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The cost of recovering Australia's threatened species

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April E. Reside[1,2], Josie Carwardine[3], Michelle Ward[1,2,4], Chuanji Yong[1,2,5], Ruben Venegas Li[1,2], Andrew Rogers[1,2], Brendan A. Wintle[6], Jennifer Silcock[1,2], John Woinarski[7], Mark Lintermans[8,9], Gary Taylor[10], Anna F. V. Pintor[11] & James E. M. Watson[1,2]

Accounting for the cost of repairing the degradation of Earth's biosphere is critical to guide conservation and sustainable development decisions. Yet the costs of repairing nature through the recovery of a continental suite of threatened species across their range have never been calculated. We estimated the cost of in situ recovery of nationally listed terrestrial and freshwater threatened species (n = 1,657) across the megadiverse continent of Australia by combining the spatially explicit costs of all strategies required to address species-specific threats. Individual species recovery required up to 12 strategies (mean 2.3), predominantly habitat retention and restoration, and the management of fire and invasive species. The estimated costs of maximizing threatened species recovery across Australia varied from AU$0–$12,626 per ha, depending on the species, threats and context of each location. The total cost of implementing all strategies to recover threatened species in their in situ habitat across Australia summed to an estimated AU$583 billion per year, with management of invasive weeds making up 81% of the total cost. This figure, at 25% of Australia's GDP, does not represent a realistic biodiversity conservation budget, but needs to be accounted for when weighing up decisions that lead to further costly degradation of Australia's natural heritage.

Halting biodiversity loss and achieving the recovery of threatened species are central goals of international conservation[1] and a core tenet (Goal A and Target 4) of the recently ratified Kunming–Montreal Global Biodiversity Framework[2]. The repair of historic decline is also required to build resilience to ongoing and future threats such as climate change[3]. Yet robust estimates of the budget needed to achieve the recovery of threatened species on continental scales are unavailable, with recent costing efforts focusing on protected area expansion[4] or based on broad assumptions[4–6]. Cost estimates for the reparation of species decline are needed to understand the scale of biodiversity impacts that have occurred, and to recognize the true cost of ongoing biosphere degradation and loss. Importantly, this information can enable effective future decision-making that contrasts the costs of preventing further loss with those of restoring nature and recovering threatened species.

Costing the recovery of threatened species requires accounting for individual species' current and likely distributions, the threats and recovery actions needed, and robust estimates of the necessary extent

[1]School of the Environment, University of Queensland, Brisbane, Queensland, Australia. [2]Centre for Biodiversity and Conservation Science, The University of Queensland, Brisbane, Queensland, Australia. [3]CSIRO, Land and Water, Brisbane, Queensland, Australia. [4]Centre for Planetary Health and Food Security, School of Environment and Science, Griffith University, Nathan, Queensland, Australia. [5]School of Agriculture and Environment, University of Western Australia, Perth, Western Australia, Australia. [6]Melbourne Biodiversity Institute, School of Agriculture, Food and Ecosystem Sciences, University of Melbourne, Victoria, Australia. [7]Research Institute for the Environment and Livelihoods, Charles Darwin University, Darwin, Northern Territory, Australia. [8]Centre for Applied Water Science, Institute for Applied Ecology, University of Canberra, Canberra, Australia. [9]Fish Fondler Pty Ltd, Bungendore, New South Wales, Australia. [10]Australian Centre for Evolutionary Biology and Biodiversity, and School of Biological Sciences, University of Adelaide, Adelaide, South Australia, Australia. [11]Australian Institute of Tropical Health and Medicine, James Cook University, Cairns, Queensland, Australia. e-mail: a.reside@uq.edu.au

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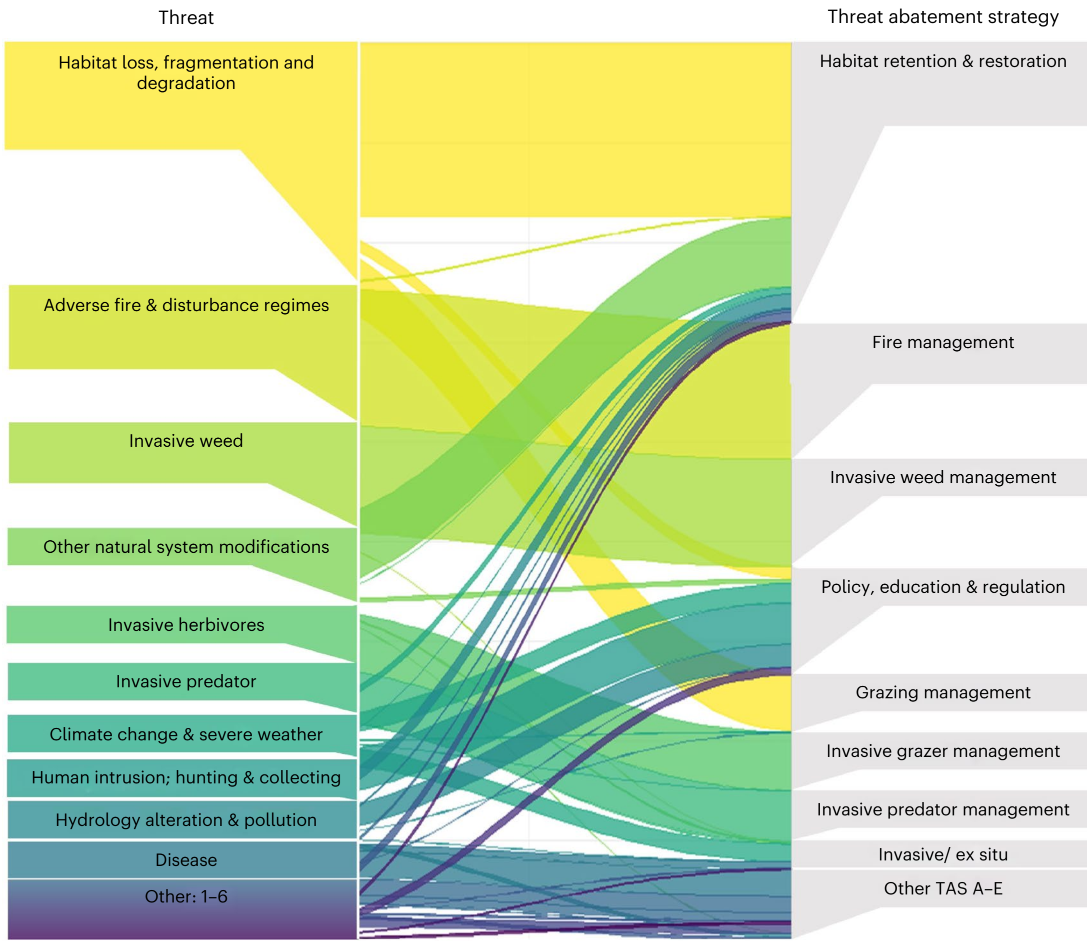

Fig. 1 | Threats and TAS for Australia's threatened species. The number of threatened species impacted by threat categories[10] (left) and requiring TAS[13] assigned to address each threat (right). Horizontal bar heights indicate the relative number of species in each category. Threats 'Other: 1–6' are problematic native species, invasive animals (not otherwise stated), invasive fish, biological resource use (fisheries, forestry), small/restricted population, and invasive/problematic birds and bees. TAS in the 'Other: A–E' category are disease management and biosecurity, native herbivore management, invasive/problematic bird and bee management, invasive fish management, and aquatic connectivity. Note that the strategy 'intensive/ex situ' was not considered further in analyses, and non-spatial policy-based TAS are not included in this figure but are detailed in Supplementary Tables 1 and 2, and in ref. 13.

of each action and the financial resources required for their implementation across time and space[7]. Costing the recovery on a species and location basis helps to quantify the likely costs of future land-use decisions (at any scale) that will lead to species decline, where repair and recovery efforts will be necessary to meet national and international biodiversity conservation obligations[1,2,8].

Here we provide a fine-scale assessment of the cost of recovering extant threatened species in their habitats across the Australian continent, a nation with one of the highest contemporary species losses[9]. We synthesized information on each of the 1,657 threatened Australian terrestrial and freshwater species as of 31 December 2020[10], and the best methods for abating threats to achieve each species' recovery. Our costed actions focused on the on-ground management of current threats. We assumed that recovery of each species would be enabled through the effective management of threats across the distribution in which each species was mapped as 'known', 'likely' and 'may occur'[11,12]. We assumed that this required the retention of habitat and management of all threats to the species across its range, and that the management of threats would substantially increase the probability that the species can occupy the area in which it had been mapped to 'may occur'. However, we recognize that even if all required management is implemented, the recovery of some species is unrealistic because parts of their habitat have been transformed beyond the point of feasible restoration, and some threats cannot, with currently available methodologies, be feasibly abated in all areas (for example, invasive fish). We did not include the costs of land acquisition, lost opportunities or ex situ actions such as captive breeding, seed propagation or translocations. However, we recognize that these responses are needed for some species, especially as future threats amplify current stresses.

We applied 17 established, fine-scale threat abatement strategies (TAS) that were previously developed for costing threatened species recovery[13] to calculate the full scale of resourcing required to achieve this recovery goal across continental Australia (Fig. 1 and Supplementary Table 1). Each threat abatement strategy included standardized costs of pre-action planning, implementing the actions, post-action monitoring and evaluation; and the expected costs of labour, travel, consumables and equipment[13]. Strategies were only costed once for each location, regardless of the number of threatened species in the location requiring that strategy (that is, not double costed). Strategies were generalized rather than prescriptive at the site scale because implementation needs to be planned at local scales in partnership with local landholders, Indigenous custodians and the broader community[14]. Following ref. 13, we present estimated costs as an annualized figure based on a 30-year time horizon and a 4% discount rate. We also estimate some co-benefits of implementing these strategies: jobs created, extent of ecosystems restored and carbon sequestered.

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Results

Assigning a TAS to each species impacted by each threat revealed complexities and challenges associated with managing many of the threats facing threatened species (Fig. 1). While in some cases there was a straightforward matching of threat (for example, adverse fire regimes) to TAS (fire management), other threats required a nuanced approach. Notably, habitat restoration was required to address loss of habitat area and quality due to agriculture, forestry, mining, urban development, roads and climate change. It was also the best strategy to address other, often related, threats such as salinization, erosion, water quality, hydrology alteration and in some cases, diseases of freshwater species (Supplementary Tables 1–3). As a result, habitat retention and restoration was the most frequently required TAS (*n* = 1,095 species; Fig. 1), followed by management of fire (*n* = 676) and weed control (*n* = 528) (Supplementary Tables 1 and 2). When all the 'policy, education and regulation' TAS were combined, they made up the fourth most commonly assigned strategy (Supplementary Table 2).

Individual threatened species needed up to 12 TAS, but the largest number of species (*n* = 669) required only one (Fig. 2) and the mean number of strategies is 2.3. There was strong taxonomic bias with the number of strategies required: over 50% of plant species were assigned only one strategy, compared with 5% of fish and 11% of birds.

Calculating the cost per area of the TAS across Australia highlighted the difference in cost effectiveness among strategies. TAS that were required broadly across the continent, such as reinstating ecological fire management and controlling invasive predators, large herbivores and rabbits had a low cost per area (Fig. 3). Others had similar costs per area but were required at a smaller extent: restricting (human) access to critical sites, managing problematic native herbivores and problematic birds, and managing livestock grazing. In contrast, habitat restoration had a substantially greater cost per area than all other strategies, consistent with other studies highlighting the challenge and resource intensiveness of habitat restoration[15,16]. Here we only costed habitat restoration over a relatively small area (Supplementary Fig. 1), limited to areas not under intensive land use, to increase the feasibility of its implementation. While the full objective of this strategy was to retain and restore habitat (Supplementary Table 1), the 'retention' aspect was not costed because (1) estimating the costs involved in avoided loss of threatened species habitat, such as opportunity costs, were out of scope; and (2) in theory, there are legal protections for threatened species habitat[13,17]. Controlling invasive weeds had the second highest cost per area (Fig. 3 and Extended Data Fig. 1). TAS that were required by only freshwater threatened species, aquatic connectivity and managing invasive fish, had relatively high cost per area but were only required in small areas (Fig. 3).

The combined cost of implementing all the TAS required to recover species across Australia was AU$583 billion per year (Fig. 4). As per uncertainty estimates in ref. 13, the true costs may vary by −34% and 55% (ref. 13), and accuracy is likely to increase with improved data on actions and their costs. The most expensive overall TAS (managing invasive weeds) cost more than all other strategies combined, comprising 81% of the total cost due to its labour intensity and the extensive area required (Fig. 4). Compared with the other TAS, costing for managing invasive weeds was also impaired by the lack of specificity. For example, much of the information on the threat that weeds posed to threatened species lacked the species name of the weed (Supplementary Table 2); and, when the species was known, accurate distribution maps were missing for many[13]. Furthermore, weed control is specific to the type of weed (for example, herbaceous or woody) and the surrounding vegetation and land use. Future work will require more detailed site- and weed-species costings. Finally, implementation of our other TAS such as managing livestock grazing, fire, invasive herbivores and biosecurity required for disease management can assist in weed management. If we considered the total cost of TAS without 'managing invasive weeds', the total cost was $111 billion per year (that is, a decrease of 81%). Removing the 'managing invasive weeds' TAS had a greater reduction in overall cost than removing the most expensive places (81% versus 22% reductions for removing the 25% most costly cells; Extended Data Figs. 1 and 2).

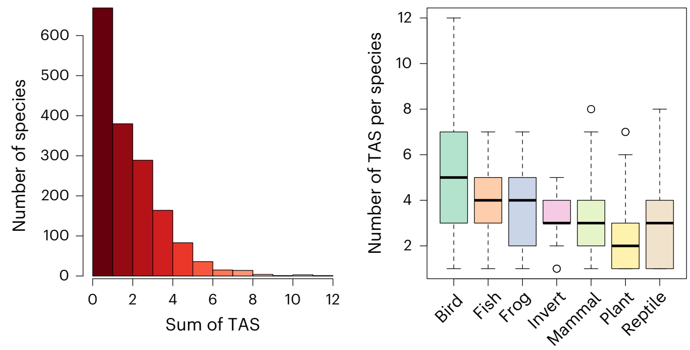

Fig. 2 | The number of TAS required by individual species and across taxonomic groups. Left: the number of species (*y* axis) requiring each sum of TAS (*x* axis), out of a total of 17 TAS (Supplementary Table 1). Right: the number of TAS required per species compared across taxonomic groups. In boxplots, the centre line indicates the median, the box limits indicate the first and third quartiles, and the whiskers show the minimum (1) and maximum (up to 12) TAS.

If our recovery actions were only implemented for those species most at risk of extinction, that is, those listed as critically endangered (*n* = 234, 14% of threatened species), the costs would be reduced to 30% of the overall total (Extended Data Fig. 3 and Supplementary Fig. 2). Implementing TAS for critically endangered and endangered species (55% of threatened species, leaving out those listed as vulnerable) was 96% of the total cost (Supplementary Fig. 2). These figures (for critically endangered and endangered species, *n* = 913) without the 'managing invasive weeds' TAS would be 9% and 16% of the overall total respectively. The largest proportional differences across individual TAS for only implementing critically endangered species were for the 'disease management' and 'ecological fire management' TAS, where costs were substantially increased if also costed for endangered species (which make up 41% of threatened species; Supplementary Figs. 2 and 3). Critically endangered species required TAS over less than half the continent, missing most of western and north-western Australia; but when examined together with endangered species, TAS are required almost as extensively as when considering all threatened species (including vulnerable) (Extended Data Fig. 3).

We showed that partial implementation of TAS by iteratively removing TAS starting with the most expensive had a sharp impact on the number of species that would not have all their threats managed (Supplementary Fig. 4). Not funding the three most expensive TAS (managing invasive weeds, managing invasive fish and habitat restoration) will lead to only 22% of species receiving management of all their threats.

Investigating the total costs of the TAS where they were required to benefit all threatened species highlighted the spatial variation in costs from AU$0–$12.6 million per km^2, or AU$12,626 per ha (Fig. 5). Substantial variations in total costs across Australia were driven by spatially restricted, high-cost-per-area TAS such as habitat restoration; areas of high-cost invasive weed management; and by spatial variation in the numbers of threatened species (Fig. 5, Extended Data Figs. 1 and 2, and Supplementary Fig. 1). Areas with a potentially high return on investment for threat management may occur where there are many threatened species and management costs are comparatively low, such as across northern Australia, particularly tropical Northern Territory and north-west Western Australia (Fig. 5). Region-specific approaches will be particularly needed in areas of high overall cost largely driven by weed management (Extended Data Figs. 1 and 2 and Supplementary Fig. 1) yet very few threatened species occur such as inland Queensland

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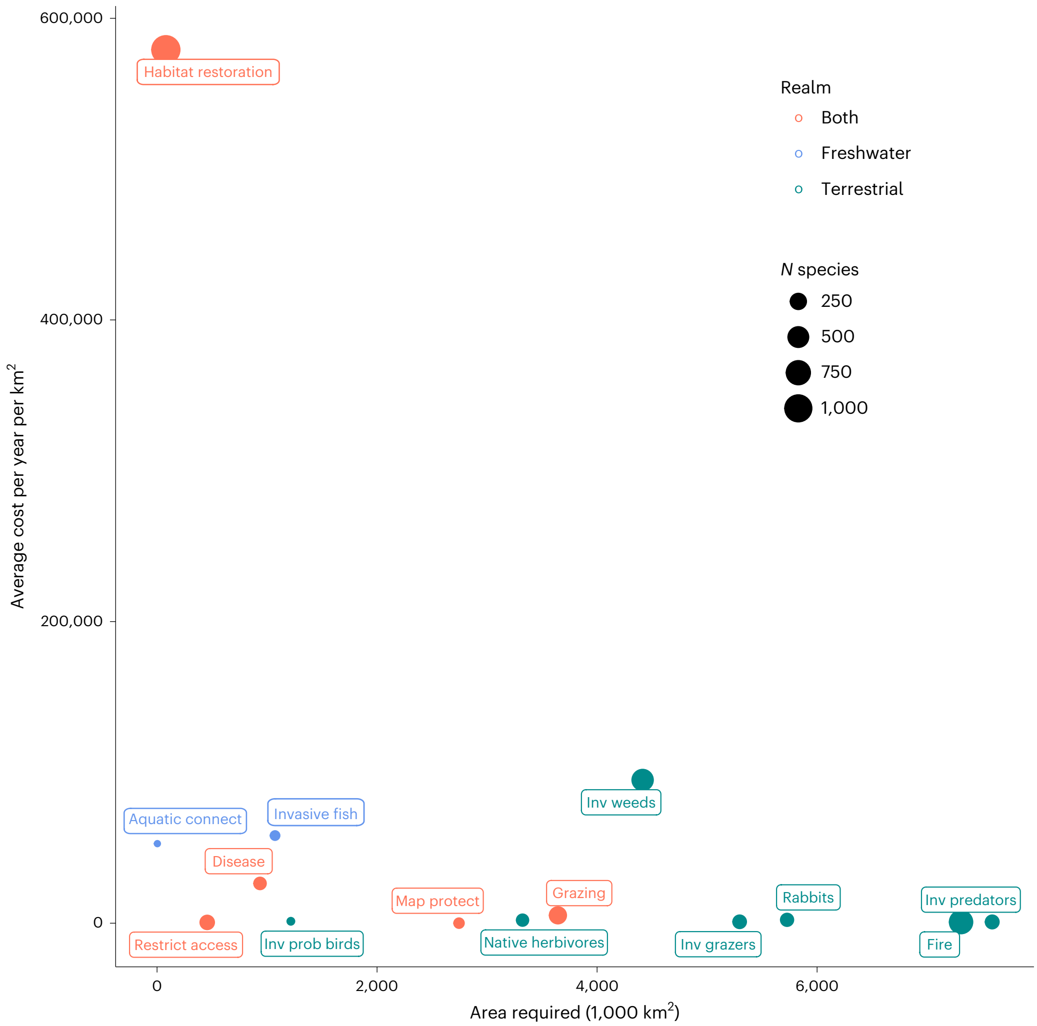

Fig. 3 | Average cost per year per km^2 of each of the spatially costed TAS compared with the total area requiring the strategy. Labels in blue indicate strategies for freshwater species, green for terrestrial species and orange for both terrestrial and freshwater species. The size of each point indicates the relative number of species each strategy was costed for. For context, total land area of Australia is 7,688,287 km^2. The codes are outlined in Supplementary Table 1. Inv, invasive.

and New South Wales (Fig. 5). Australia's east and south-west coastal regions contain the greatest number of threatened species, the highest estimated threat abatement costs and the highest human density. These areas have also experienced the most habitat modification, amplifying the importance of threat management and the challenge it presents in these areas.

Actions that restore threatened species and their habitat increase benefits to people through connections with nature, improved soil stability, decreased run-off and cleaner waterways and oceans[18]. Restored habitat areas would also add to the retention of important ecosystems across Australia. Currently, 27 of Australia's 89 biogeographic regions have less than 10% of their area protected under conservation tenure[19]. Efforts to restore vegetation for threatened species would contribute to the conservation of more than 29,000 km^2 of nationally listed threatened ecological communities, and 77,000 km^2 of habitat would be restored outside protected areas in those bioregions that are under-represented (<10% protected) (Supplementary Table 11). In addition to increases in the extent of threatened species habitat, areas of extant habitat would be improved through management of threats such as adverse fire regimes. Habitat restoration would also be of benefit to most of the ~340,000 non-threatened terrestrial and freshwater species and ecosystems across Australia, reducing the likelihood of these becoming threatened in the future. The cumulative

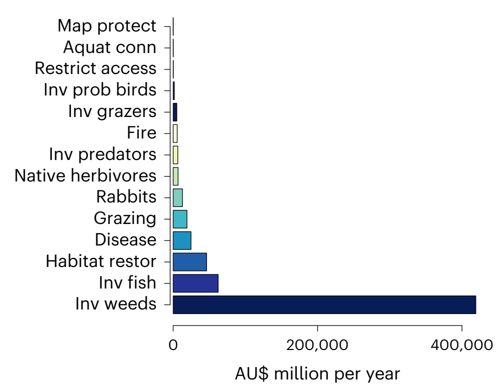

Fig. 4 | TAS costed spatially (excluding policy, regulation and education strategies) and their relative total cost per year across all species affected by that threat. Sequentially, the full titles of the strategies are Map and protect refugia, Aquatic connectivity, Restrict access to critical sites, Invasive/problematic birds and bee management, Invasive grazer management, Ecological fire regime management, Invasive predator management, Native herbivore management, Invasive rabbit management, Grazing management, Disease management, Habitat restoration and retention, Invasive fish management, and Invasive weed management (Supplementary Table 1).

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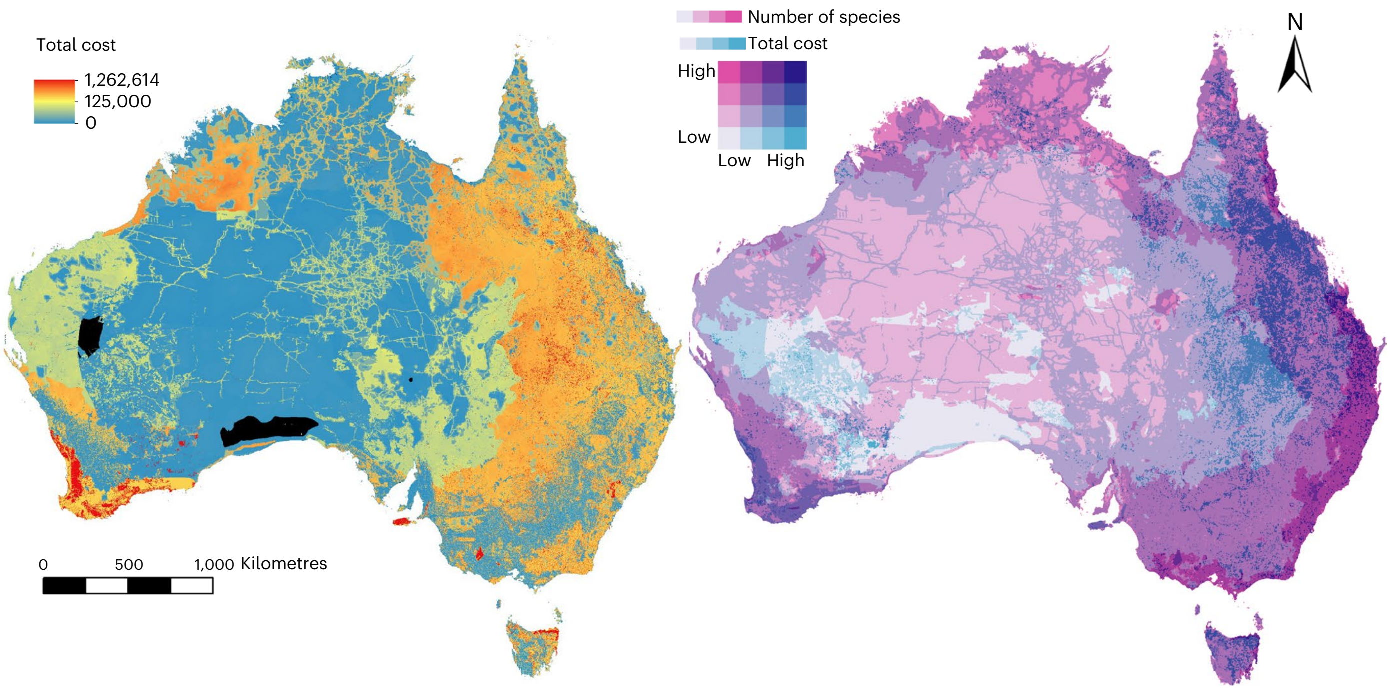

Fig. 5 | Spatial variation in the cost of all TAS and threatened species ranges. Left: costs of implementing all TAS per 1 × 1 km per year across their relevant extent in Australia (legend shows amount in Australian dollars); black indicates no cost, because no threatened species occur there; colours represent costs. Right: implementation costs compared with the number of threatened species occurring across Australia. Paler areas denote lower cost and fewer species, dark purple denotes high cost and a greater number of species.

impact of multiple threats has been implicated in ecosystem collapse[20], hence improved threat management is likely to increase ecosystem health and resilience in the face of climate change. At maturity, the restored vegetation would sequester at least 10.9 million tonnes of CO_2 in above- and belowground biomass (Supplementary Table 12), worth AU$331 million under the carbon price at time of writing[21].

While the co-existence of people and threatened species can create potential conflicts, the abatement of threats to enable species recovery can provide substantial benefits beyond threatened species[9]. We estimated that the implementation of TAS to benefit threatened species would involve 954,275 full-time jobs ongoing over 30 years (9.6% of Australia's current full-time workforce[22]) (Supplementary Table 13). This includes jobs in remote and rural Australia (Fig. 5), including economically disadvantaged regions, and could strengthen opportunities and funding for Indigenous-led management and ranger groups[23]. Many of the TAS are already a priority for sectors outside conservation; for example, the agricultural industry currently carries much of the burden of controlling invasive species such as foxes, cats, pigs, rabbits, goats, starlings and weeds across Australia[24].

Discussion

The AU$583 billion annual costs of our TAS for species recovery equates to ~25% of Australia's 2022 Gross Domestic Product[25]. Current spending on threatened species management by Australian, State and Territory Governments represents only ~0.02% of our estimate of required management cost[6]. This AU$583 billion is more than double the estimated current expenditure on nature conservation globally (up to US$143 billion)[26] and more than half the target funding proposed by the Convention on Biodiversity[2] to halt biodiversity loss worldwide. Furthermore, the list of species that qualify as threatened is growing as more information on species and their status comes to light[27] and severe stochastic events (for example, megafires) stimulate status revisions[28]. We did not include the costs of species-specific emergency actions (including ex situ conservation such as translocation, seed and gene banking or captive breeding)[29,30], industry and community consultation, specific climate change-adapted management or monitoring[30]. Our analyses also omit the costs and relative value of research, policy and practice change to address the underlying drivers of threats causing biodiversity declines. Improved information, including at local scales, could enable more accurate and nuanced cost estimates. However, our analysis shows the range of possible investments in on-ground threat abatement for species recovery across Australia and the value of decisions that avoid further biodiversity declines.

Decisions about how, when and where to implement TAS require collaboration with landowners, managers and traditional custodians to identify opportunities and trade-offs and negotiate shared aspirations and benefits. Threatened species and their threats occur broadly across Australia; therefore, opportunities for improving threatened species recovery occur across most of the continent. This is probably the case for most countries, given the degree of degradation across the planet[31] and the pervasive nature of climate change and spread of invasive species and disease[32,33]. Many TAS in Australia and probably elsewhere could benefit threatened species over large areas in synergy with current land uses and at a relatively low cost per km^2. For example, resources could be strengthened for managing fire and invasive species in areas of native vegetation used for livestock grazing, which constitutes 82% of Australia's agricultural land[24,34]. The management of fire, and invasive predators, herbivores and weeds is beneficial for multiple sectors across Australia, with implementation already occurring through a range of government and non-government actors, including the agricultural sector, Indigenous groups, non-government organizations and landholders[34].

Our analyses indicate that, to meet the target set for species recovery in the Global Biodiversity Framework[4], threat abatement activities would probably be required across vast regions. This highlights the importance of a collaborative approach that includes benefits and opportunities in a nature-based economy and society. For example, First Nations Australians have rights and responsibilities over substantial portions of the Australian continent, including threatened species habitat[35], and play vital roles in threatened species recovery[36].

We were unable to incorporate Indigenous cultural values into our analysis, but we acknowledge that species and their relationships with Country and people are complex, interconnected and vary across First Nations groups. Strengthening the inclusion of cultural values, engagement protocols and First Nations leadership opportunities are critical for threatened species recovery[37]. In particular, culturally important species and places require a commitment to culturally appropriate decision-making and management led by traditional custodians, and broader recognition of cultural values and shared benefits[38].

We estimated costs using a generalized approach and recognize that the costs and benefits of threat abatement at any location will vary over space and time due to local-scale complexities such as species–threat–action interactions, economies of scale, cost sharing opportunities and trade-offs with other land use values and aspirations. The costs of some threats may reduce over time: for example, effective weed control may drive local extirpations of weeds such that subsequent costs are reduced; effective rabbit control could reduce the need for invasive predator control particularly in arid regions[39]; and habitat restoration could reduce the impact of aggressive native birds on threatened bird species[40]. In other cases, threats are likely to require greater on-ground effort, particularly as new invasive species arrive and spread[41,42] and the impacts of climate change intensify[43]. Shifting production and development priorities could see land use intensification in new areas, compounding existing and emerging threats[44]. Notably, full species recovery is unlikely for many species due to legacy impacts and climate change[33], and realistic recovery targets require a more nuanced approach. The dynamic nature and interactions between human society, species populations, ecosystems and threats, particularly under climate change, necessitate ongoing evaluation of management actions.

It is unrealistic to expect governments to spend 25% of GDP for species recovery and to manage solely for threatened species outcomes across most of Australia, given current trade-offs between species needs and human activities and values[31,45]. However, our approach can be utilized at any scale to inform current and future biodiversity recovery, from single species recovery plans to bioregional and state biodiversity planning. Accounting for the full cost of biodiversity impacts and degradation has not been previously possible due to a lack of available costing tools, which has probably contributed to the chronic underestimation of biodiversity impacts and recovery costs[6]. The cost estimation approach we provide can inform the consequences of planning decisions that will degrade nature, by estimating post-activity repair and restoration, which is critical for guiding adequate payments into offset funding pools to redress planned biodiversity impacts[8,46].

Biodiversity loss is a material financial risk at all levels of economic activity[47,48], which has been recognized by the Australian Government[49]. The considerable cost of recovering threatened species across a large continent indicates that substantial resourcing, along with the avoidance of further impacts, are needed to address the biodiversity crisis. Timely action results in lower costs, better outcomes[5] and a lower legacy burden bequeathed to future generations. Ultimately, reducing the risks of biodiversity loss requires a cross-sectoral and transformational approach that improves the compatibility between the interconnected needs of nature and humanity[50].

Methods

Overview

The present study was the culmination of a multipart collaborative project where the first stage compiled all threats for terrestrial and freshwater threatened species across Australia[10] (see 'Threatened species, their threats and TAS'); the second stage developed actions and costed TAS to address the threats[13] ('Threatened species, their threats and TAS' and 'Cost models'); and the third stage (the present study) assigned TAS to each combination of species–threat ('Assigning TAS to species and locations'), mapped out the distributions of each species requiring each strategy, calculated the total cost of implementing each strategy where it was required for each impacted species, and calculated the total cost of all TAS (Supplementary Fig. 1). We provide the full database of species, their threats and the assigned TAS in Supplementary Table 2. Finally, we show some of the co-benefits that are likely to result from the implementation of our TAS including employment, protection of vegetation communities and carbon sequestration ('Estimating co-benefits').

We defined recovery as full reparation of the species occupancy across the areas in which it is mapped as known, likely and may occur[11,12]. Therefore, we assumed that to achieve this goal, all threats impacting on a species would need to be managed across all areas in which the species does or could occur (suitable habitat) that also contain a known threat[10]. It is important to note that for many species, the total extent of the mapped 'known', 'likely' and 'may occur' distributions is a very small proportion of their pre-European range[51,52].

Threatened species, their threats and TAS

We included 1,657 extant threatened species listed nationally as of 31 December 2020[17], occurring in terrestrial and freshwater environments, on mainland Australia and its continental islands (Supplementary Table 5). Listed entities[17] include species, subspecies and populations, referred to here as 'species' for consistency with international literature. Species range data were 1 ha grids indicating the 'known to occur', 'likely to occur' or 'may occur' distributions of each species[12]. We used species threat data that were compiled from existing sources (such as the Australian Government's Species Profiles and Threats Database[53], individual species Recovery Plans, Conservation Advice, Conservation Action Plans and state databases) and verified by experts across Australia for the first stage of this broader project, detailed in ref. 10. Threat abatement strategies[13] were generated by reviewing each threat and management actions recommended by individual species recovery plans, conservation advice, threat abatement plans and peer-reviewed and grey literature, and through discussion with species and management experts (detailed in Supplementary Table 3), to find the most useful balance between generality (applicable to more species or geographic areas) and specificity (relevant to the impacted species). Through collating all the species and their threats across Australia (first project stage), it became evident that on-ground management was the overwhelmingly dominant approach required to address the vast majority of threats; in most cases on-ground management was required by multiple species in each area and probably required by all non-threatened biodiversity also present. Creating new protected areas was not required for most threats (for example, managing invasives, fire), providing that habitat clearing ceased. Intensive ex situ actions such as captive breeding were not required by many species, but were also not economically feasible or cost-effective when compared with on-ground management. The objectives for each TAS are shown in Supplementary Table 1.

Where available, we used spatial models for the extents of threats generated by ref. 54 (Supplementary Table 7). Where threat distribution data were required, we clipped the spatial extent of cost models to both the extent of the threat and the combined extent of the distributions of species that required the TAS. If management would be required to prevent a threat occurring outside its current location, the TAS was costed wherever the species that was impacted by this threat occurred. For example, disease control and prevention need to occur both where the disease occurs and where the disease does not yet occur but the susceptible species does. Therefore, the components of the disease management TAS pertaining to biosecurity to prevent disease spread were costed in areas where the susceptible species occurred (Supplementary Table 1). In cases where there were specific threats listed for a small number of species (for example, 'Lack of pollinators' $n = 5$) that we could not find any further detail about or the location of the threat, we assigned either the uncosted

TAS 'Intensive/ex situ' or 'habitat restoration' where appropriate (Supplementary Table 2). In the case of habitat restoration, we were unable to map the full extent of where species' habitat was degraded, because this would be a species-by-species definition (for example, 'degraded' for an arboreal species such as koala *Phascolarctus cinereus* is likely to be a different definition from 'degraded' for a granivorous bird requiring seeding grasses such as black-throated finch *Poephila cincta cincta*). Furthermore, restoration may be passive (removing existing land use such as grazing) in areas with some levels of degradation. Therefore, we costed habitat restoration using a 'cleared and potentially restorable' spatial layer (detailed below) that excluded land that is unlikely to be available for restoration, including irrigated production, intensive use, rural residential areas and water[55]. Habitat retention, per se, was not explicitly costed but remains a key assumption throughout, because threatened species recovery is unlikely if ongoing habitat loss occurs. Where more than one species occurred that required the same TAS, the TAS was only costed once.

In addition to all the on-ground action costs, we added a standardized annual cost allocation for policy, planning, development of educational resources and compliance, to be conducted nationally for each TAS. All detail of cost model development is outlined in ref. 13.

We accounted neither for the costs of the following emergency actions required to prevent an extinction event: intensive ex situ conservation[29,56,57], knowledge gathering for understanding the efficacy of the actions such as monitoring and research[30], and socioecological factors such as the social engagement that would be needed to achieve feasibility and uptake[50], nor for the opportunity costs arising from species conservation and habitat recovery. Furthermore, conservation will necessarily require adaptation to account for the increased pressure of anthropogenic climate change[58], and it was out of scope to apply TAS for threats which could occur in the future. Given the widespread nature of many of our TAS, it is likely that some actions will already be costed for species' future distribution extents. We assumed that the actions will be beneficial or at least not harmful for co-occurring non-threatened species and ecosystems. We acknowledge that all actions need to be undertaken ethically and effectively, with appropriate Indigenous consultation and supported opportunities for decision making and leadership by traditional custodians. We calculated costs on the basis of the area of 'known', 'likely' and 'may occur' mapping. We neither included analysis of future likely important areas, nor excluded management of areas currently occupied that could be unsuitable under future climatic conditions.

Cost models

We used the cost models developed for 17 TAS from the second stage of the broader project, each including a suite of actions, such as pre-action office planning, on-ground management and post-action evaluation[13]. All spatially explicit cost models included travel to site costs and non-spatial costs. On-ground actions were costed out over 100 km^2 units to optimize cost efficiencies; for example, the action planning was costed once for each of the implementation units. At this step, the cost per unit area was estimated for area-based costs and the cost per unit area per km distance for travel to site costs. Costs varied spatially where they were influenced by land use, tenure, terrain ruggedness (which influences the time taken to complete tasks while walking), vegetation type and remoteness (which influences travel time to location) (Supplementary Table 8). The intensity of effort of the TAS varied where required and where it could be accounted for. For example, habitat restoration and managing invasive weeds were scaled into 'intensive', 'moderate' and 'light' categories, and the ratios of these categories depended on the intactness of the recipient ecosystem. Each model included cost components for labour, travel within site, consumables and equipment.

Travel to site costs were estimated using the number of trips required to each site for onsite management to be completed in multiples of 21 days of field work. The travel cost per hour included vehicle cost and time compensation cost for personnel. We translated the action and travel costs to spatial layers by incorporating the relevant threat, landscape resistance and travel time layers[59] (Supplementary Table 8).

Most of the TAS were costed spatially including pre-action office planning at the start, pre-action field planning, the actions specific to that TAS, followed by post-action monitoring and evaluation at the end (Supplementary Table 9). Non-spatial costs were included for actions that are typically implemented centrally, such as policy change. Policy change was a generalized labour cost to cover tasks including policy development, education, compliance and enforcement (Supplementary Table 9), and was included every year and added for each policy-specific TAS, for example, fisheries management and wind turbine planning (Supplementary Table 1).

The underlying cost estimates for each TAS were presented as annualized costs as done in ref. 13, to allow easy comparison across all management actions that had different intervals of payment frequencies (see ref. 13 for more detail of payment frequencies). Our costing spanned a 30-year horizon (31 December 2020 to 31 December 2050), and we acknowledge that over that time some threats may require less abatement if management is highly successful, while others may magnify. Many of our TAS will require ongoing implementation, albeit the intensity of effort needed is likely to shift across space (that is, areas that initially require high intensity of effort could need lower intensity of effort as the threat is managed, such as restoring degraded habitat).

Cost uncertainty and validation. The cost uncertainty and validation was done as part of the earlier stage of this broader project, outlined in detail in ref. 13. In brief, to explore how true costs might vary from estimated values, ref. 13 conducted Monte Carlo simulations varying 17 most commonly included parameter values to find the 10th, 50th and 90th percentiles of the parameter values (1,000 iterations)[13]. Probability distributions were constructed for each of these parameters to find the 75% confidence value. From these, an overall range in costs (Supplementary Table 10) indicated the underlying variation from the sensitivity analysis of underlying TAS costs, detailed in Supplementary Material 6 in ref. 13. Validation of total cost estimates for actions was undertaken by comparing costs reported in the literature and expert judgements[13].

Assigning TAS to species and locations

Through our review of threatened species peer-reviewed and grey literature[10,53], and discussion with experts (Supplementary Table 3), we assigned a TAS to each combination of species and threat (Supplementary Table 2). In some cases, there was straightforward matching of threats to action; for example, where current fire regimes were a threat, reinstating ecological fire management was generally the allocated TAS. However, there were many instances where there was no information about the nature of threats impacting individual species that were listed in existing government databases. For example, there is no current method for effectively abating the threat of cane toads where they currently pose a threat to threatened species, but intact habitats are in many cases less suitable for cane toads than disturbed habitats, which is why 'habitat restoration' was often the best action. Other pertinent examples include where increased frequency and length of drought threatened small birds in dry environments, such as the Gawler Ranges short-tailed grasswren (*Amytornis merrotsyi pedleri*), the best course of action[60] was to map and protect climate change refugia. In contrast, for other birds threatened by increased frequency and length of droughts, the recommended actions ranged from management of grazing (for example, golden-shouldered parrot, *Psephotus chrysopterygius*) to changes to water policy, planning and regulation (for example, superb parrot *Polytelis swainsonii* and Australian painted-snipe *Rostratula australis*). For plants impacted by droughts (for example, Bolivia wattle *Acacia pycnostachya*), the actions sometimes included management of large invasive grazers. Due to this complexity, we reviewed all literature such as species-specific conservation advices, recovery plans and scientific publications, and liaised with numerous species experts (entered as 'Pers. Comm.' in Supplementary Table 3) to ensure we allocated the most appropriate action to address the threat for each species' context. Supplementary Table 3 'Threat–Action notes' details the species, specific threat and assigned TAS, and provides notes and key references for where further information on the nature of the threat and required actions were sourced to lead to our decision of the best action required.

Land potentially available for habitat restoration identified through creation of a 'cleared, restorable' spatial layer. While habitat retention and restoration was required by 1,095 species, we acknowledge that active habitat restoration is only feasible in some circumstances. We used the Catchment Scale Land Use of Australia[55] to define areas that could potentially be available for habitat restoration for threatened species. To qualify as 'potentially available', the land had to be currently cleared of native vegetation and not currently under an intensive land use. We included a third category, which was 'not cleared' according to the Forest and Woodland Loss data[61], but was in a non-irrigated agricultural land use. In this 'restorable, non-cleared' category, we costed out weed management if it overlapped spatially with a threatened species that was impacted by weeds (Supplementary Table 11). Three-quarters (75.4%) of the land area that we scored as 'cleared and restorable' was currently under 'production native vegetation' (livestock grazing); 9.4% was 'land in transition' and 9.2% was 'grazing modified pastures'.

Much of the land that was mapped to be both cleared and potentially restorable was found across Queensland, with some patches throughout the other states and territories (Supplementary Fig. 1). Because the purpose of this study was to cost out the recovery of threatened species, we did not include a feasibility component to understand the actual likelihood of land being available for threatened species. We assumed that all site-level decisions for any TAS would be made with managers, stakeholders and partners responsible for the area.

Creating 'action' maps. Spatial analyses were conducted in the projection GDA 1994 Australia Albers. Spatial cost models were limited to the spatial extent of the threat, or where the threat did not (yet) occur but prevention strategies were required (particularly biosecurity for the prevention of disease spread)[13]. We intersected the distributions of species impacted by each threat with the relevant spatial cost model to create the costed TAS extent (Supplementary Table 1). We calculated the area of each action map and summed the cost of each TAS using zonal statistics as a table function in ArcMap v.10.8.

Caveats. While we acknowledge the importance of climate change as a threat to biodiversity and ecosystems[62,63], we did not account for climate change in species distributions (that is, likely future habitat suitability under likely climate projections) or for the influence of climate change on threats in our spatial analysis because this was beyond the scope of this study. Furthermore, including climate change projections substantially increased the uncertainty for all components of our study (species locations, persistence and interspecific interactions; threat locations, severity and interactions; action efficacy and so on)[58,64]. By addressing all other threats, species are likely to have the greatest chance of persisting in the face of climate change impacts[3].

Testing the impact of removing expensive places and TAS. The full cost of all TAS was calculated by summing all TAS 'action' maps spatially and adding the total cost of the policy-specific TAS. Exploring the underlying factors driving the high costs was done by comparing the spatial variation in total cost with spatially costed habitat restoration and weed management TAS (Supplementary Fig. 1). Next, we compared the impact on the total cost of all TAS by removing the top 5% most expensive places, then the top 10% and 25% most expensive places with the total cost excluding the weed management TAS (Extended Data Figs. 1 and 2). We also outlined the relative impact score that invasive weeds had on each of the threatened species impacted by this threat (Extended Data Fig. 1, full detail in Supplementary Table 2).

Partial implementation scenarios for the most threatened species. We investigated the impact to the overall cost of implementing all TAS if the TAS were only costed for where those listed as critically endangered (that is, the most at risk of extinction of the species considered in this analysis) required the actions. We repeated this partial implementation again for species listed as either critically endangered or endangered (excluding species listed as vulnerable). As there are often multiple threatened species in each management unit location, the total cost is not a simple addition of each species threat category costs as there are spatial overlaps. We investigated how these partial implementation scenarios (that is, those focused on the most imperilled species) impacted the cost of implementing each TAS (Supplementary Figs. 2 and 3) and location of the TAS (Extended Data Fig. 3).

Estimating co-benefits

Managing the threats to Australia's threatened species could generate substantial additional benefits for biodiversity, the environment more generally, and society. Where applicable, we used our mechanistic cost models to quantify the additional benefits of threat management at a greater level of detail across a broader scale than has been previously possible. Here we focused on benefits to specific stakeholders resulting from threat management rather than attempt to quantify the benefits of the retained or improved persistence of threatened species themselves or their habitats. A fully comprehensive analysis of the additional benefits of reducing threats to threatened species across Australia is outside the scope of this analysis. Rather, we showcase a snapshot of three types of benefit, which can be created through:

1. Restoring the integrity and extent of threatened species habitat in ways that create additional environmental benefits, as well as improving the outlook for threatened species
2. Creating jobs and livelihoods
3. Reducing threats that impact on the economic outcomes of other sectors, such as agriculture

Co-benefits associated with restoring threatened species habitat. We calculated the carbon benefits of restoring the proposed areas outlined in the habitat restoration TAS on the basis of the sum of the maximum potential dry biomass[65] of the area to be restored. The total potential dry mass values came from the maximum aboveground biomass (M) spatial layer[66]. Belowground biomass was assumed to be 26% of aboveground biomass following ref. 67. The total potential dry biomass was converted into equivalent CO_2 using the equation:

$$\text{Total}CO_2(\text{tonnes}) = (\text{Total dry biomass} \times 0.5) \times 3.66, \quad (1)$$

where the weight of the total dry biomass is multiplied by 0.5 to get the total weight of carbon because carbon is assumed to be 50% of dry biomass[68]. The weight of carbon is converted to equivalent CO_2 by multiplying it by 3.66 following 'Trees for the Future'[68] because the ratio (based on molecular weight) of CO_2 to C is 43.999915/12.001115 = 3.6663.

We calculated the potential economic benefit (in Australian dollars) to this carbon sequestration if it were to be traded as Australian Carbon Credit Units (ACCUs), which represent one tonne of carbon dioxide equivalent[69]. ACCUs were traded between \$30.50 and \$32.00 in the September quarter of 2023[21]. We took the lower, more conservative value of \$30.50 per ACCU to multiply this by total tonnes of CO_2 sequestered in our estimates. Given that our habitat restoration TAS concentrated on cleared land with at least a modicum of feasibility that it could be restored (Supplementary Table 11), we made the assumption that most of this restoration would be eligible for the ACCU market under the 'Carbon Credits (Carbon Farming Initiative) Act 2011'[16].

We calculated the area of vegetation of conservation significance (for example, under-represented bioregions[19,70–72]) restored by implementing the habitat retention and restoration TAS (Supplementary Table 12).

We calculated the jobs created by the 17 TAS by summing the number of full-time equivalent (FTE) jobs required across all strategies. The FTE jobs were calculated by dividing the total labour cost by the annual salary of $110k p.a. ($84,000 with 30% of on-costs) (Supplementary Table 13).

Co-benefits from reducing threats that impact on the economic outcomes of other sectors, such as agriculture. We estimated the financial co-benefits of terrestrial invasive species management by summarizing the costs of invasive species to the agricultural industry[73–75], divided by the proportion of spatial overlap between the invasive species TAS and the relevant land use type.

Invasive predators. Invasive predators move large distances across landscapes; therefore, we assumed that predator control in all land use types would benefit areas under agricultural land use. We calculated the additional benefits of managing invasive predators intersecting the invasive predator management TAS spatial extent with the current distribution for wild dogs/dingos (*Canis lupus familiaris* and *C. lupus familiaris* combined, hereafter 'dog'), red foxes (*Vulpes vulpes*, hereafter 'fox') and cats (*Felis catus*)[54]. For cats, we allocated the cost of cat management across the overlap of cat distribution and of sheep grazing land and urban areas. For sheep grazing land, we used all grazing that could potentially have sheep across Australia, which includes the land-use categories[55]: grazing native vegetation, grazing modified pastures, irrigated pastures, intensive animal and plant production, and rural residential and farm infrastructure. The cost of dogs and foxes came from the 'Cost of Pest Animals in NSW and Australia, 2013–14' report[73]. This report includes impacts to livestock and agriculture in the form of management (control) and production loss. The costs of feral predators from the report were: $89 m (dogs) and $28 m (foxes). The cost of cats came from ref. 75 who estimated the economic costs of cat-dependent pathogens in Australia to be $6 billion per year. Reference 75 found that cats transmitted disease to sheep (causing production loss) as well as causing minor illness in humans. We used a standard inflation rate of 1.5% to adjust the values in the reports to 2021 Australian dollar value. We estimated that our invasive predator management TAS would reduce the impact and cost of dogs by 99.53%, foxes by 98.1% and cats by 98.74%.

Invasive herbivores and birds. We used a similar approach to estimate the benefit of managing invasive herbivores and invasive birds. We used a subset of the area of our TAS for invasive grazer management (large herbivore), invasive grazer management (rabbits) and problematic invasive birds (invasive/problematic birds and bees management) to account for the occurrence of only the invasive species that have substantial impact to agriculture, such as feral pigs (*Sus scrofa*), goats (*Capra hircus*), rabbits (*Oryctolagus cuniculus*) and starlings (*Sturnus vulgaris*). Costs were extrapolated from ref. 73 and included both the cost of management and production loss. We assumed that impacts occurred across the entire range of each invasive species and, therefore, the benefit to agriculture would be the percent of their range in which species were controlled multiplied by the total cost of those species. Costs of each species from the report were: $216 m (rabbits), $69 m (introduced birds), $14 m (pigs) and $7 m (goats). We used a standard inflation rate of 1.5% to adjust the values in the reports to 2021 Australian dollar value. We estimated that management actions would reduce the impact and, therefore, the cost of rabbits by 91.8%, starlings by 21.9%, pigs by 63.3% and goats by 87.5%.

Weeds. To estimate the additional benefit of controlling weeds, we overlaid the spatial extent of our invasive weed management TAS with the broad agricultural and production land uses likely to be impacted by weeds from the Australian Collaborative Land Use and Management Program[55]. We calculated the benefit of weed management by multiplying the percent overlap in proposed weed management area and agricultural land uses with the cost of weeds to the agricultural sector. The broad land use categories were grazing native vegetation, grazing modified pastures, dryland cropping, dryland horticulture, irrigated pastures, irrigated cropping, irrigated horticulture, intensive animal and plant production, and rural residential and farm infrastructure. The cost of weeds to agriculture and livestock production was taken from ref. 74 who estimated the costs of weeds to be an average of $3,927 million in 2018. The cost value included the annual cost of weed control, yield losses and loss of economic surplus. We used a standard inflation rate of 1.5% to adjust the values in the reports to the 2021 Australian dollar value. This cost was estimated to an average of $3,927 million in 2018, which when adjusted using a 1.5% annual inflation rate, equates to $5,210 million per year. Adjusting for inflation, we estimate that weeds cost Australia between $3,583–3,737 million per year. Our proposed invasive weed management TAS would reduce the cost of weeds across 90.66% of the agricultural areas impacted by weeds. The average benefit of our proposed weed action would be $3,720 million per year.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Threatened species threat data are detailed in ref. 10, and all cost models are detailed in ref. 13. We build on this here to add in details of actions required and threat abatement strategy assigned, detailed in Supplementary Tables 1–6. Species distribution maps are managed by the Australian Government.

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Author contributions
J.E.M.W., J.C. and B.A.W. conceived the idea. A.E.R., J.E.M.W., J.C., M.W. and C.Y. designed the research, with input from all authors. A.E.R., J.S., J.W., M.L., G.T. and A.F.V.P. assigned threat abatement strategies to address threats to species. A.E.R., M.W., R.V.L., A.R. and C.Y. analysed the data. A.R. collated co-benefits information. All authors contributed to the writing and editing of the paper.

Competing interests
The authors declare no competing interests.

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Correspondence and requests for materials should be addressed to April E. Reside.

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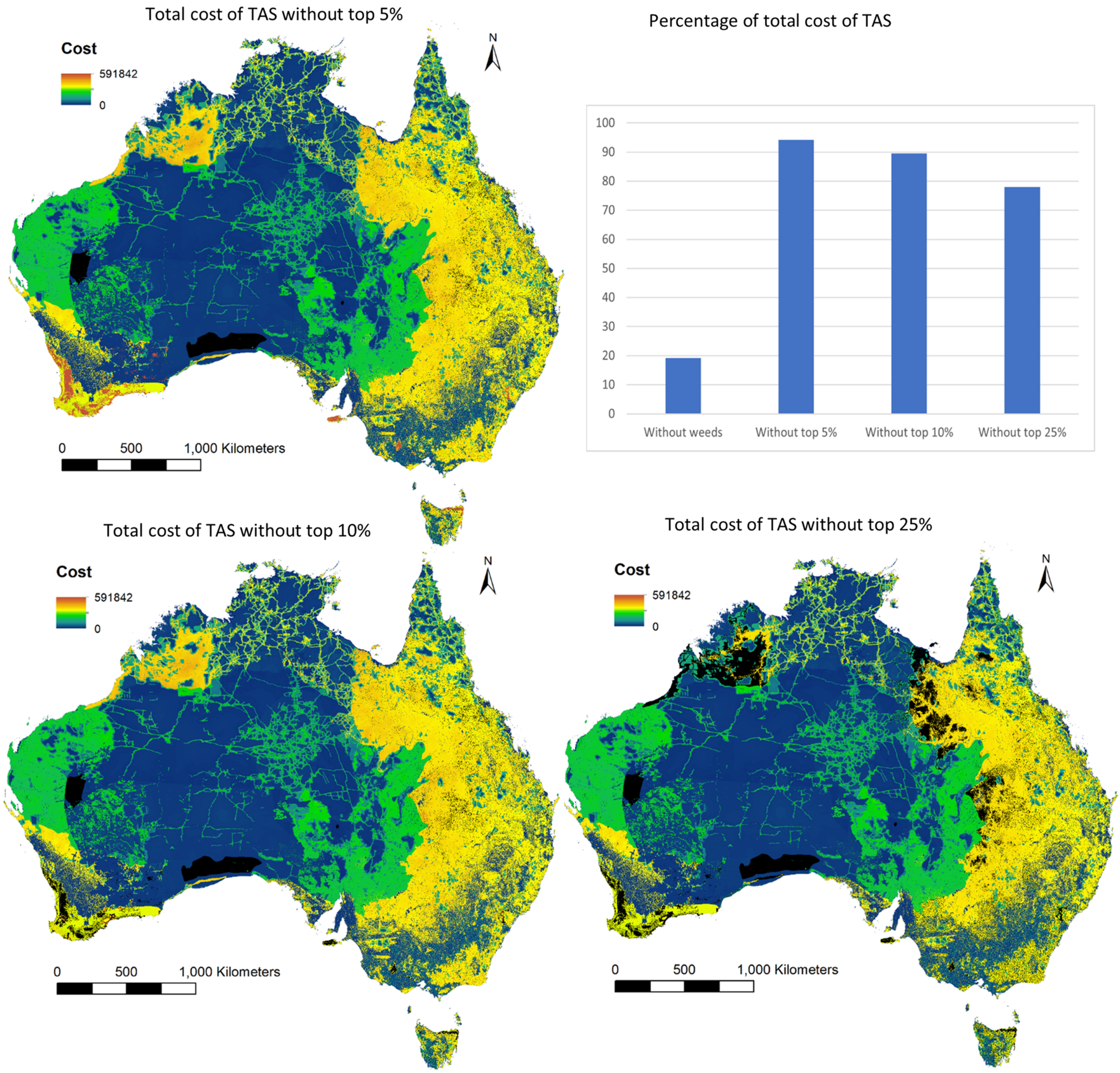
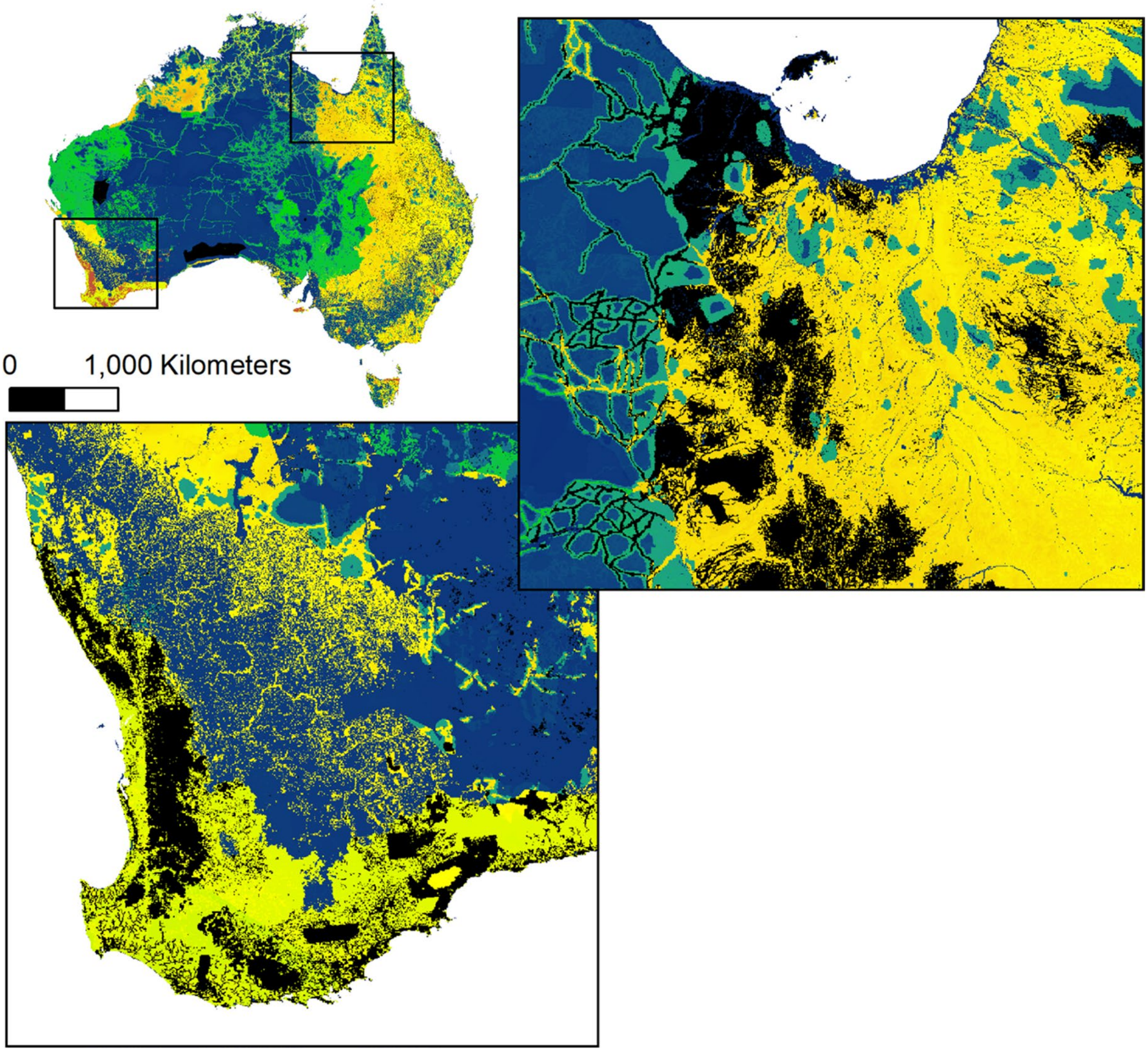


	Low impact	Medium impact	High impact
Invasive weed	100	403	25

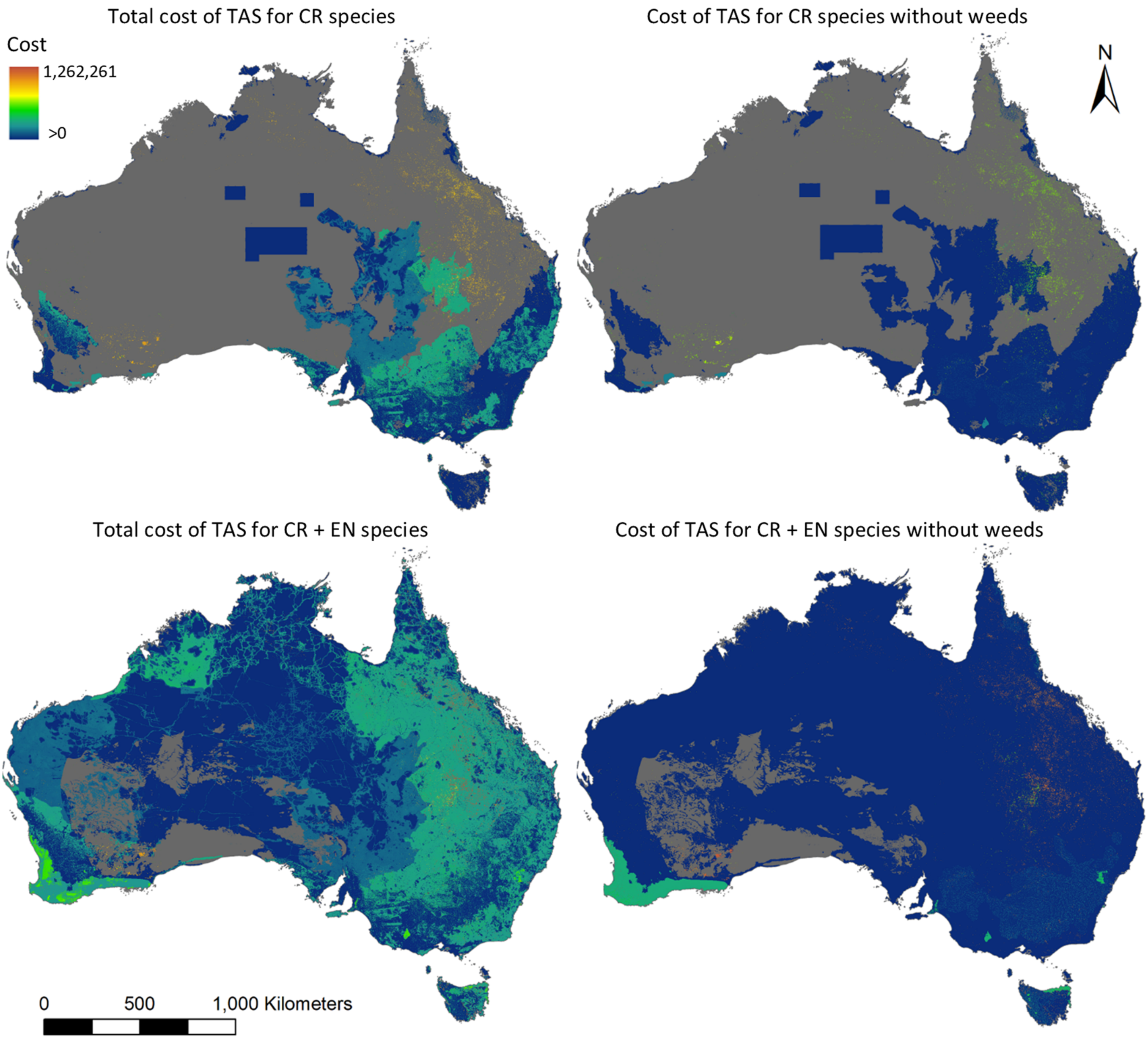
Extended Data Fig. 1 | The total cost of all TAS comparing the total without the top 5%, top 10% and top 25% of most costly places. Areas in black are uncosted. Graph: the percentage of the total cost of all TAS comparing dropping the most costly places with removing the 'Invasive weeds' TAS. Table: the number of species impacted by invasive weeds where the impact is low, medium or high.

https://doi.org/10.1038/s41559-024-02617-z



Extended Data Fig. 2 | The total cost of all TAS comparing the total without the top 25% of most costly places, zoomed in to show areas without TAS costed. Areas in black are uncosted. Bottom left: southwest Western Australia. Top right: northern gulf country of Northern Territory and Queensland.

 https://doi.org/10.1038/s41559-024-02617-z



Extended Data Fig. 3 | The spatial extents of Threat Abatement Strategies required across species' threat status. Mapped for only that required by Critically Endangered (CR) species (top left); mapped for Critically Endangered and Endangered (EN) species (bottom left). These are shown with all Threat Abatement Strategies (left column), and all Strategies except weed management for Critically Endangered species (top right) and Critically Endangered and Endangered species (bottom right). Grey indicates no cost; colours indicate costs above zero.

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Corresponding author(s): *Double-anonymous peer review submissions: write DAPR and your manuscript number here instead of author names.*

Last updated by author(s): 3/5/2024

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For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

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☐	☒	The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement
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☐	☒	A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☒	☐	For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐	Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	We collated publicly available data and have made the outputs available with this manuscript. The sensitive fine-resolution maps species are from the Australian Government and can be sourced with permission from them.
Data analysis	Our analyses involved procedures in ArcMap that did not involve code

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

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All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
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Data are published along with the manuscript as a supplementary file; underlying species distribution models accessed from the Australian Government are sensitive and not publicly available

Research involving human participants, their data, or biological material

Policy information about studies with human participants or human data. See also policy information about sex, gender (identity/presentation), and sexual orientation and race, ethnicity and racism.

Reporting on sex and gender	NA
Reporting on race, ethnicity, or other socially relevant groupings	NA
Population characteristics	NA
Recruitment	NA
Ethics oversight	NA

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	We accessed existing fine resolution maps of all of Australia's freshwater and terrestrial threatened (endangered) species, and the full compilation of all of their threats, and designed Threat Abatement Strategies to mitigate the threats. We developed spatially explicit cost models for each Threat Abatement Strategy, and calculated the full cost of all of the strategies if they were implemented everywhere that they were needed.
Research sample	We covered 1657 freshwater and terrestrial threatened species, and all of their threats, across Australia's mainland and continental islands. The 17 Threat Abatement Strategies were developed and detailed in Yong, C. et al. 2023 The costs of managing key threats to Australia's biodiversity. Journal of Applied Ecology 60
Sampling strategy	We chose all extant freshwater and terrestrial species listed as nationally threatened as of June 2019, across Australia's mainland and continental islands.
Data collection	We accessed the species maps from the Australian Government. We published species threat data in an earlier publication (which was collated through existing literature and expert knowledge). The cost models were detailed in Yong et al 2023.
Timing and spatial scale	Our cost models were costed as of 2020 and spanned a 30 year horizon. Our work spanned ustralia's mainland and continental islands
Data exclusions	We excluded species endemic to Australia's offshore islands because specialised costings would occur for these species, for example, Macquarie Island has its own specialised invasive species eradication program. Our appendices list the island species that we included and excluded in our analyses.
Reproducibility	All of the species threats are published; our manuscript details our assumptions and detail on how we assigned each species-threat combination to a Threat Abatement Strategy. The cost model assumptions and methods are described in extremely fine detail in Yong et al 2023.
Randomization	NA
Blinding	NA

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern
☒	☐ Plants

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Plants

Seed stocks	*Report on the source of all seed stocks or other plant material used. If applicable, state the seed stock centre and catalogue number. If plant specimens were collected from the field, describe the collection location, date and sampling procedures.*
Novel plant genotypes	*Describe the methods by which all novel plant genotypes were produced. This includes those generated by transgenic approaches, gene editing, chemical/radiation-based mutagenesis and hybridization. For transgenic lines, describe the transformation method, the number of independent lines analyzed and the generation upon which experiments were performed. For gene-edited lines, describe the editor used, the endogenous sequence targeted for editing, the targeting guide RNA sequence (if applicable) and how the editor was applied.*
Authentication	*Describe any authentication procedures for each seed stock used or novel genotype generated. Describe any experiments used to assess the effect of a mutation and, where applicable, how potential secondary effects (e.g. second site T-DNA insertions, mosiacism, off-target gene editing) were examined.*