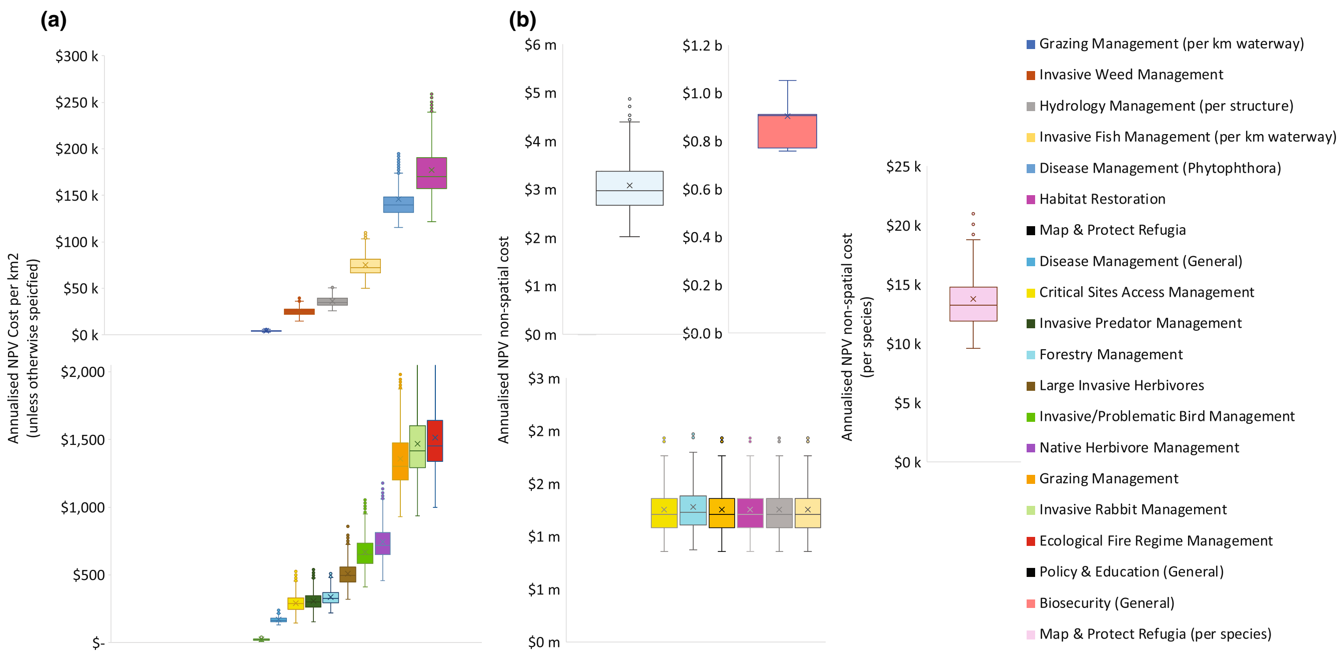


FIGURE 3 An uncertainty analysis (*N* = 1000) reveals the range of annualised Present Value (PV) costs for each TAS, simulated based on the discrete probability distributions of 17 parameters that were used in the majority of the Threat Abatement Strategy (TAS) cost models (hereafter, global parameters) and an extra uncertainty parameter (see Supporting Information 6). This includes 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 for Australia-wide non-spatial costs. 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.

baseline (−21%, +34%) (Figure 3 and Supporting Information 6; Table 2).

3.4 | 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 and the travel to site cost (Supporting Information 3). We projected 16 TAS costs across the threat range or Australia-wide if there was no specific threat range and excluded continent-wide non-spatial actions and TASs (Biosecurity and Policy and liaison only had continent-wide actions). Including travel to site costs, the annualised TAS cost estimates were $24–$1,022,803/km^2 (Figure 4, Supporting Information 10 for individual spatial cost maps).

TASs with fewer or less pronounced spatial variables were relatively uniform 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 ($411–$1422 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 ($1380–$7460/km^2), which includes different fencing costs at each location depending upon whether riparian zones fencing was prescribed (Figure 4).

TASs with higher management costs per unit were often associated with smaller management areas or limited threat ranges. For example, Habitat Restoration had high costs ($219–$1,022,803/km^2) driven by the relatively large labour effort required to regenerate ecosystems but was only projected across a smaller management area (1.6% of Australia–areas that have been previously cleared and could potentially be restored) (Figure 4). Similarly, Phytophthora management has a high cost/km^2 ($139,877–$144,206/km^2) but a small geographical range of 9.3% of Australia. In contrast, Ecological Fire Regimes ($315–$1823/km^2) and Invasive Rabbit management ($1426–$2670/km^2) have lower associated management costs but are projected over a large extent of Australia (100% and 82%) (Figure 4). The exception was Invasive Weed Management that had a moderate to high cost per km^2 ($219–$200,101/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 lower action costs, the travel cost in these

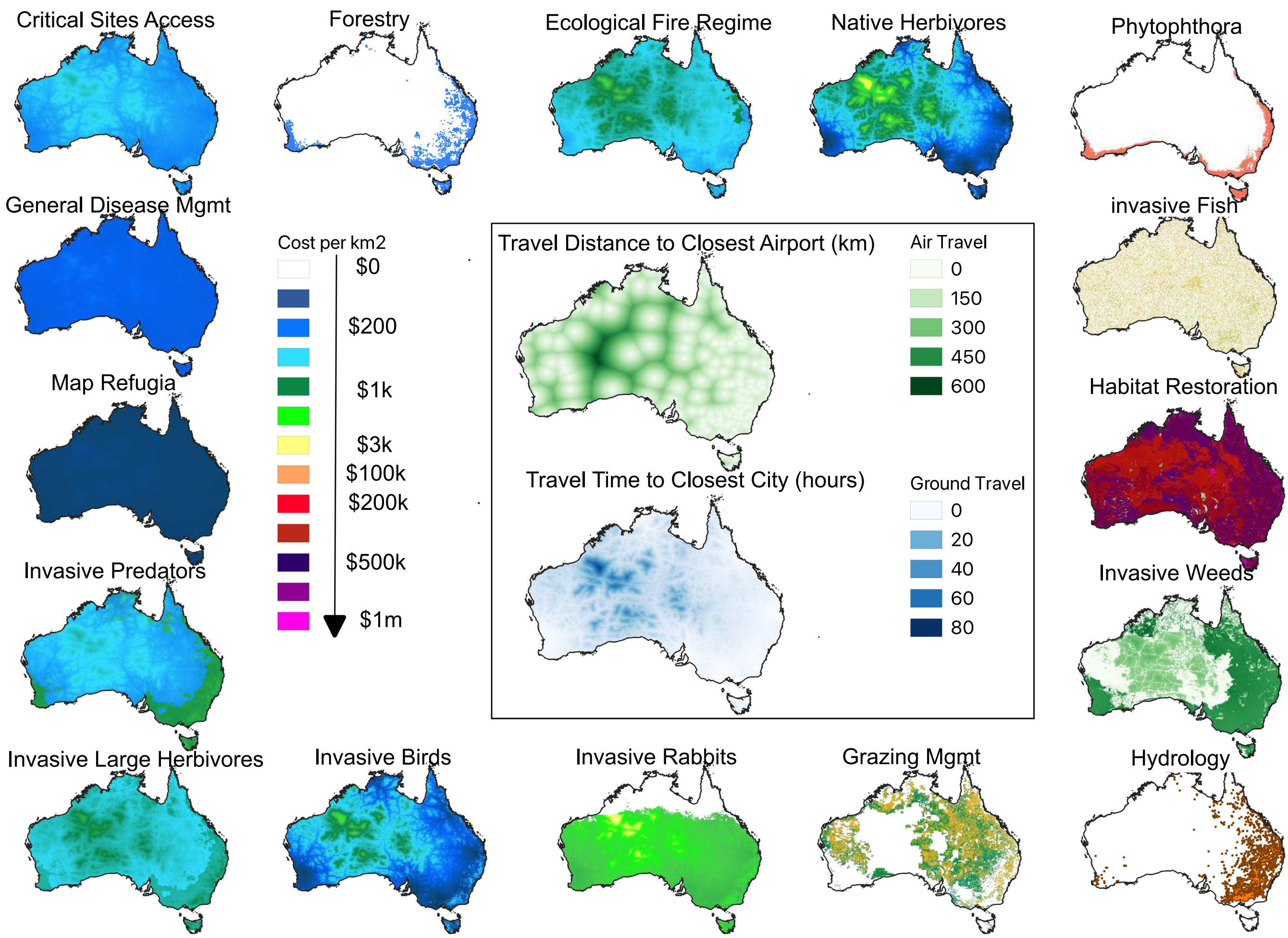


FIGURE 4 The spatial cost layers for 16 spatially variable Threat Abatement Strategies that include the travel time to site (inset ground travel time and air travel distance) projected to threat range or Australia-wide if there was no pre-determined threat range.

regions represented a larger proportion of overall costs (TASs on the left half of Figure 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, Disease management and Invasive Rabbit management had expensive pockets in remote areas increasing by up to ~2 fold due to travel to site and viral consumable delivery costs (the initial biocontrol reduction of a 10-yearly administration of RHVD1-K5 to induce rabbit haemorrhagic disease virus (RHDV) or myxomatosis) (Supporting Information 12). For higher cost/km^2 TASs, the travel to site costs were not as observable due to the lower contributing proportions. For example, Invasive Weed Management had a labour-intensive weeding action cost that dominated the 'remoteness' travel to site cost, with spatial variation instead driven mostly by intactness and aridity (Supporting Information 12).

4 | 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 presented are useful for program managers who work at larger scales (e.g. region, state or national recovery programs), with the approach transparent and can be updated when better information on the models and assumptions are available. However, the costing framework lends itself to all spatial scales of costings and can be used by on-ground managers who work at the local scales with appropriate adjustment of cost models and the underlying assumptions to account for the spatial resolution of actions.

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 cost estimation efforts at smaller spatial scales (Carwardine et al., 2019; Cattarino et al., 2018; Thomson et al., 2020; Wenger et al., 2018).The three outputs include a set of expert-derived assumptions that define the 18 TAS, a mechanistic cost model for each strategy that can be applied or modified to suit the locally determined locations and extent of management, and spatially variable TAS cost maps that can estimate management effort across large scales. These outputs can inform on-ground management and decision-making across broader scales, allowing systematic budget estimates that lead to informed planning and funding applications. When coupled with benefits, they could also be used to inform a cost-effectiveness or cost–benefit analysis and subsequent prioritisation of management actions.

Our models show that the cost of managing a threat to biodiversity across Australia are likely to vary from \$24 to \$1.02 m/km^2, depending on the TAS required, the site characteristics and travel distance. 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 overheads (Supporting Information 7).

Current conservation investments largely occur without reliable information on their costs, and conservation expenditure is not typically recorded in ways that can improve current knowledge of conservation costs. The importance of cost inclusion within environmental decision making has been realised globally and has expanded rapidly over the last two decades (Ando & Langpap, 2018; Carwardine, Wilson, Ceballos, et al., 2008; Gordon et al., 2020; Jantke & Schneider, 2011; Murdoch et al., 2007; Naidoo & Iwamura, 2007; Wilson et al., 2007). No extensive and intensive scale costing exercise like this has been done for environmental management and the application of this work could provide a useful way to validate and improve cost estimates in conservation.

The set of TASs proposed and costed here are unique to the threats that mainland Australian threatened species face; however, the actions that sit within the TASs are modular and they can be applied to other regions of the world with updated assumptions. When using these cost models at a different spatial scale or resolution, the assumptions will need to be tailored to the relevant scale that is required (e.g., 5 baits/km^2 for predator control across Australia accounts for the range of predator intensity across the landscape but does not translate to an area that is only 3 km^2 that might have a high density of predators).

The costing model structure we provide can inform, and be improved by, the collection of additional cost information. We have allocated general management actions for each TAS (e.g., post-action monitoring and post-action evaluation) that are placeholders for ongoing evaluation and improvement of the TASs. Ideally, conservation managers can consistently record relevant information contributing to better quality cost estimates within the project over time and creating comparable costs across different conservation organisations.

The targeted data collection of conservation expenditure should be performed by decision-research scientists or data modellers to improve the accuracy and precision in the presented cost models. Our uncertainty analysis indicated our estimates varied widely (−34%, +55%) for the baseline TAS values, and this variation can be improved through better assumptions with a more certain range. We only simulated global parameter variation, and further investigation could reveal action specific parameters that are influential of cost estimates. As described briefly in the Methods, Value of Information analyses can help prioritise the collection of improved information for the parameters (Bolam et al., 2019). We strongly recommend this as a complementary exercise to the ongoing collection of data.

The cost models presented here are the first attempt at systematic nation-wide cost estimates of threat abatement, and they are by no means perfect nor complete. The estimates are useful in their current form and can be applied with periodical revisions. However, given their novelty these cost models should be treated as a starting point for discussion and improvement, where the model structure and underlying assumptions can be challenged, verified and/or replaced with superior models and assumptions.

5 | CONCLUSIONS

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 analyse 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 sector 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

Chuanji Yong, James Watson, Michelle Ward, April Reside, Josie Carwardine conceived the ideas and designed the methodology; Chuanji Yong collected the data with contribution and direction from Stephen van Leeuwen, Sarah Legge, William Geary, Mark Lintermans, Mark Kennard, and Stephanie Stuart. Chuanji Yong and Michelle Ward analysed the data; Chuanji Yong, James Watson and Josie Carwardine led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

All authors declare that there are no conflicts of interest.

DATA AVAILABILITY STATEMENT

This manuscript does not directly use data but instead generates the output through cost models. The models, assumptions and output (Supporting Informations 1, 5, 9 and 10) are made available on the *University of Western Australia Research Repository* https://doi.org/10.26182/xd3d-7914 (Yong & Ward, 2023).

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REFERENCES

Ando, A. W., & Langpap, C. (2018). The economics of species conservation. *Annual Review of Resource Economics*, *10*, 445–467.

Armsworth, P. R. (2014). Inclusion of costs in conservation planning depends on limited datasets and hopeful assumptions. *Annals of the New York Academy of Sciences*, *1322*, 61–76.

Auerbach, N. A., Tulloch, A. I. T., & Possingham, H. P. (2014). Informed actions: Where to cost effectively manage multiple threats to species to maximize return on investment. *Ecological Applications*, *24*, 1357–1373.

Bolam, F. C., Grainger, M. J., Mengersen, K. L., Stewart, G. B., Sutherland, W. J., Runge, M. C., & McGowan, P. J. K. (2019). Using the value of information to improve conservation decision making. *Biological Reviews*, *94*, 629–647.

Brazill-Boast, J., Williams, M., Rickwood, B., Partridge, T., Bywater, G., Cumbo, B., Shannon, I., Probert, W. J. M., Ravallion, J., Possingham, H., & Maloney, R. F. (2018). A large-scale application of project prioritization to threatened species investment by a government agency. *PLoS One*, *13*, e0201413.

Carwardine, J., Martin, T. G., Firn, J., Reyes, R. P., Nicol, S., Reeson, A., Grantham, H. S., Stratford, D., Kehoe, L., & Chadès, I. (2019). Priority threat management for biodiversity conservation: A handbook. *Journal of Applied Ecology*, *56*, 481–490.

Carwardine, J., Wilson, K. A., Ceballos, G., Ehrlich, P. R., Naidoo, R., Iwamura, T., Hajkowicz, S. A., & Possingham, H. P. (2008). Cost-effective priorities for global mammal conservation. *Proceedings of the National Academy of Sciences of the United States of America*, *105*, 11446–11450.

Carwardine, J., Wilson, K. A., Watts, M., Etter, A., Klein, C. J., & Possingham, H. P. (2008). Avoiding costly conservation mistakes: The importance of defining actions and costs in spatial priority setting. *PLoS ONE*, *3*, e2586.

Cattarino, L., Hermoso, V., Carwardine, J., Adams, V. M., Kennard, M. J., & Linke, S. (2018). Information uncertainty influences conservation outcomes when prioritizing multi-action management efforts. *Journal of Applied Ecology*, *55*, 2171–2180.

Chan, W.-S., & Tse, Y.-K. (2017). *Financial mathematics for actuaries*. World Scientific.

Cook, C. N., Pullin, A. S., Sutherland, W. J., Stewart, G. B., & Carrasco, L. R. (2017). Considering cost alongside the effectiveness of management in evidence-based conservation: A systematic reporting protocol. *Biological Conservation*, *209*, 508–516.

Craik, W., Palmer, D., & Sheldrake, R. (2017). *Priorities for Australia's biosecurity system—An independent review of the capacity of the National Biosecurity System and its underpinning intergovernmental agreement*. Commonwealth of Australia.

DPIE. (2021). *Saving our Species—Year in Review 2019–20*. Environment, Energy and Science, Department of Planning, Industry and Environment.

Frontier Economics. (2022). Transition support for the NSW native forest sector. A report for the World Wide Fund for Nature-Australia.

Gordon, E. R., Butt, N., Rosner-Katz, H., Binley, A. D., & Bennett, J. R. (2020). Relative costs of conserving threatened species across taxonomic groups. *Conservation Biology*, *34*, 276–281.

Iacona, G. D., Sutherland, W. J., Mappin, B., Adams, V. M., Armsworth, P. R., Coleshaw, T., Cook, C., Craigie, I., Dicks, L. V., Fitzsimons, J. A., McGowan, J., Plumptre, A. J., Polak, T., Pullin, A. S., Ringma, J., Rushworth, I., Santangeli, A., Stewart, A., Tulloch, A., … Possingham, H. P. (2018). Standardized reporting of the costs of management interventions for biodiversity conservation. *Conservation Biology*, *32*, 979–988.

Jackson, W. J., Argent, R. M., Bax, N. J., Bui, E., Clark, G. F., Coleman, S., Cresswell, I. D., Emmerson, K. M., Evans, K., Hibberd, M. F., Johnston, E. L., Keywood, M. D., Klekociuk, A., Mackay, R., Metcalfe, D., Murphy, H., Rankin, A., Smith, D. C., & Wienecke, B. (2016). *Australia state of the environment*. Australian Government Department of the Environment and Energy.

Jantke, K., & Schneider, U. A. (2011). Integrating land market feedbacks into conservation planning—A mathematical programming approach. *Environmental Modeling and Assessment*, *16*, 227–238.

Kearney, S. G., Carwardine, J., Reside, A. E., Fisher, D. O., Maron, M., Doherty, T. S., Legge, S., Silcock, J., Woinarski, J. C. Z., Garnett, S. T., Wintle, B. A., & Watson, J. E. M. (2019). The threats to Australia's imperilled species and implications for a national conservation response. *Pacific Conservation Biology*, *25*, 231–244.

Kujala, H., Lahoz-Monfort, J. J., Elith, J., & Moilanen, A. (2018). Not all data are equal: Influence of data type and amount in spatial conservation prioritisation. *Methods in Ecology and Evolution*, *9*, 2249–2261.

Margoluis, R., Stem, C., Salafsky, N., & Brown, M. (2009). Design alternatives for evaluating the impact of conservation projects. *New Directions for Evaluation*, *2009*, 85–96.

McNamee, P., & Celona, J. (1990). *Decision analysis with Supertree*. Scientific Press.

Merrow, E. (2013). Oil and gas industry megaprojects: Our recent track record. *Oil and Gas Facilities*, *1*, 38–42.

Mooney, C. Z. (1997). *Monte Carlo simulation*. SAGE, Thousand Oaks.

Murdoch, W., Polasky, S., Wilson, K. A., Possingham, H. P., Kareiva, P., & Shaw, R. (2007). Maximizing return on investment in conservation. *Biological Conservation*, *139*, 375–388.

Naidoo, R., Balmford, A., Ferraro, P., Polasky, S., Ricketts, T., & Rouget, M. (2007). Integrating economic cost into conservation planning. *Trends in Ecology & Evolution*, *21*, 681–687.

Naidoo, R., & Iwamura, T. (2007). Global-scale mapping of economic benefits from agricultural lands: Implications for conservation priorities. *Biological Conservation*, *140*, 40–49.

Pannell, D. J., & Gibson, F. L. (2016). Environmental cost of using poor decision metrics to prioritize environmental projects. *Conservation Biology*, *30*, 382–391.

Raiffa, H., & Schlaifer, R. (1961). *Applied statistical decision theory*.

Redlands, C. (2016). *ArcGIS (version 10.4)*. (ed. I. Environmental Systems Research Institute, 2010).

Salafsky, N., Salzer, D., Stattersfield, A. J., Hilton-Taylor, C., Neugarten, R., Butchart, S. H. M., Collen, B., Cox, N., Master, L. L., O'Connor, S., & Wilkie, D. (2008). A standard lexicon for biodiversity conservation: Unified classifications of threats and actions. *Conservation Biology*, *22*, 897–911.

Thomson, J., Regan, T. J., Hollings, T., Amos, N., Geary, W. L., Parkes, D., Hauser, C. E., & White, M. (2020). Spatial conservation action planning in heterogeneous landscapes. *Biological Conservation*, *250*, 108735.

Waldron, A., Mooers, A. O., Miller, D. C., Nibbelink, N., Redding, D., Kuhn, T. S., Roberts, J. T., & Gittleman, J. L. (2013). Targeting global conservation funding to limit immediate biodiversity declines. *Proceedings of the National Academy of Sciences of the United States of America*, *110*, 12144–12148.

Ward, M., Carwardine, J., Yong, C. J., Watson, J. E. M., Silcock, J., Taylor, G. S., Lintermans, M., Gillespie, G. R., Garnett, S. T., Woinarski, J. C. Z., Tinglet, R., Fensham, R., Conrad, H. J., Hines, H. B., Roberts, J. D., Kennard, M. J., Harvey, M. S., Chapple, D. G., & Reside, A. E. (2021). A national-scale dataset for threats impacting Australia's imperiled flora and fauna. *Ecology and Evolution*, *11*, 11749–11761.

Weiss, D. J., Nelson, A., Gibson, H. S., Temperley, W., Peedell, S., Lieber, A., Hancher, M., Poyart, E., Belchior, S., Fullman, N., Mappin, B., Dalrymple, U., Rozier, J., Lucas, T. C. D., Howes, R. E., Tusting, L. S., Kang, S. Y., Cameron, E., Bisanzio, D., … Gething, P. W. (2018). A global map of travel time to cities to assess inequalities in accessibility in 2015. *Nature*, *553*, 333–336.

Wenger, A. S., Adams, V. M., Iacona, G. D., Lohr, C., Pressey, R. L., Morris, K., & Craigie, I. D. (2018). Estimating realistic costs for strategic management planning of invasive species eradications on islands. *Biological Invasions*, *20*, 1287–1305.

Wilson, K. A., Underwood, E. C., Morrison, S. A., Klausmeyer, K. R., Murdoch, W. W., Reyers, B., Wardell-Johnson, G., Marquet, P. A., Rundel, P. W., McBride, M. F., Pressey, R. L., Bode, M., Hoekstra, J. M., Andelman, S., Looker, M., Rondinini, C., Kareiva, P., Shaw, M. R., & Possingham, H. P. (2007). Conserving biodiversity efficiently: What to do, where, and when (conserving biodiversity efficiently). *PLoS Biology*, *5*, e223.

Yong, C., & Ward, M. (2023). Data from: The costs of managing key threats to Australia's biodiversity. *The University of Western Australia Research Repository*, https://doi.org/10.26182/xd3d-7914

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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