

1 **The costs of abating threats to Australia's**

2 **biodiversity**

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46

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 km²/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

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

82

83 **Keywords:** Cost model, threat management, biodiversity conservation,

84 budget

85

86 **Introduction**

87 Understanding the financial resources required to manage threats and
88 achieve conservation goals is important for budgeting, investigating value of
89 alternative actions, target-setting and prioritising limited conservation
90 resources (Cook *et al.* 2017; Iacona *et al.* 2018). However, the costs of
91 implementing a conservation action are often challenging to estimate, and
92 most conservation investments occur without reliable estimates of their return
93 on investment (Auerbach, Tulloch & Possingham 2014). This is, in part, due
94 to the lack of readily applicable cost data available to the conservation sector
95 (Iacona *et al.* 2018). Where conservation cost data are available it often lacks
96 critical information on how estimates are produced, and what is included and
97 excluded (Armsworth 2014). The influence of a cost layer in prioritisation can
98 be as high as the joint influence of thousands of species layers (Kujala *et al.*
99 2018), and absence of high quality cost data can be sub-optimal (Naidoo *et*
100 *al.* 2007; Carwardine *et al.* 2008) driving up to 35% loss of environmental
101 value benefits (Pannell & Gibson 2016).

102

103 Local and regional scale conservation budgeting tools (Iacona *et al.* 2018;
104 Wenger *et al.* 2018; Thomson *et al.* 2020) can contribute to more accurate
105 project cost predictions (Cook *et al.* 2017), improve cost data collection
106 processes (Iacona *et al.* 2018) and estimate the efficiency of delivering
107 conservation outcomes at the scale that the models have been applied
108 (Margoluis *et al.* 2009). However, estimates generated by these tools are not
109 generalisable for larger scale strategic planning that must occur across vast
110 areas and land tenures. Hence, cost estimates cannot easily be compared
111 across studies and applications, nor confidently extrapolated to other
112 locations (Cook *et al.* 2017; Iacona *et al.* 2018). For example, while it is
113 possible to find one or more locations with accurate cost information for
114 managing weeds, we lack information on larger scale to strategically budget
115 at a regional or continental scale (Kearney *et al.* 2019). The knowledge gap
116 in the budget required to achieve a conservation outcome at the broad-scale
117 cannot easily be filled by combining multiple sources of local scale cost

118 estimates that have been derived using different approaches or delivery
119 agents. Further effort is needed to build cost models and budgets applicable
120 across broad landscapes, with adjustable assumptions to enable transparent
121 comparisons of costs across different regions, actions and contexts.

122

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

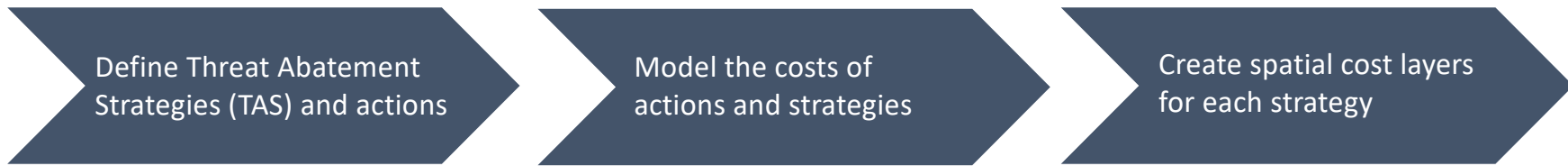
140 **Methodology**

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

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

153

154 We applied this knowledge and information to estimate the costs of threat
155 abatement strategies following three steps (Fig. 1). First, we described each
156 threat abatement strategy (hereafter, TAS), the actions involved to complete
157 each strategy over a 30-year time frame. Within each action (e.g. pre-action
158 office planning, aerial baiting, post-action valuation), we defined four cost
159 components: labour (L), travel within site (T), consumables (C) and
160 equipment (E) (Table 1) (see Supp. Material 4 for details). Second, we
161 structured generic models to estimate the cost of each strategy, as a function
162 of the contributing action costs (spatial and non-spatial) and travel to site
163 costs for all actions included in the strategy. Third, we extrapolated the
164 estimated action and travel costs across Australia to create spatial cost
165 layers at 1km² resolution, using information on the locations of threats,
166 landscape resistance levels and travel time. We created spatial cost models
167 for each TAS separately for areas across Australia where the strategy is
168 likely to be relevant, based on available information about the spatial extent
169 of threats.



- Define actions, TAS and assumptions for cost components, through literature and expert consultation
Output 1: TAS assumptions

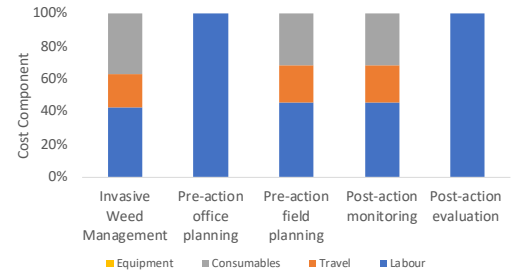
Example of Invasive Predator TAS

- Annual aerial baiting:
- 1 FTE annually to administer bait from aircraft (Labour)
 - 50 baits/km² at \$0.50/bait delivered at 500m transects (Consumables)
 - Sweating rack of \$15k to prepare baits (Equipment)
 - Aircraft at \$850/hr for petrol and pilot flying at 130km/h with refueling distance of 400km and transit speed of 250km/h (Travel).
 - Accommodation and food at \$210 per person per day (Consumables).
 - Aircraft at \$880/hr (\$850+\$30 hourly travel compensation labour rate) for aircraft, pilot and person from the closest airport (Travel).

- Estimate cost/unit and trips required
 - Discount, annualise and apply multipliers
Output 2: Cost/km² per action and trips required per action

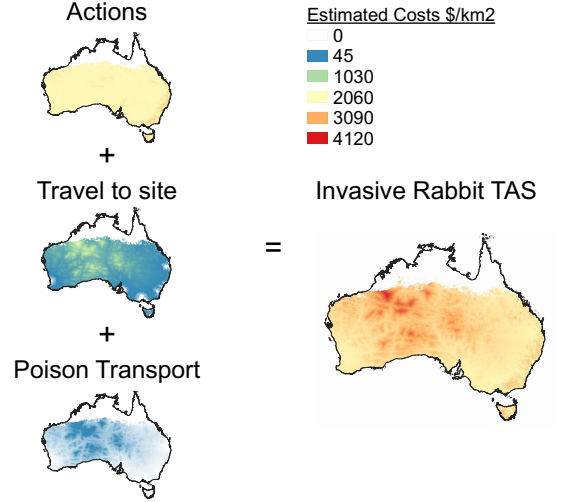
Example of invasive weed management TAS in a typical location

Action	Annualised NPV/km ²	Trips to site
Invasive weed management		
Arid/semi-arid - Moderate	\$ 24,300	77
Standardised Actions		
Pre-action office planning	\$ 66	0
Pre-action field planning	\$ 44	1
Post-action monitoring	\$ 44	1
Post-action evaluation	\$ 66	0
Grand Total	\$ 24,519	79



- Create national cost layers based on cost/km², threats and resistance + travel cost layers based on trips required and travel_distance
Output 3: Cost and travel layers by TAS

Example of invasive rabbit TAS



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 171
 172
 173

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.

174 **Defining Threat Abatement Strategies and actions**

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

187
188 For each strategy (detailed in Supp. Material 2) we defined the set of actions
189 involved throughout the planning, implementation, and evaluation process of
190 carrying out the strategy (adapted from (Iacona *et al.* 2018; Wenger *et al.*
191 2018; Carwardine *et al.* 2019). The implementation actions were specific to
192 each strategy, however we defined four standardised actions that covered
193 the planning and evaluation stages for all threat abatement strategies: pre-
194 action office planning, pre-action field planning, post-action monitoring and
195 post-action evaluation, and made general assumptions on the level of effort
196 required for each (Table 1).

197
198 We defined implementation actions generically, rather than attempting to
199 prescribe site-specific details of actions, which would require more detailed
200 local scale information. However, actions and their costs vary based on
201 spatial variables like terrain ruggedness, vegetation type and human
202 population density (see Supp. Material 3). All actions and strategies were
203 considered over a 30-year time period, and we assigned a frequency of re-
204 occurrence for each action (e.g. every "X" years over 30 years). We assumed

205 all actions are performed humanely, are undertaken by competent/skilled
 206 practitioners that follow best practices, and that landholders and stakeholders
 207 are willing to participate.

208

209 Table 1. Standardised planning and evaluation actions that are included in
 210 each Threat Abatement Strategy, the general description of each, and the
 211 assumed effort required for each action and finally, the cost components
 212 relevant to each action. These standardised actions are additional to the on-
 213 ground implementation efforts involved with each strategy. The assumptions
 214 regarding amount of effort used was based on expert knowledge and grey
 215 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

216

217

218 **Model the costs of actions and strategies**

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

224 **Generic Cost Model**

225 The total cost of a strategy within a management area is a function of its
226 spatial action costs, travel to site costs, and non-spatial costs (Equation 1),
227 with the action costs per km² calculated as the sum of the cost components
228 (Equation 2), and the travel to site cost per km² determined by the cost of the
229 return trips required for each action (Equation 3). To account for efficiencies
230 of scale we typically assumed actions were carried out over a management
231 area window of 100 km² (Table 2). The time horizon for each action, and
232 hence the cost models, is 30 years from 31st of December 2020 to 31st of
233 December 2050. We present all final cost estimates as an annualized cost of
234 the 30-year Present Value (PV) as at 31st of December 2020 accounting for
235 the frequency of actions and using a real discount rate of 4% and assuming
236 constant real costs into the future (see Supp. Material 3 for detail). The
237 description of model parameters is shown in Table 2.

238

$$\begin{aligned} 239 \quad TAS \text{ cost} = & \sum_{actions} (Action \text{ cost per km}^2 \times Action \text{ area}) \\ 240 & + \sum_{actions} (Travel \text{ to site cost per km}^2 \text{ per km distance} \\ 241 & \times Action \text{ area} \times Distance \text{ to site} \times 2) \\ 242 & + \sum_{actions} Non \text{ spatial costs} \end{aligned} \tag{1}$$

244 where

245 *Action cost per km²*

$$246 \quad = \sum_{L,T,C,E} \text{Annualised Cost components} \times \text{multipliers}$$

$$247 \quad \times (\text{management grid window size})^{-1}$$

248 (2)

249 and

250 *Travel to site cost per km² per km distance*

$$251 \quad = \text{Annualised Travel cost per hour} \times (\text{transit speed})^{-1}$$

$$252 \quad \times \text{Number of trips required} \times \text{multipliers}$$

$$253 \quad \times (\text{management grid window size})^{-1}$$

254 (3)

255
256 Table 2. Cost model parameter description from Eq. 1, 2 and 3.

Cost Model		
Equation	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.

257

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

265

$$266 \quad \ddot{a}_n = P \times \frac{1 - (1 + i)^{-n}}{i} \times (1 + i) \quad (4)$$

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

$$271 \quad \ddot{a}_{rk} = P \times \frac{1 - (1 + I)^{-rk}}{I} \times (1 + I) \quad (5)$$

272

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

276

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

289 Action and travel to site costs

290 Based on the model assumptions (see Supp. Material 3) and cost component
291 assumptions (see Supp. Material 4), we modelled the action costs within
292 each TAS at the relevant unit of measurement (Eq. 2) (see Supp. Material 5).
293 The relevant unit of measurement was typically per km², with management
294 actions that occurred along a waterway estimated per km of waterway length
295 (e.g. waterway fencing in Grazing Management TAS, Trout Barrier
296 Installation in Invasive fish management TAS), and management actions that
297 occurred for Hydrology TAS were estimated per in-stream structure (see
298 Supp. Material 2 & 5). We converted the PV costs for each action to an
299 equivalent annual value (see annuity calculation above). We then divided all
300 the costs by the standardised area to calculate a per unit of measurement
301 and applied the corresponding cost multipliers for the relevant cost
302 components. We estimated the Travel to site costs per km² per unit area (Eq.
303 3) driven by the mode of transport, travel distance and the number of trips

304 required (for detail see Supp. Material 3 for cost models see Supp. Material
305 5).

306 **Uncertainty in Costs**

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

318

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

323

324 **Cost estimate validation**

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

330

331 **Applying cost models to create spatial cost layers**

332 We created spatial layers at 1km² grid cells of the estimated costs of each
333 TAS over its potential management area across Australia, a summation of

334 the spatially variable action and travel to site costs, excluding any continent-
335 wide costs (Eq. 1 excluding non-spatial costs). All analyses were carried out
336 in ArcGIS version 10.4 (Redlands 2016).

337

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

343

344 To create the spatial cost layers for each action, we intersected the models
345 with spatial information that determined the cost estimates to capture the
346 spatial variation in efforts and costs over the potential management area. The
347 action cost layers reflect the approximate effort that is needed in each 1km²
348 grid cell, rather than prescribing detailed local scale actions. For each grid
349 cell, we summed of the number of annualized trips required for the
350 corresponding actions within a strategy, forming a spatial travel cost layer.
351 These travel cost layers differed by land, air, and poison transport (see Supp.
352 Material 3) that were calculated using a time to city map and the closest
353 airport (see Supp. Material 8).

354

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

361 **Results**

362 **Cost estimates for Threat Abatement Strategies**

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

367
368 More complex TASs required a higher number of actions (Table 3) due to
369 addressing multiple threats (e.g., Invasive Fish Management has Tilapia and
370 Trout across different river types) and multiple management requirements
371 (e.g., Grazing Management required liaison with landowners, land and
372 waterway fencing). There were 52 actions across the TASs, with some
373 actions that were common across the TASs. Policy was the most common
374 continent-wide action across 6 TASs, with other non-spatial actions including
375 refugia mapping in Map Refugia, liaison in Grazing Management, extent
376 mapping in Forestry Management, and Biosecurity. The remaining actions
377 were largely unique to each TAS, except for the ground shooting action that
378 applied to Invasive Predator Management, Large Invasive Herbivore
379 Management, Native Herbivore Management and Invasive Rabbit
380 Management, and the key habitat fencing action that applied to Native
381 Herbivore management and Grazing Management (see Supp. Material 9).

382
383 The annualised spatial cost estimates of Threat Abatement Strategies ranged
384 from \$25/km² (\$0.25/ha) for the cheapest strategy of Map Refugia to
385 \$0.88m/km² (\$8.8k/ha) for the most expensive strategy of Habitat Restoration
386 in Rainforests (Table 3, see Supp. Material 11 for more detail). Cost
387 estimates of TASs varied depending on the underlying action type and effort
388 required, influenced by characteristics like action suitability, environment
389 type, vegetation type and human population density (see Supp. Material 3).
390

391 The continent-wide costs were estimated for efforts that pertained across
392 Australia but were centrally carried out and independent of specific areas.
393 The highest non-spatial costs were estimated for Biosecurity was \$932m
394 (Table 3) that was largely adapted from the reported and recommended
395 spending from the Australian biosecurity enquiry (Craik, Palmer & Sheldrake
396 2017) (see Supp. Material 2). Map Refugia was costed non-spatially but
397 applied per species, and the total cost of this strategy when applied can be
398 multiplied by number of species that need this TAS (i.e. 10 species would
399 require $10 * \$13,899$).

400 Table 3. The range of annualised PV cost per unit estimated for each Threat Abatement Strategy summed across the management
 401 actions (“number of actions”), compared across all possible cost variation scenarios (“# cost variation scenarios”), where costs could
 402 vary by topographic resistance level (low, medium and high) and the spatially varying types and costs of management actions (i.e.
 403 aerial vs ground, vegetation type, intactness, etc.). We show the median, minimum, and maximum cost, and the mode, or the most
 404 common cost of each TAS across Australia (“most common across Australia”), determined from the highest proportion of projected
 405 threat management area at a national level. Hydrology management was costed per instream structure, invasive fish management
 406 and fencing for riparian zones in Grazing management was costed per km of waterway, and when not specified the remaining were
 407 costed per km² area. Any non-spatial estimated costs were also displayed separately as “continent-wide”, these were either entire
 408 Threat Abatement Strategies (i.e. Biosecurity) or the non-spatial component associated with the Threat Abatement Strategy (i.e.
 409 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	-	-	-

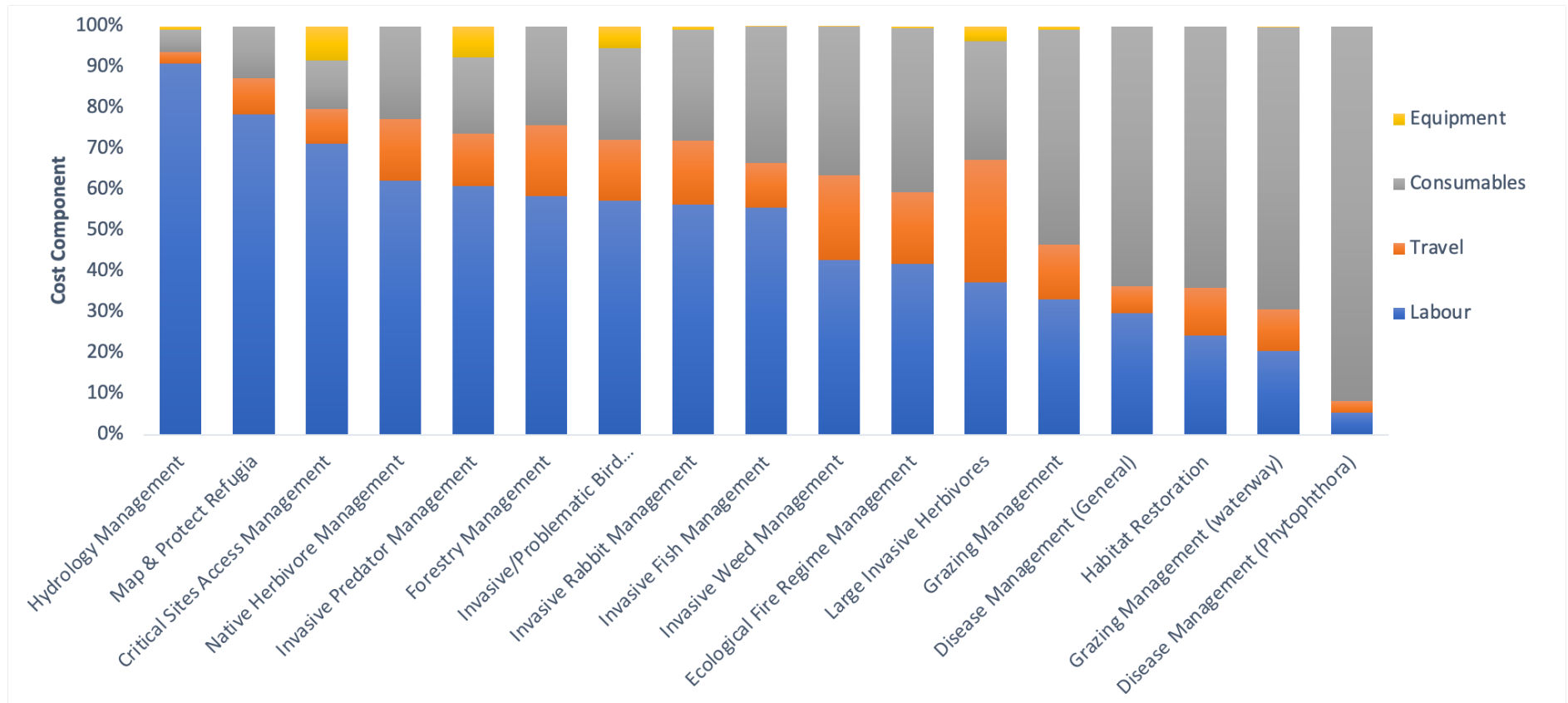
3	Disease Management – General	Per km ²	4	3	\$196	\$192	\$202	\$192
4	Disease Management – Phytophthora	Per km ²	6	3	\$139,948	\$139,877	\$140,089	\$139,877
5	Ecological Fire Regime Management	Per km ²	8	54	\$1,505	\$1,461	\$2,403	\$1,464
6	Forestry Management	Per km ²	6	3	\$334	\$328	\$346	\$328
		Continent- 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	-	-	-

410

411 **The proportion of budget for each cost component**

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



428

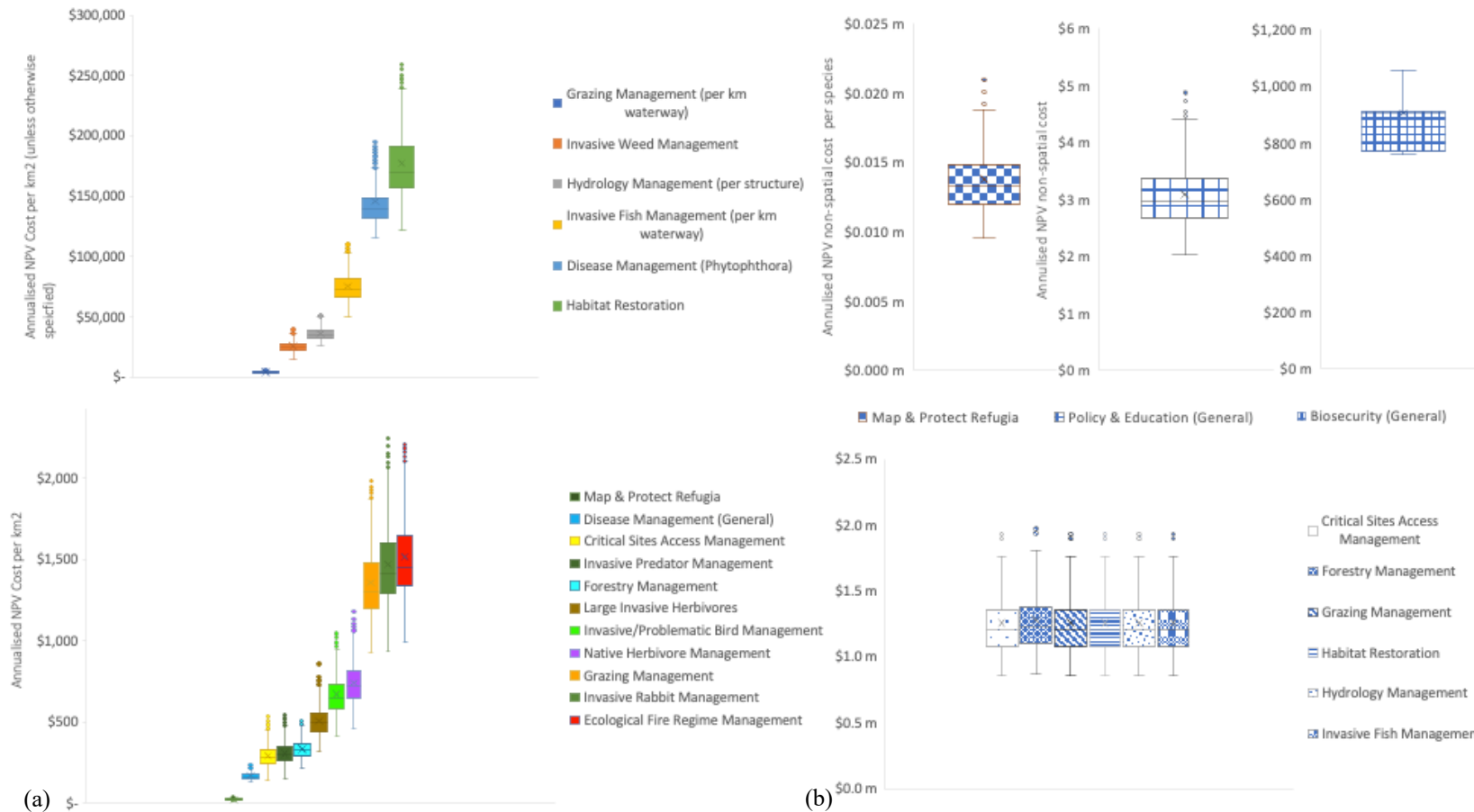
429 Figure 2. The cost component composition of each Threat Abatement Strategy displayed for the most common management option
 430 (determined from the highest proportion of projected threat management area at a national level), sorted by decreasing proportion of
 431 labour. We include spatial costs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

432 **Uncertainty in Cost estimates**

433 We estimated the impact of uncertainty for the TAS cost estimates by investigating how costs
434 changed over 17 global input variables and including an uncertainty multiplier (Fig. 3). The
435 overall relative distance of the lower and upper bound of TAS estimates from the baseline were
436 -34% and 55% (Supp. Material 6 Table 2). Labour intensive TASs demonstrated higher relative
437 uncertainty, as the global variables in the analysis mostly related to labour. The three most
438 uncertain TAS cost estimates were for Map Refugia (-62%, +116%), Critical Sites Access (-
439 51%,+84%) and Invasive Predator Management (-50%,+77%) (Supp. Material 6 Table 2).

440

441 Threat Abatement Strategies with higher cost/km² had a higher absolute variation in cost
442 estimates under uncertain global parameters. For example, the cost estimate for Habitat
443 Restoration ranged from \$122k to \$259k per km² (a difference of \$137k) with % variation from
444 the baseline (-31%,+46%), and Phytophthora Management had the second highest absolute
445 range in values from \$115k to \$195k per km² (a difference of \$80k) with relative distance from
446 baseline (-21%,+34%) (Fig. 3 and Supp. Material 6 Table 2)



447
 448 Figure 3 (a) and (b). An uncertainty analysis (N=1000) performed on discrete probability distributions of 18 global variables (Supp.
 449 Material 6) reveals the range of annualised NPV costs for each Threat Abatement Strategy (TAS), including: (a) spatially variable
 450 costs using the baseline (mode) cost value, determined from the highest proportion of projected threat management area at a
 451 national level), and b) the baseline total Australia-wide cost for strategies without spatial variation. Box plots show the median, the
 452 quartiles and interquartile ranges, with the mean marked with an X and the outliers with dots. The chart groupings were determined
 453 by the axis range of costs of each TAS.

454 **Spatial variation in the costs of actions**

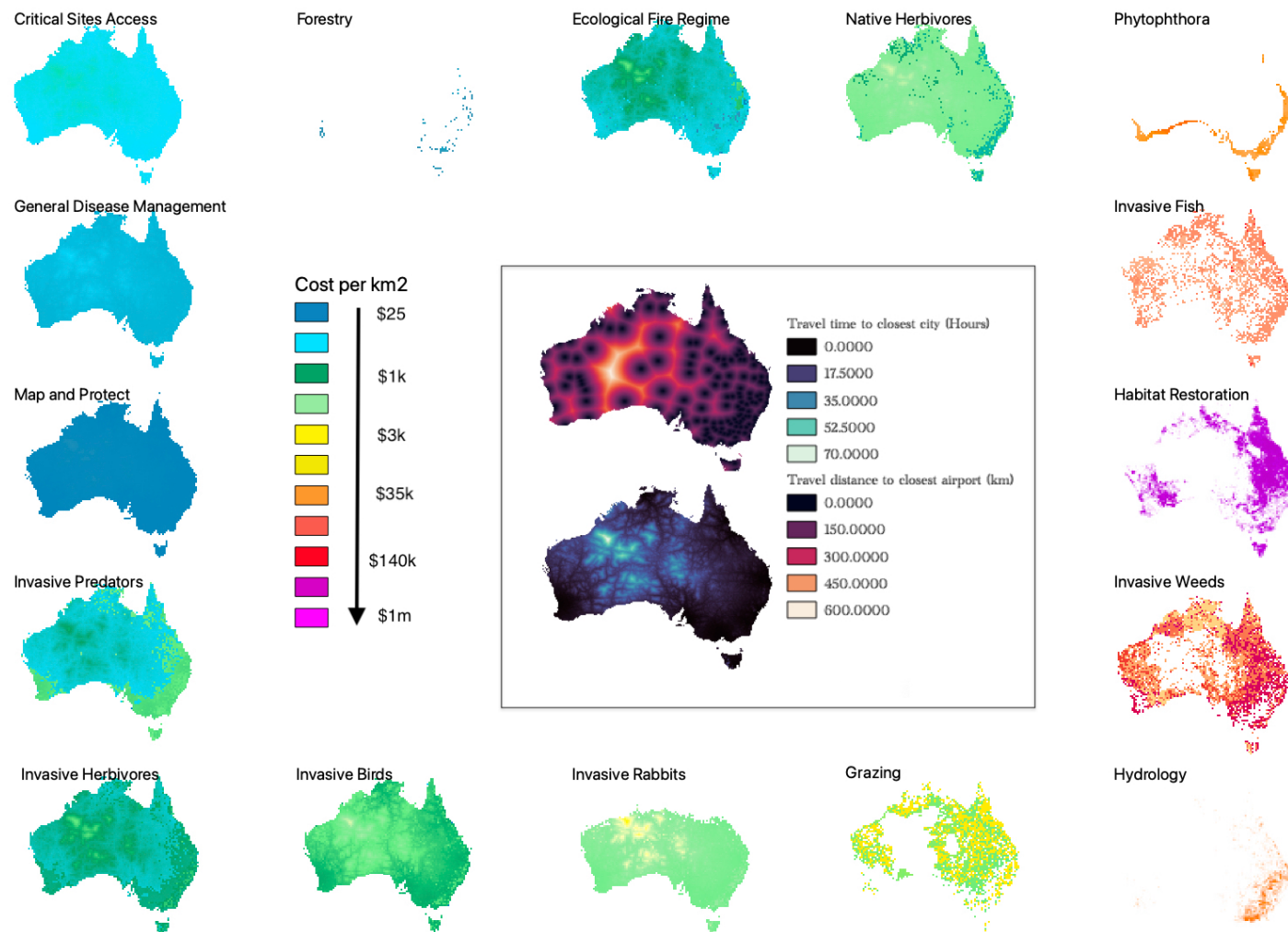
455 The cost of implementing a TAS at a location was a summation of the contributing action costs,
456 accounting for spatial variables at the location (vegetation type, terrain ruggedness, action
457 suitability, etc.) and including the travel to site cost (distance from the closest city or airport)
458 (see Supp. Material 3 for detail). Excluding continent-wide non-spatial actions and TASs
459 (Biosecurity and Policy and liaison only had continent-wide actions), we projected 16 TAS costs
460 across the threat range or Australia-wide if there was no specific threat range, with the cost
461 estimates including travel to site costs being \$24 - \$1.02m /km² (Fig. 4, see Supp. Material 10
462 for individual spatial cost maps).

463
464 The costs of Threat Abatement Strategies with fewer or less impactful spatial variables were
465 relatively consistent throughout Australia, such as Map Refugia (\$24 - \$72/km²) where the only
466 spatially variable action was ground surveys that varied by terrain ruggedness and travel to site
467 costs. In contrast Large Invasive herbivore management (\$0 - \$255/km²) included divergent
468 cost estimates for aerial and on-ground actions that were prescribed at a location depending
469 upon the suitability of each action, and Grazing management (\$0- \$7460/km²), which includes
470 different fencing costs at each location depending upon whether riparian zones fencing was
471 prescribed (Fig. 4).

472
473 TASs with higher management costs per unit were often associated with smaller management
474 areas or limited threat ranges. For example, Habitat Restoration has high costs (mode of
475 \$176k/km²) driven by the relatively large labour effort required for the regeneration of an area,
476 but only projected across a smaller management area (1.6% of Australia) (Fig. 4). Similarly,
477 Phytophthora management has a high cost/km² (mode of \$140k/km²) and a small range of
478 9.3% of Australia. In contrast, Ecological Fire Regimes and Invasive Rabbit management have
479 lower associated management costs (mode of \$1,464/km² and \$1,426/km²) but are projected
480 over a large extent of Australia (100% and 82%) (Fig. 4). The exception was Invasive Weed
481 Management that had a moderate to high cost per km² (mode of \$24.5k/km²) but was required
482 across a broad range of Australia (64%).

483
484 Travel costs were generally higher in the central-west of Australia, and for strategies with the
485 lower labour, consumable and equipment costs, the travel cost in these regions represented a

486 larger proportion of overall costs (TASs on the left half of Fig. 4). For TASs with action costs
487 that had low spatial variation the travel to site costs represented the source of overall cost
488 variation. For example, for Disease management and Invasive Rabbit management, expensive
489 pockets occur in remote areas due to travel to site and viral consumable costs increasing by up
490 to ~2 fold (Supp. Material 12). For higher cost/km² TASs, the travel to site costs were not as
491 visible due to the lower contributing proportions. For example, Invasive Weed Management had
492 a labour-intensive weeding action cost that out shadowed the “remoteness” travel to site cost,
493 with the spatial variation instead driven mostly by intactness and aridity (Supp. Material 12).



494
 495 Figure 4. The spatial cost layers for 16 spatially variable Threat Abatement Strategies that include the travel time to site (inset
 496 ground travel time and air travel distance). These were projected to the threat range, and Australia-wide if there was no determined
 497 threat range.

498 **Discussion**

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

515
516 Our models show that the cost of managing a threat to biodiversity across
517 Australia are likely to vary from \$24 - \$1.02m /km², depending on the TAS
518 required, the travel distance to site and the site characteristics. Our per km²
519 cost estimates were similar or higher than cost estimates from previous
520 analyses, which is likely due to the comprehensive inclusion of all cost
521 components in our cost models, including planning, travel to site and labour
522 on-costs (see Supp. Material 7).

523
524 Improving the use of consistent standardised financial reporting is important
525 for the effectiveness of the conservation sector (Cook *et al.* 2017; Iacona *et*
526 *al.* 2018). Current conservation investments largely occur without reliable
527 information on the costs of how the investment will be spent, and
528 conservation expenditure is typically not recorded in ways that can improve

529 current knowledge of conservation costs. The bottom-up costing model
530 structure we provide can inform, and be improved by, the collection of
531 additional cost information. By consistently recording the costs of
532 individualised components of threat abatement activities, it becomes possible
533 to understand the make-up of a total strategy cost and leverage these
534 estimate costs elsewhere.

535

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

549 **Conclusion**

550 Every year billions of dollars are spent on conservation management
551 worldwide (Waldron *et al.* 2013). This expenditure largely occurs without a
552 priori estimates of conservation management costs across broad scales and
553 is not recorded in ways that can inform future conservation management
554 budgets and analyses comparing the relative cost-effectiveness of actions.
555 Our work provides new guidance on consistent approaches for estimating,
556 recording, and informing cost estimates that can be built on or adapted with
557 additional information from local to national scales. We aim to enable the
558 conservation industry to match other sectors in articulating the investment
559 required to achieve its sought goals. By continuing to progress knowledge on

560 the costs of managing threats to biodiversity, more strategic revenue raising
561 and improved use of available resources to achieve conservation outcomes
562 are possible.

563 **Author Contributions**

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

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571 expert input during two online workshops and follow-up discussions in 2020-
572 2021, involving the co-authors and additional participants (see Supp. Material
573 13).

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