Threatened Species Recovery Hub

National Environmental Science Programme

A knowledge synthesis to inform a national approach to fighting extinction

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Cover image: Cactus Dryandra (*Banksia anatona)*. Image: Australian Network for Plant Conservation

A knowledge synthesis to inform a national approach to fighting extinction

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Executive summary

Thanks to concerted investment in research on Australia's threatened species, including through the NESP TSR Hub, we now have a wealth of knowledge about where and how to manage threats to improve the outlook for threatened species. However, an effort was needed to draw this knowledge together into a coordinated assessment of actions for mitigating key threats to threatened species and calculating the likely costs of these actions.

In this report we attempt to synthesise research and expertise across threatened species in Australia to generate and evaluate actions that could assist in the recovery of all threatened species across Australia. This report attempts to answer the questions: *what threat abatement strategies are required to ensure threatened species recovery across Australia; and what is the spatial extent, likely cost and co-benefits of abatement strategy implementation?*

We defined a species recovery as the functional persistence of the species across its potential range in Australia and assumed that the management of all impacting threats is required across the species habitat to achieve this outcome. We focussed the assessment on 1,659 extant terrestrial and freshwater species listed as threatened under the *Environmental Protection and Biodiversity Conservation Act* (1999; EPBC Act). We estimated the resources to implement the actions the implementation of actions required to recover species over the next 80 years. Cost estimates are reported as annualised net present value as of 31st December 2020.

We recognise the ambitious nature of this definition of species recovery. We do not assume that all actions will be undertaken in all locations that threatened species do and could exist. Our analysis aims to provide an understanding of the extent of effort needed, budget and to explore possibilities for species recovery against an upper baseline representing the full potential of species recovery. We also recognise the importance of integrating regional and local knowledge and aspirations for decision making and implementation of all threat abatement strategies.

The information generated in this report is useful from a budgeting perspective to help planners and decision makers understand the likely resources and actions that will be required to achieve species recovery at a range of scales. It also attempts to help address priorities and needs for a broad range of stakeholders in threatened species recovery across governments, non-government organisations, Indigenous organisations, industry, and other landholders. The information can be used for coordinated action of threat mitigation, species recovery; and help inform options to support the management of protected areas and other important conservation areas. Furthermore, the information can provide input for strategic assessments, and also contribute to frameworks that identify measures of success in threatened species recovery. It will help inform policy processes across different jurisdictions (e.g., EPBC Act 'significant' impact assessments) and identify opportunities for investments that benefit multiple species and achieve broader environmental outcomes. Importantly this information can also help guide future assessments into the likely consequences of management and land-use change on species persistence (and the likely costs of recovery of the species if the land use change activity is to be undertaken).

The report is set out as three research chapters:
A synthesis of all threats and threat-impacts to species by drawing on expert elicitation for all EPBC-listed species (**Chapter 1**).

A detailed set of Threat Abatement Strategies to address these threats and their modelled costs (**Chapter 2**).

In light of the catastrophic megafires of 2019-20 ('Black Summer'), the project provided a rigorous assessment of post-megafire recovery action by collating information to generate spatial layers of actions for fire management, recovery responses, and costs for these actions across Australian ecosystems. As such, a specific section has been included to deal specifically with threatened species recovery post-megafire (**Chapter 3**).

The report concludes with a forward-looking section on implications, applications, gaps and future research priorities.

Main findings

A summary of the main findings of this project are:

1. Australian species listed under the EPBC Act are threatened by a myriad of processes. We classified these threats into eight broad-level threat categories - Adverse fire regimes; Changed surface and groundwater regimes; Climate change and severe weather, Disrupted ecosystem and population processes; Habitat loss, fragmentation and degradation; Invasive species and diseases; Overexploitation and other direct harm from human activities; and Pollution and 51 nested sub-category threats.

2. The three most frequent threats to all species are:
    - Habitat loss, fragmentation, and degradation (n= 1,210 taxa),
    - Invasive species and diseases (n= 966 taxa),
    - Adverse fire regimes (n= 683 taxa).

3. We identified 18 distinct Threat Abatement Strategies to address these threats to species. Fourteen of these were costed spatially, the remaining four strategies were policy-focused and therefore costed non-spatially.

4. The Threat Abatement Strategy that focussed on habitat restoration was assigned to 1,095 species (66%) to address loss of habitat and decline in quality driven predominately by land use activities associated with agriculture, forestry, mining, urban development, transport infrastructure, and climate change. It was also allocated to address other threats such as salinisation, erosion, water quality, hydrology alteration, and diseases of freshwater species. The retention of current and potential future habitat is also a fundamental need for threatened species to maintain and improve their recovery status across Australia.

5. The need for Threat Abatement Strategies differed across taxonomic groups, with more strategies assigned to better known taxon. Over 50% of plant species were assigned only one Threat Abatement Strategy, compared with 5% of fish and 11% of birds. On average, birds were assigned the most, with five bird species requiring more than 10 Threat Abatement Strategies.

6. Our preliminary assessment shows that the total cost of implementing all Threat Abatement Strategies across Australia is ~ $610 billion per year. This estimation is subject to change as the cost models are currently being peer-reviewed

7. Controlling weeds required the most financial resources, making up 69% of total costs. The next highest total costs were estimated for managing invasive fish, habitat restoration, and managing disease. Habitat restoration had the greatest cost per area of any Threat Abatement Strategy. We costed habitat restoration only where there was some likelihood of restoring the habitat, excluding land under intensive agriculture, urban and industrial development; therefore, for some species we do not consider that their entire habitat extent could be restored.

8. In addition to helping recover Australia's most imperilled species, the Threat Abatement Strategies will likely have many co-benefits to other industries in many locations. For example, our models showed that implementing Threat Abatement Strategies to control invasive animals such as cats (*Felis catus*) and rabbits (*Oryctolagus cuniculus*) could save the agricultural industry over $266 million per year. Restoration of threatened species habitat could sequester and store up to 8.6 million tonnes of above-ground carbon, and over 2.2 million tonnes of below-ground carbon over our time horizon (80 years). Implementing all threat abatement strategies could result in over 900,000 ongoing jobs. However, we also acknowledge that threat abatement for biodiversity can conflict with other societal priorities – for example, some introduced species such as rabbits and pigs have become important Indigenous cultural values and food source in many places, highlighting the need for appropriate governance and local scale decision-making.

9. Some threats are becoming more prevalent, especially those associated with climate change – such as severe megafire events. The 2019–2020 megafires in southern Australia impacted 290 threatened species which require immediate conservation action for post-megafire recovery. The most frequently required actions for species impacted by the megafires were the same as those for general recovery: habitat retention, fire management, and invasive weed management. We found that it would cost AUD$422 million – AUD$635 million to manage the top 30% (c.142,000 km^2) of priority locations for megafire-impacted threatened species.

10. There are other important costs of recovering every threatened species that were beyond the scope of this study. These include the resources needed for comprehensive community engagement and planning that accounts for local values and aspirations, including supporting Indigenous leadership in decision making for culturally significant species and places, monitoring of threatened species populations, the costs of responding to climate change adaption needs of species, the opportunity costs of avoiding land use activities that are not compatible with threatened species persistence, intensive and ex-situ conservation (such as captive breeding or seed banking) for species unlikely to be recovered through broad-scale threat management alone, the cost of research to support recovery action, and threatened species recovery on offshore islands. Much of this work is being done by other NESP TSRH groups, in collaboration with a range of different stakeholders, and costing these out is a priority for future efforts at appropriate scales.

Importantly, this assessment was not designed to inform *where we should recover species.* The maps we provide of potential areas for threat abatement strategies are not priorities per se as we have considered only the benefits to threatened species at a broad scale. We acknowledge that there will be more suitable information and preferences needed for guiding decision making at regional and local scales, which we were unable to include at the national scale. In addition, information on species threats, actions, priorities and costs are evolving and need to be continually updated. Therefore, we aim to provide a systematic rationale and framework to enable rigorous, justifiable budgeting, information collation and support of appropriate local-scale decision making for threatened species along with other local scale priorities. This includes supporting Indigenous-led processes for decision making that can appropriately account for cross-cultural priorities, especially for decisions about species on the Indigenous Estate.

Overall, this research shows that extensive recovery efforts and resources are required to create a future where our threatened species are no longer at significant risk of loss and can flourish as part of healthy ecosystems across their natural range. The loss of species habitats poses a significant risk of failure in achieving this goal, given the vast expense and uncertain outcomes of habitat restoration, and the loss of areas for habitat restoration to intensive land uses. However, much of the management involved in abating threats is compatible and even beneficial to current land use but requires differences in management practices. If implemented effectively, fairly, and in culturally appropriate ways, threatened species recovery could result in improved habitat for non-threatened species, ecosystems, jobs and cultural values, providing significant benefits for Australia's environment and people.

Finally, our project team supports the commitment of resources and increased leadership opportunities for Indigenous Australians to lead in the design and implementation of research to ensure similarly suitable information is available for species that require attention due to their cultural and customary values, in addition to those which are threatened from a conservation perspective.

This project generated a set of products to assist in threatened species recovery and decision making: databases on threats and their impacts on each species, Threat Abatement Strategies for each species, costings of these Threat Abatement Strategies and the associated spatial data (see Appendix 10 for a full list of data products).

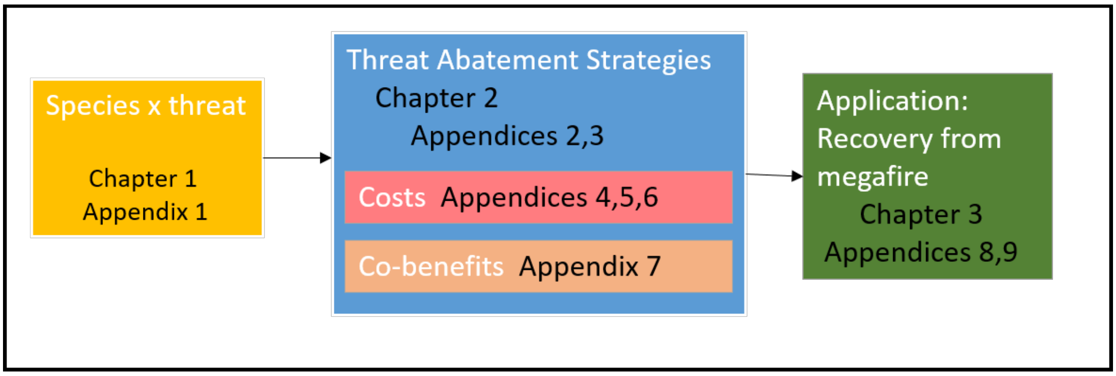

Fig I. The report components and their relationship to chapters and appendices.

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Chapter 1: A national-scale dataset for threats impacting Australia's imperilled flora and fauna

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Abstract

Australia is in the midst of an extinction crisis, having already lost 10% of terrestrial mammal fauna since European settlement and with hundreds of other species at high risk of extinction. The decline of the nation's biota is a result of an array of threatening processes; however, a comprehensive taxon-specific understanding of threats and their relative impacts remains undocumented nationally. Using expert consultation, we compile the first complete, validated, and consistent taxon-specific threat and impact dataset for all nationally listed threatened taxa in Australia. We confined our analysis to 1,795 terrestrial and aquatic taxa listed as threatened (Vulnerable, Endangered or Critically Endangered) under Australian commonwealth law. We engaged taxonomic experts to generate taxon-specific threat and threat impact information to consistently apply the IUCN Threat Classification Scheme and Threat Impact Scoring System, as well as eight broad-level threats and 51 sub-category threats, for all 1,795 threatened terrestrial and aquatic threatened taxa. This compilation produced 4,877 unique taxon-threat-impact combinations with the most frequently listed threats being *Habitat loss, fragmentation, and degradation* (n=1,210 taxa), and *Invasive species and disease* (n=966 taxa). Yet when only high-impact threats or medium-impact threats are considered, *Invasive species and disease* become the most prevalent threats. This dataset provides critical information for conservation action planning, national legislation and policy, and prioritizing investments in threatened species management and recovery.

Key words

IUCN Threat Classification Scheme; IUCN Threat Impact Scoring System;
Threatened species; Threat impacts; EPBC Act; Australian threatened species

Introduction

The sixth mass extinction is arguably the worst environmental crisis humanity currently faces (Ceballos et al. 2020), with species becoming extinct 100–1,000 times faster than Earth's biota has experienced over the last ten million years (Barnosky et al. 2011; Pimm et al. 2014; Ceballos et al. 2015). Recent estimates show that one million species are now threatened with extinction (hereon 'threatened') globally and could go extinct in the next century (IPBES 2018), with at least 515 terrestrial vertebrates likely to be lost within the next 20 years (Ceballos et al. 2020). In Australia, 25 taxa (ten birds, seven mammals, six reptiles, one butterfly, and twenty fish) are likely to become extinct within the next 20 years unless major conservation action is undertaken ('taxa' is used through the manuscript to collectively refer to species, subspecies, and important populations)

(Geyle et al. 2018, 2021a, 2021b; Lintermans et al. 2020). This decline is driven by rapidly increasing direct and indirect pressures of human activities on species survival.

Australia is a large, sparsely populated continent that was geographically isolated until the late Miocene when biotic interchange with Asia commenced (Woinarski et al. 2015; Commonwealth of Australia 2019). That isolation, coupled with harsh climates, rapid climate changes, and ca. 50,000 years of anthropogenically driven fire and hunting (Johnson 2006; NSW Government 2010; Crisp et al. 2011; Black et al. 2012; Wroe et al. 2013) has resulted in the unique evolution of biodiversity that is megadiverse and globally important (Mittermeier, R. A., and Mittermeier 1997; Lindenmayer et al. 2010; Black et al. 2012). Since 1788, European settlement has significantly changed the Australian environment by introducing novel species (e.g., woody and herbaceous weeds, cane toads, and cats (Woinarski et al. 2011; Lintermans 2013a)), widespread clearing of native vegetation for intensive agriculture and urban development (Ward et al. 2019), ungulate grazing (e.g., sheep and cattle (Kuiper & Parker 2013)), spreading alien disease (e.g., *Phytophthora cinnamomi*, *Batrachochytrium dendrobatidis* (Skerratt et al. 2007)), and altering fire regimes (Woinarski et al. 2015). These changes have resulted in threatening processes that have an especially profound impact on native species. However, the state of knowledge of the most important threats and threat impacts responsible for the declines and extinctions is fundamentally lacking.

Previous efforts to assess threats to Australia's Environment Protection and Biodiversity Conservation (EPBC) Act listed threatened species include the Australian Government's Species Profiles and Threats Database (hereafter 'SPRAT' (Allek et al. 2018; Kearney et al. 2019; Commonwealth of Australia 2021a)), where 'invasive species and disease' is listed as the most prevalent of a set of key threats impacting on nationally threatened Australian fauna and flora (Allek et al. 2018; Kearney et al. 2019, 2020). However, the SPRAT dataset, does not address habitat loss, fragmentation, and degradation as a threat, nor include the most up-to-date knowledge on the level of impact each threat has on each taxon. This more detailed knowledge held by relevant experts has, until now, been uncollated or undocumented at a national scale. Consequently, policy-makers, decision makers, and practitioners are unable to access a comprehensive dataset of taxon-specific threats, including information that systematically differentiates between negligible threats from those that cause significant, catastrophic declines over contemporary time periods (*29*).

Australia requires an improved dataset that identifies the importance of different threats at the taxonomic level at which the entity is listed as threatened. The IUCN's Threats Classification Scheme (IUCN n.d.) and Threat Impact Scoring System (IUCN 2012a) are globally recognised approaches for classifying threats and ranking the level of impact each threat has on specific species (IUCN 2012a). The IUCN Threat Impact Scoring System includes information on the timing of the threat, the proportion of the total population affected, and the overall declines caused by the threat. This method has been applied to IUCN Red List assessments of some species globally, including Australian species such as koala (*Phascolarctos cinereus*), quokka (*Setonix brachyurus*), freshwater fishes, and all Australian birds (Birdlife International 2018; Brooks et al. 2019; Garnett et al. 2019; Lintermans & Allan 2019; Burbidge & Woinarski 2020; Woinarski & Burbidge 2020), but not yet comprehensively for all threatened taxa.

Here, we engaged taxonomic experts in generating taxon-specific threat and threat impact information to consistently apply the IUCN Threat Classification Scheme and Threat Impact Scoring System to produce the most up-to-date data on currently recognised threatening processes affecting all nationally listed threatened taxa in Australia. We produced a comprehensive taxon–threat–impact dataset that identifies all IUCN threat types and detailed threat notes, in addition to eight new broad-level threats and 51 sub-category threats, for all 1,795 threatened terrestrial and aquatic threatened taxa. We created this novel categorisation based on extensive discussion with experts and managers, which draws heavily upon existing categories but is modified in order to have a classification that was fit to the Australian context of threats, governance of threatened species recovery, and threat abatement planning. The categories can also be used for communicating the major causes of threatened species decline to a range of audiences. In total, our dataset contains 4,877 taxon-threat-impact combinations, which includes timing, scope, and severity for all combinations, where available. This information will allow for comprehensive, consistent, national-scale assessment of taxon-specific threatening processes and their degree of impact, to guide appropriate conservation actions that will facilitate taxa to persist and recover in the future.

Methods

Threatened species in Australia

Under Australia's *Environment Protection and Biodiversity Conservation Act* 1999 (EPBC), there are six categories of threat status, including Extinct, Extinct in the Wild, Critically Endangered, Endangered, Vulnerable, and Conservation Dependent. We confined our analysis to 1,795 terrestrial and aquatic taxa listed as threatened (Vulnerable, Endangered, Critically Endangered, or Extinct in the Wild) under Australia's EPBC Act as of July 2018. We excluded taxa that were listed as Extinct or Conservation Dependent (the latter pertaining only to commercially harvested fish taxa, that have a specific conservation program, however the cessation of which would result in the species becoming Vulnerable, Endangered or Critically endangered). For species that are not endemic to Australia, information was compiled on all threatening processes.

Knowledge synthesis process

To synthesise knowledge and collate the taxon–threat–impact dataset, we followed five key steps: (i) identifying key data needs; (ii) designing and preparing the expert assessment; (iii) implementing the expert consultation (Hadwen et al. 2011; Pullin et al. 2016) (iv) encoding the expert responses; and (v) completing a technical validation. The expert consultation process was carried out from December 2019 to September 2020. As facilitators of the assessment process, we emailed fourteen experts to first describe the data required (i.e., threats and threat impact scores per taxon), provide instructions for the assessment, and distribute datasheets required for the assessment. Experts were chosen based on their extensive expertise in taxon groups, of which many had already begun the process of consolidating information on threats for their respective taxa of interest. The experts then consulted with relevant colleagues and searched existing literature to identify and complete the dataset (see Appendix 1) for taxon–specific threats and the components of each threat needed to estimate its likely impact using timing, scope, and the overall severity of the threat. In some cases, full systematic Conservation Action Planning workshops were completed for individual taxon to detail their threats and the likely impact of each (Black-throated Finch Recovery Team 2020). The overall threat impact is then classified as high, medium, low, negligible or insufficient data (i.e. missing values from timing, scope, and severity) using the IUCN Threat Impact Scoring System (IUCN 2012a; Garnett et al. 2019). Once the information was received and reviewed, follow-up consultations were conducted with the lead experts to resolve any uncertainty and seek additional clarification regarding specific threats. Facilitators then encoded the expert's responses resulting in a consistent, comprehensive list of all threats and the impact of each threat to every taxon, where knowledge was available. The dataset was encoded to include the IUCN threat categories (variable name: *IUCN threat level 1*, *IUCN threat level 1 description*, *IUCN threat level 2*, *IUCN threat level 2* *description*, *IUCN threat level 3*, and *IUCN threat level 3 description*), eight broad-level threat categories, and 51 sub-category threats (variable name: *Broad-level threats, Sub-category threats*; Table 1.1). The additional broad-level threats and sub-category threats were necessary as the IUCN threat categories failed to capture some threats that Australian taxa are exposed to, including *Habitat loss, fragmentation, and degradation* and *Disrupted ecosystem and population processes*. The threat categories developed here deviate from the IUCN approach in an effort to identify what threats taxa experience (e.g., habitat loss, degradation, and fragmentation) as well as the ultimate cause of those threats (e.g., housing development). These categories also allow a threatened species manager to understand the direct threat to the species and hopefully have more information on actions. For example, a biodiversity officer in a state government likely cannot do much about a climate change resulting in habitat alteration, but might be more equipped to address habitat loss, degradation, and fragmentation. While the IUCN does provide a Stresses Classification Scheme (IUCN 2012b), we found that these categories were not fit for purpose. For example, ecosystem conversion and ecosystem degradation are usually inextricably linked; and in many cases species are impacted by both. In addition, we required a classification which linked the threat to an action. If the same threat stresses two species differently, the threat abatement at a high level would remain the same. Therefore, for this research, it was better to focus on using threats that could be more easily linked to threat abatement actions. These categories were discussed and decided upon during three workshops held from July–August 2020 with independent experts from the Australian Threatened Species Scientific Committee (TSSC) (Commonwealth of Australia 2020) and close collaborators of the TSSC. During these workshops, participants used relevant literature (*27*, *54*) to help guide discussion and decide upon Australian-specific broad-level and sub-category threats.

Table 1.1. The eight broad-level threat categories and 51 sub-category threats used in the Australia-wide analysis on what threatening processes impact threatened taxa. The symbols are used in Fig 1.2.

Broad-level threats	Symbol	Sub-category threats
Adverse fire regimes		Increase in fire frequency/intensity Suppression in fire frequency/intensity Other change in fire regime/trend unspecified
Changed surface and groundwater regimes		Alteration to groundwater levels Alteration to surface water flows and infiltration Dams and altered flow regimes
Climate change and severe weather		Climate change and severe weather-Unspecified Habitat shifting and alteration Increased frequency/severity of droughts Sea-level rise Storms and flooding Temperature extremes
Disrupted ecosystem and population processes		Genetic introgression/hybridisation Lack of recruitment Problematic native species Small, restricted and reduced population
Habitat loss, fragmentation and degradation		Agriculture and aquaculture Energy production and mining Fisheries Forestry Geological events Military development Transportation and service corridors Urban and commercial development and maintenance Other natural system modifications
Invasive species and diseases		Disease Invasive amphibian Invasive bird Invasive fish

		Invasive invertebrate Invasive predator Invasive rabbit Invasive reptile Invasive rodent Invasive ungulate Invasive weed
Overexploitation and other direct harm from human activities		Collision Direct harvest Human intrusion Persecution Unintentional poisoning Unintentional hunting Entanglement Bycatch
Pollution		Effluent and wastewater Garbage and solid waste Herbicides and pesticides Light pollution Nutrient loads Oil spills Seepage from mining

IUCN Threat Impact Scoring System

The IUCN Threat Impact Scoring System (Table 1.2) scores threats to a taxon based on the timing of the threat (i.e., past, ongoing, future), the scope of the threat (defined as the proportion of the whole population affected), and severity of the threat on the taxon (i.e., the overall declines caused by the threat (IUCN 2012a; Garnett et al. 2019)). The IUCN threat impact scores are summed to provide the overall threat impact (based on IUCN 2012 (IUCN 2012a); (Table 1.3)). For example, Mary River Cod (*Maccullochella mariensis)* is threatened by fishing and harvesting, which is an ongoing (timing = 3) threat, affecting the whole population (scope = 3), and causes slow, but significant declines (severity = 1). The overall impact is 7, resulting in an overall impact score of 'medium'.

Table 1.2. IUCN Threat Impact Scoring System (based on IUCN, 2012 (IUCN 2012a)) applied in the Australia-wide analysis on threatening processes impacting threatened taxa.

Criteria	Categories and scores
Timing	
Only in the past and unlikely to return	0
In the past but now suspended and likely to return	0
Ongoing	3
Only in the future	1
Unknown	0
Scope	
Affects the whole population (>90%)	3
Affects the majority of the population (50-90%)	2
Affects the minority of the population (<50%)	1
Unknown	0
Severity	
Causing or likely to cause very rapid declines (>30% over 10 years or three generations; whichever is longer)	3
Causing or likely to cause rapid declines (20–30% over 10 years or three generations; whichever is longer)	2
Causing or likely to cause relatively slow but significant declines (<20% over 10 years or three generations; whichever is longer)	1
Causing or likely to cause fluctuations	1
Causing or likely to cause negligible declines	0
No declines	0
Unknown	0

Table 1.3. IUCN threat impact scores where timing, scope, and severity are summed (based on IUCN 2012 (IUCN 2012a)). Relative levels of impact are colour-coded as: dark purple (high impact), maroon (medium impact), tangarine (low impact), and bronze (negligible impact).

	Ongoing threat (3)				Future threat (1)			
Severity / Scope	Very rapid (3)	Rapid (2)	Slow (1)	Negli-gible (0)	Very rapid (3)	Rapid (2)	Slow (1)	Negli-gible (0)
Whole (3)	9	8	7	6	7	6	5	4
Majority (2)	8	7	6	5	6	5	4	3
Minority (1)	7	6	5	4	5	4	3	2
Negligible (0)	6	5	4	3	4	3	2	1

High impact	Medium impact	Low impact	Negligible/No impact

Experts were provided with datasheets that elicited their estimates of scope, severity, and timing. The overall threat impact scores were automatically calculated in the datasheet based on pre-defined IUCN thresholds driven by the summed value of the timing, scope, and severity scores (>7 = high impact, >5 = medium impact, >2 = low impact, and >0 = negligible impact). Some taxonomic groups had existing information that was included in the datasheets before they were sent to experts (Table 1.4).

Table 1.4. Existing threat data used in the data collation process to assist in synthesising and formulating the taxa–threat–impact dataset.

Taxonomic group	**Experts**	**Data incorporated**
Mammals	John Woinarski, Andrew Burbidge	Woinarski et al. (2014) (55) comprehensively reviewed the conservation status of all Australian mammals. We used this dataset to initially describe the threats and scores based on their scoring method. These threats and impact scores were then verified by experts during the elicitation process.

Birds	Stephen Garnett	Garnett et al. 2019 (Garnett et al. 2019) and Garnett et al. (2021) (*56*) provided data for each threatened Australian bird taxon; threats, and threat scores which were directly embedded within this dataset. The original Garnett et al. (2019) (Garnett et al. 2019) bird datasets contains 244 taxa (118 from the 2020 dataset and 126 from the 2019 dataset). Of the 135 non-extinct EPBC-listed bird taxa, 57 had updated data from the 2020 assessment (Garnett et al. 2021) (*56*); and data for the remaining 78 bird taxa came from Garnett et al 2019. These threats and impact scores were verified by experts during the expert consultation process.
Reptiles	Reid Tingley, David Chapple	We incorporated all data from Tingley et al. (2019) (*57*) and Chapple et al. (2019) (*58*), who identified all threatening processes impacting Australian squamates. These threats and impact scores were directly embedded within this dataset and then verified by experts during the expert consultation process. Data for all other reptile taxa were gathered during the expert consultation.
Frogs	Graeme Gillespie, David Hunter, Conrad Hoskin, Harry Hines, Dale Roberts	Existing data for Australian frogs (Gillespie et al. 2020 and Heatwole et al. 2018) (59, *60*) were incorporated and additional threat impact information was elicited from relevant experts.
Fish	Mark Lintermans, Mark Kennard, Helene Marsh, Colin Simpfendorfer, and Lesley Gidding-Reeve	Data for Australian threatened freshwater taxa from existing threat assessments was incorporated (e.g. Lintermans, 2013 and Lintermans, 2013) (*20*, *61*). Additional threat impact information was sourced from the 2019 freshwater and marine Red List assessment and elicited from relevant experts.
Invertebrates	Gary Taylor	While there are existing data (Taylor et al. 2018)(*62*) for Australian threatened invertebrates, additional threat impact information was required for data consistency.

		Therefore, the expert elicitation process outlined above was undertaken. Existing data for threats to EPBC-listed invertebrates(*63*) were guided by threat impacts identified in their EPBC listing and IUCN red list (*64*) (not exhaustive, restricted to the perceived main threats), and supplemented with data from expert consultation process.
Plants	Jennifer Silcock, Rod Fensham	Existing data for threats to EPBC-listed plants (Silcock & Fensham, 2018 and Silcock et al. 2020) (*65*, 66) were supplemented with data from expert elicitation.

Technical validation

We developed the final dataset in R (version 1.2.5033), which encompassed a validation process. This validation process was undertaken by each of the expert teams by cross-checking threat categories (IUCN, broad-level, and subcategories), threat codes, and threat impact scores, taxonomy, and standardizing taxon names and threat statuses.

Results

Australia's threatened taxa

Of all the EPBC Act listed threatened taxa in Australia, plants are the numerically dominant threatened group (74.6%), yet only 7.2% of 18,706 accepted/described plants in Australia are threatened. Mammals represent only 6% of all listed threatened taxa, yet ~28% of all Australian mammals are listed as threatened (Table 1.5). On average, each taxon was threatened by three sub-category threats (median = 2; range = 1 – 15).

Table 1.5. Overview of the number of threatened taxa per group within Australia, proportion of threatened taxa within each group out of the total number of threatened taxa in Australia, and proportion of threatened taxa within each group out of the total taxa in each group within Australia (Chapman 2009; Commonwealth of Australia 2021a).

Group	**No. of threatened taxa**	**% of total threatened taxa**	**No. of taxa in Australia**	**% of group listed as threatened**
Plants	1,339	74.6%	18,706	7.2%
Birds	135	7.5%	828	16.3%
Mammals	107	6.0%	386	27.7%
Invertebrates	65	3.6%	320,000	0.02%
Reptiles	61	3.4%	917	6.6%
Fish	51	2.8%	5,000 (or 315 freshwater fish)	1.0% (or 12% of freshwater fish)
Frogs	37	2.1%	227	16.3%
Total	1,795			

Broad-level and sub-category threatening processes

Our investigation summarises threats using eight broad-level threats and 51 sub-category threats that together impact upon 1,795 terrestrial and aquatic taxa, totalling 4,877 unique taxon–threat combinations. The most frequently listed broad-level threats were *Habitat loss, fragmentation, and degradation* (n= 1,210 taxa), *Invasive species and diseases* (n= 966 taxa), and *Adverse fire regimes* (n= 683 taxa). However, different taxonomic groups are threatened by different pressures (Fig 1.1). For example, while *Habitat loss, fragmentation, and degradation* is the key threatening process for invertebrates, fish, reptiles, and plants, *Invasive species and diseases* threaten the most birds, frogs, and mammals.

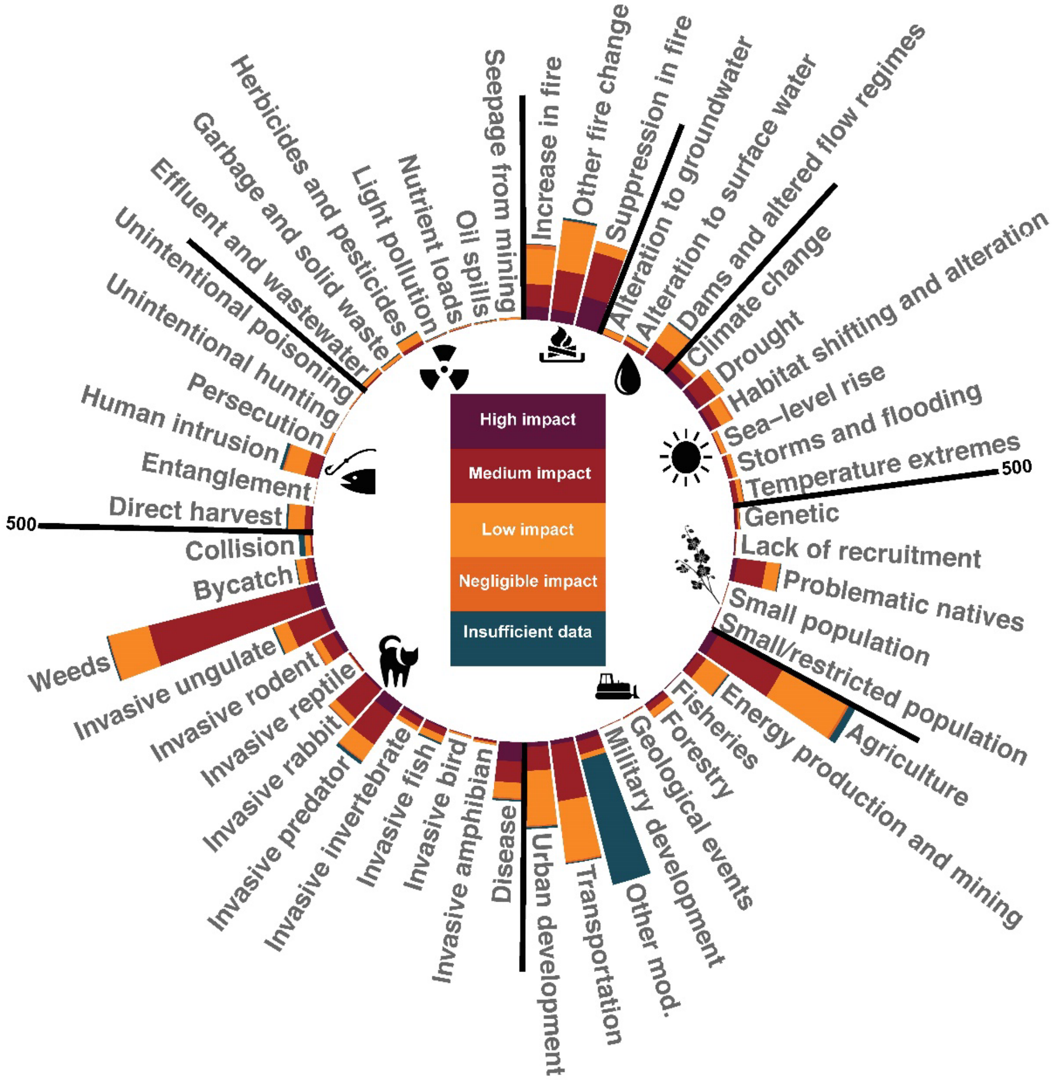

Fig. 1.1. Proportion of Australian threatened taxa impacted by broad-level threats. Each barchart represents a different group, including plants, invertebrates, fish, frogs, reptiles, birds, and mammals. Threats including *Habitat loss, fragmentation, and degradation* (dark blue), *Invasive species and disease* (indigo), *Adverse fire regimes* (purple), *Disrupted ecosystem and population processes* (magenta), *Overexploitation and other direct harm from human activities* (coral), *Changed surface and groundwater regimes* (orange), *Climate change and severe weather* (gold), and *Pollution* (yellow).

Examination of the sub-category threats can aid understanding of the main causes of each broad-level threat within which it is nested (Fig 1.2). The most frequently listed sub-category level threats were *Invasive weeds* (nested within *Invasive species and disease* with n= 565 taxa), *Agriculture and aquaculture* (nested within *Habitat loss, fragmentation, and degradation* with n= 411 taxa), and *Other natural system modifications* (also nested within *Habitat loss, fragmentation, and degradation* n= 398 taxa).

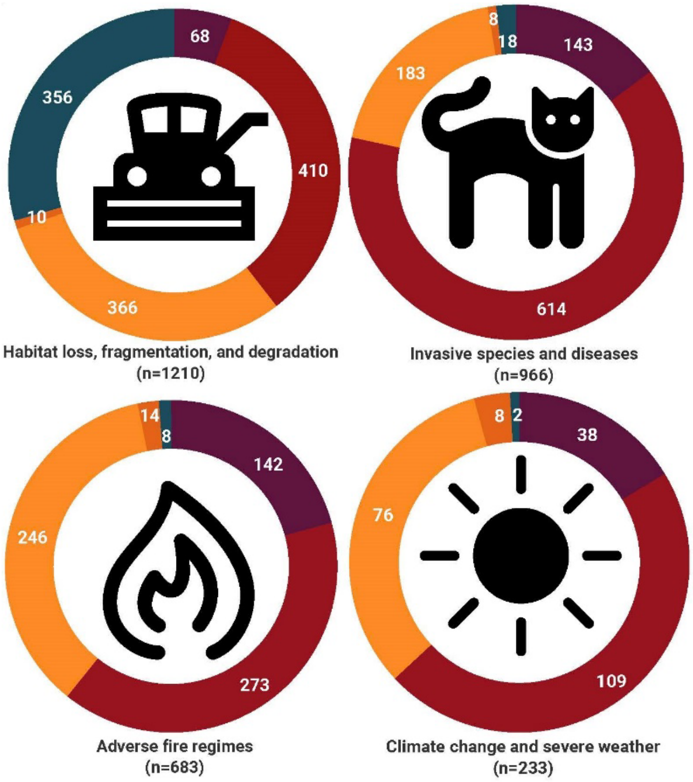

Fig. 1.2. Number of threatened Australian taxa and relative level of impact for each sub-category threat, nested within the corresponding broad-level threat class. See Table 1.2 for symbols representing each broad-level threat. Relative levels of impact are colour-coded as: dark purple (high impact), maroon (medium impact), tangerine (low impact), bronze (negligible impact), and teal (insufficient data). The scale bar indicates the cumulative number of taxa impacted per threat.

Impact of threats across taxa

The ranking of threats changes when the impact of the broad-level threat is considered (Fig 1.3). When only high-impact or medium-impact threats are considered, *Invasive species and diseases* (n=143 taxa and n=614 taxa, respectively), become the key threats to taxa compared to *Habitat loss, fragmentation, and degradation* (n=68 taxa and n=410 taxa, respectively). For 9.6% (n=464) of taxon-threat combinations, impact scores were unattainable due to insufficient data, which appear to be associated with a lack of understanding of the level of impact that habitat modifications have on threatened species. This outcome reflects the reality of complex threatening processes, and critical knowledge gaps concerning threats to Australia's threatened biodiversity, where experts are able to identify a possible threat but are not able to confidently evaluate the degree of impact it has on a particular taxon.

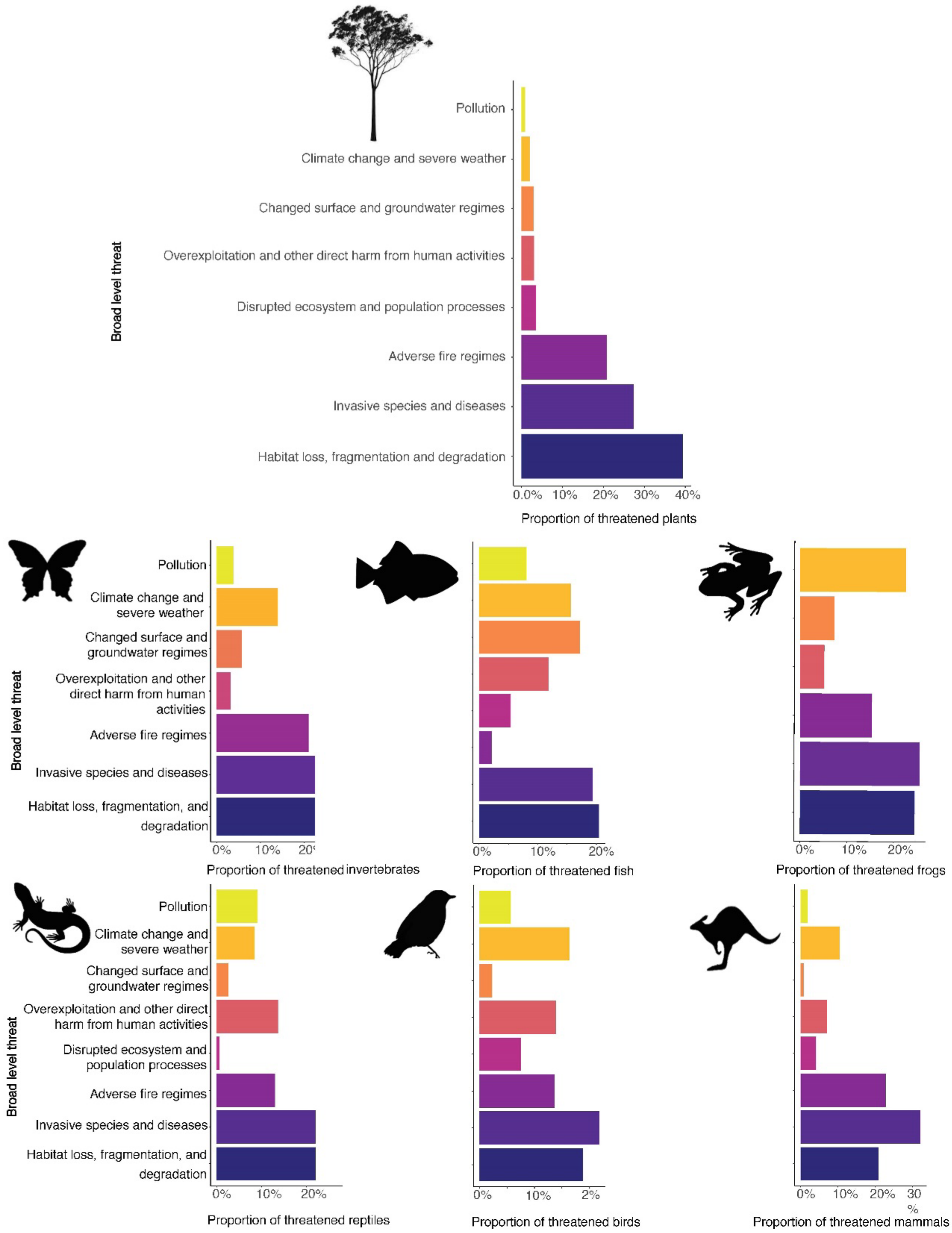

Fig. 1.3. The most important threats to threatened Australian taxa change when impact is considered. The diagrams show the number of taxa per impact score within the broad-level threat A) *Habitat loss, fragmentation, and degradation*, B) *Invasive species and diseases*, C) *Adverse fire regimes*, and D) *Climate change and severe weather*. Impact was determined through the evaluation of timing, severity, and scope for each threat per taxon. Where a taxon was threatened by multiple subcategories within a broad threat, we used the maximum impacting level in this analysis. For example, if a taxon was assessed as being threatened by *Residential and commercial development* at a low impact and *Agriculture and aquaculture* at a high impact under the IUCN classification scheme, which both fall under the broad-level threat of *Habitat loss, fragmentation, and degradation*, the broad level threat was considered high-impact for that taxon.

Discussion

Our results build on other global and continental analyses that have explored which threatening processes affect most taxa. Global analyses have revealed overexploitation as the prevalent threatening process (Yiming & Wilcove 2005; Maxwell et al. 2016), but across Australia we show that mitigating the impacts of habitat loss, fragmentation, and degradation will benefit the greatest number of taxa overall. Since 2000, 85% of Australia's threatened species lost habitat, equating to 7.7 million hectares, and efforts to ameliorate this ongoing loss have had little effect (Ward et al. 2019). As habitat loss is primarily driven by agriculture and urban development (Evans 2016), it is a politically polarising issue (Lindenmayer 2014). However, habitat is the most fundamental need of species, and its continued loss will result in ongoing declines regardless of how well other threats are managed. Threats such as invasive species are also severely affecting Australian threatened taxa, despite many initiatives aimed at reducing their impacts; for example, Non-Governmental Organisations and Commonwealth and state governments have invested heavily in the creation of predator-proof refuges and managing feral cats at various geographical scales via massive baiting efforts (Commonwealth of Australia 2014; of the Environment 2015). Our dataset shows that mitigating habitat loss, invasive species, and disease, along with improving fire regimes, and where possible, adaptation to climate change, is crucial for curbing species declines.

We anticipate this dataset will provide critical information to help inform conservation and management strategies for Australia's threatened species and threatening processes at local, regional, and national scales. For example, when used in combination with other key climate information, this dataset could assist in guiding action to build species resilience in the face of climate change and other related catastrophic events, such as the 2019-2020 megafires (Legge et al. 2020; Ward et al. 2020). Our dataset can help guide actions for abating existing threats to bushfire-impacted species to help aid recovery and avoid further declines. This taxon-threat-impact dataset can also be used to infer the benefit of managing a particular threat and aid in recovery planning (Cattarino et al. 2015, 2018). For example, the Endangered south-eastern subspecies of the spotted-tailed quoll (*Dasyurus maculatus maculatus*) has 12 recorded threats, one of which is considered to be of high impact, two are of medium impact, and nine are of low impact. This indicates that while the one high-impacting threat, invasive foxes, is a high priority for mitigation, lower-impacting threats such as cane toads and mortality associated with road traffic are likely to be lower priorities for mitigation. The dataset may be used at the local scale, where decision-makers can use the severity score to decide which of the threats present in their jurisdiction are the most important and feasible to address. Another example might be Southern Bent-wing Bat (*Miniopterus orianae bassanii*) which is known to be threatened by human intrusion. This threat is continuing (timing = 3), primarily problematic in maternity caves (scope = 1), and can cause very rapid declines (severity = 3). Therefore, while the scope is low, the overall impact of human intrusion is medium, and managers of these important roosts (e.g., Warrnambool City Council and Naracoorte Lucindale Council) may decide to prioritise protecting these roosts from human disturbance (Lumsden & Jemison 2015). This dataset can also be used to refine regulatory processes given the level of impact to particular taxa. For example, under the EPBC Act, actions associated with a particular development proposal or other activities that are likely to cause 'significant impact' to a threatened taxon require special consideration (Department of the Environment 2013). This dataset may aid decision-makers in determining 'significant impact' of potential activities for each of Australia's nationally listed threatened taxa. Our results highlight the urgent need to address the many high and medium impact threats, the majority of which consisted of invasive species and diseases and habitat loss, fragmentation, and degradation. This newly collated, consistent, national-scale information contributes to taxon-specific or threat-specific assessment to guide appropriate conservation actions that will facilitate taxa to persist and recover in the future.

A limitation of this taxon-threat-impact dataset is that it only integrates historic and recent information up to present day. This dataset therefore cannot be used to assess the impacts of changes in threat exposure and intensity over time, but we hope future revisions of the dataset will enable this. Being national in scale means that spatially variable differences or threats from other countries have also not been considered. Interactions among threats are not specifically considered, but there is increasing evidence of cumulative and synergistic impacts of co-occurring and interacting threats (Legge et al. 2019). A further limitation is that the dataset focuses on nationally listed taxa as of 2018 and many taxa potentially eligible for listing are currently unlisted (e.g. Lintermans et al. 2020) and this number is likely to increase as Australia' biota experiences broad-scale catastrophic events such as the 2019-2020 bushfires (Ward et al. 2020). Therefore, there are likely to be many taxa threatened with extinction for which management efforts, such as legislative instruments, to mitigate threats are currently non-existent. While this is the most up-to-date data available, there are several threats such as anthropogenic-driven climate change resulting in adverse fire regimes, increased droughts, spreading invasive species, and range shifts that are expected to worsen in impact and threaten more species than are currently listed. Such emerging threats must be incorporated in future iterations of this threat analysis. It is our vision that this dataset will periodically be updated and improved. We recommend that the most reliable way for this dataset to be maintained and sustained is to tie it to the formal EPBC Act assessment process.

Data and material availability

The taxon–threat–impact dataset is available in the Appendix 1. Data for each group of taxa (i.e., mammals, birds, reptiles, frogs, invertebrates, plants and fish) are also provided in the data record to enable group-specific interrogation of information.

Acknowledgements

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Chapter 2: The cost of conservation commitment: recovering Australia's imperilled species will cost one third of annual GDP

Abstract

Australia has the second-highest extinction record in contemporary times. The scale of actions and resources required to recover Australia's threatened species as never been comprehensively assessed, despite this being critical information for guiding national and international biodiversity conservation obligations. Here, using a novel threat-abatement-cost methodological framework, we provide the first continental scale assessment of the likely cost to achieve recovery of all known terrestrial and freshwater threatened species across Australia. We defined recovery as the functional persistence of a species across as much of its natural range as possible. We first took an up-to-date database of all the threats to threatened species (see Chapter 1), and developed a set of 18 Threat Abatement Strategies to address these threats. Species differed in the number of Threat Abatement Strategies needed, and there was strong taxonomic bias evident. Many plants only required one Strategy (most often habitat restoration), whereas birds needed up to 12. Using mechanistic cost models, we costed out the implementation of these Threat Abatement Strategies where they were required by threatened species across Australia. The total cost of implementing all Strategies across Australia was AUD$610 billion per year. Managing weeds had the greatest total implementation cost, making up 69% of the total cost. The total cost of implementing each Threat Abatement Strategy did not correlate with either the number of species that required the Strategy, or the areal extent that the Strategy was required over. We note the benefits from our Threat Abatement Strategies extend far beyond the 1,659 threatened terrestrial and freshwater species that need them: this work, if implemented, could produce over 900,000 full-time equivalent jobs, provide a $9 billion benefit to the agricultural industry, and sequester over 10.8 million tonnes of carbon over the next 80 years.

Introduction

Halting the higher-than-background rate of species extinction and recovering imperilled species is now a central tenet of the post-2020 Global Biodiversity Framework of the Convention on Biological Diversity (Secretariat of the Convention on Biological Diversity 2021) of which Australia is a signatory nation. Specific Action Targets within the GBF focus on strategies demonstrated to improve species' status, such as retention and restoration of ecosystems, active management of invasive species and disease, and regulating biological resource use. These must be progressed by 2030 to meet the Convention on Biological Diversity's Vision by 2050 (Secretariat of the Convention on Biological

Diversity 2021). These Action Targets require commitments of resources by nations sufficient to reach them and a separate Action Target (AT18) in the GBF draft details this specifically. While efforts have been made to estimate the cost of implementing some elements of the GBF (Secretariat of the Convention on Biological Diversity 2021), there is not even a ballpark estimate of the extent of actions and the financial resources required to achieve the outcome target for species conservation, i.e. *to enable the management actions for wild species of fauna and flora recovery*.

The lack of information on the overall costs to a nation for achieving the recovery of their threatened species is likely due to the size and complexity of this challenge. Estimating recovery costs requires data on why each individual species is threatened and where this species is located, an understanding of the actions that would abate those threats, then additional information on the cost of implementing these actions, including how the costs scale across space. These well-established shortfalls in conservation planning and assessment (Iacona et al. 2018), are problematic; as current cost estimates (Deutz et al. 2020) are likely to substantially underestimate cost of financial commitments by nations and industry in achieving recovery and averting species collapse.

Here, using a novel threat-abatement-cost methodological framework (Fig 2.1), we provide the first continental scale assessment of what it would likely cost to achieve the ambition of recovering all of Australia's known threatened species. Our focus on the terrestrial and freshwater threatened species that inhabit megadiverse continent of Australia is a fitting case study, because Australia has experienced greater contemporary species decline and loss than any other nation except Indonesia (Waldron et al. 2017). The continent is made up of one nation which has an accepted, legislated threatened species list (Environment Protection and Biodiversity Conservation Act 1999). The government, for many years, funded efforts that map the location of these species (Australian Government 2016). In addition, Australia has a vibrant group of ecologists and biologists who have the relevant expertise to successfully generate the relevant knowledge of the threats impacting each species (Kearney et al. 2018; Ward et al. Accepted) and a long-history of conservation efforts trying to save imperilled species, meaning relevant knowledge from experts on the likely success and failure of different actions to abate these threats could be compiled in a systematic way.

By taking into account the context of each threatened Australian terrestrial and freshwater species in terms of their location and corresponding threats and the best ways of abating them, we were able to generate 18 distinct Threat Abatement Strategies that could be costed and mapped collating threatened species information on 1659 species (Fig 2.1, Table 2.1; detail in Appendices 2-3). The retention of current and potential future habitat is an additional fundamental need for threatened species to maintain and improve their recovery status across Australia. We defined a species recovery as the functional persistence of the species across its potential range in Australia and assumed that the retention of the species' habitat and the management of all impacting threats is required across the species range to achieve this outcome.

Following accepted methodological principles in conservation action budgeting (Carwardine et al. 2019; Carwardine et al. 2008; Iacona et al. 2018; Thomson et al. 2020; Wenger et al. 2017), we costed each Threat Abatement Strategy by generating models for expected labour, travel, consumables and equipment, all of which accounted for pre-action planning, implementing the component actions, post-action monitoring and evaluation (detail in Appendices 4-6). While we were unable to cost out locally important activities, we acknowledge and recommend that implementation of all Threat Abatement Strategies would be in partnership with and under full consultation of local landholders, First Nations Traditional custodians and the broader community. We costed out the implementation of the Strategies across 80 years, assuming that actions to abate threats would need to be ongoing to achieve recovery of threatened species. Cost estimates are reported as annualised net present value as of 31st December 2020.

Our work demonstrates that broad-scale management across most of Australia's landscape is required for threatened species recovery and the scale of resourcing required to meet the recovery needs of Australia's is considerable. However, by collating some of the widespread benefits to agriculture, climate through carbon sequestration, communities through job creation, and non-threatened species, we show these costs need not be seen as punitive. Regardless of whether these actions are fully implemented or not, these cost estimates (and methods) provide the necessary information for decision makers to understand the financial impacts of future actions that may lead to species becoming more threatened (such as those associated with habitat degradation and loss) and as such, allow for the start of a balance sheet of the real cost of conservation and development (Maron et al. 2021).

Methods

To cost the recovery of threatened species we established an overall problem frame, including defining threatened species recovery and the scope of our analysis, then synthesised, generated and analysed relevant data to meet this objective. These data included distributions of species and their threats, maps of relevant actions and estimates of the costs and co-benefits of these actions.

Problem framing and scope

The aim of our analysis was to estimate and map the extent and costs of actions required to achieve the recovery of threatened species across their potential range in Australia. We defined the recovery of a species as the persistence of the species at high enough population numbers to carry out its function, across as much of the species range as possible. This ambitious goal recognises that the inverse of extinction is full recovery, and that the area needs of species for down-listing are vast in many cases, and that species require habitat with no or minimal threats to flourish as part of high functioning resilient ecosystems. We assumed that to achieve this goal, all threats impacting on a species (high, medium and low impact threats) would need to be managed across this range of habitat.

We cost out generic actions, rather than attempting to prescribe detailed threat abatement actions at a local scale. We focused on abating threats to species across their range, rather than focusing on ex-situ management, monitoring, research, and extensive social engagement for achieving feasibility and uptake for implementing actions which was outside scope but is addressed to varying extents by other studies within and outside of NESP TSRH. Furthermore, we decided to not include the cost of opportunity costs involved with threatened species recovery. For example, restoration of threatened species habitat could mean a reduction in economic gain for an industry, but this is likely to fluctuate substantially with market forces, and threatened species habitat is protected under national law.

For implementation of the threat abatement strategies we describe, we assume that all actions would be undertaken ethically, efficiently and effectively, with full consultation and supporting opportunities for leadership with Traditional Custodians, but a full assessment of the actions required to do this was outside the scope of our analysis.

Species data

We included all threatened taxa listed under the Commonwealth's EPBC Act that occurs in terrestrial and freshwater environments, on mainland or continental islands. We excluded species that occurred exclusively in marine waters, as these threats and actions would be specific to these environments and outside the scope of this study. We excluded species endemic to oceanic islands from the analysis because many of these islands have their own, specific, threat abatement plans and threated species and communities recovery plans that are specific to the needs of that island (Appendix 3). We included a total of 1659 taxa, which consists of species, subspecies, and in a few cases, important populations (e.g., Koala *Phascolarctos cinereus*).

We used the Australian Government's 1 ha gridded spatial data of occurrence for each taxa, updated as of July 2020 (Australian Government 2016). The occurrence maps are classified into three categories: "known to occur", "likely to occur" and "may occur". We included all of these occurrence probability categories in our analyses, for several reasons. First, 322 taxa had no "known to occur" habitat mapped, and some of these had very small areas of "likely to occur". Second, often the combination of all these occurrence probability categories for a taxon still resulted in a small area: 832 taxa had less than 2,000 km^2 habitat with the "known to occur", "likely to occur" and "may occur" combined; which could mean that it would still be listed as threatened on range size even if it occurred in all three occurrence probability categories. In some cases habitat is classified as uncertain (e.g. "may occur") because of insufficient data on the taxon's distribution; in others its due to highly mobile habits therefore temporal shifts in occupancy, and in some cases it is because the taxon occurs in very low density in marginal habitat. Therefore, some important habitat could be missed if the "may occur" range was excluded. Finally, if threats to the taxon were addressed in the "may occur" part of its range, there would be an increased likelihood that it would be able to occupy this part of its (often former) range.

Threats

Threats to each threatened taxa were compiled and ranked using the IUCN Threat Impact Scoring System which incorporates a measure of the timing of the threat (e.g. ongoing or historic), the proportion of the population impacted, and the decline caused by the threat (IUCN 2012). Taxonomic experts vetted the threat lists and their rankings (Chapter 1). The threat categories were 'high impact', 'medium impact', 'low impact', 'negligible impact' and 'insufficient data'. We excluded all threats to species that were ranked 'negligible impact'.

Actions

Detail of threats to each taxon, in particular the nature of the threat and most appropriate action, were obtained through taxon-specific Recovery Plans and Conservation Advices, and through discussion with experts via email, phone and several online workshops held between May and July 2020 (Appendix 3). Action categories were developed through an iterative process to find the most useful balance between generality (where possible, could apply to more taxa or geographic areas) and specificity (sufficiently specific to be costable, and relevant to the impacted taxon). Where required, more than one action category was assigned to a combination of taxon-threat. For example, some threats such as alterations of water flows on aquatic species, require both policy changes to address water extraction in critical areas, as well as habitat restoration. In some cases, one action (e.g., ex-situ) was the most appropriate to address multiple threats for a taxon, but this was only costed out once per taxon.

While interactions between threats were not explicitly accounted for, wherever possible actions were selected that aligned with the recovery actions recommended for the taxa and their specific context, which often accounted for threat interactions. Often the recovery actions listed in the taxon-specific recovery plans did not specifically relate to the threat listed in the (more up to date) matrix, in which case expert feedback was sought. For example, for the 88 species where drought was listed as a threat, in few cases actions could specifically address the impact of drought, such as through changing regulation to enable environmental flows to reduce water shortages in the landscape. Instead, many of the actions were related to addressing other threats, sometimes those that are exacerbated by drought such as stock grazing (e.g., for Squatter Pigeon *Geophaps scripta scripta*) and fire (e.g., for the Grasswren species *Amytornis* spp). In many cases, interventionist conservation strategies were recommended, for example captive breeding for the King Island Brown Thornbill (*Acanthiza pusilla archibaldi*) and the King Island Scrubtit (*Acanthornis magnus greenianus*). Further details of threat and recommended actions for each taxon, see Appendix 3. From the action categories that were assigned to the individual taxon (e.g. “manage grazing”, “increase riparian buffers”), action plans were made that could (where possible) be costed spatially across the landscape. The full list of objectives for each threat-action combination can be found in Appendix 3.

Cost models

Threat spatial data

Distributions of the threats that were listed for the threatened taxa came from multiple sources. The main source was recent fine-scale mapping of threats to threatened species (Pintor et al. 2020). For the distribution of grazing, we used the ABARES grazing land use category (ABARES 2021). For some species-threat-action combinations, we concluded that the action would be best done wherever the taxon impacted by this threat occurred. For example, many of the actions to prevent the spread of important diseases should be done in the areas in which the disease occurs, and also where it does not yet occur, but the susceptible species does. Another case is for species impacted by weeds: in many cases we did not have the detail of which weed species is the main problem. Furthermore, given the rate at which some weed species spread, current distribution maps of weed species may not capture all areas in which the problematic weed needs to be controlled.

Creating cost models

We estimated costs for Threat Abatement Strategies in three broad steps (Appendix 4 Fig 1). The first step detailed the threat abatement strategies, the actions and the cost components. To maintain consistency throughout we adopted three tiers of action descriptions for costing. Threat Abatement Strategies (TAS) (e.g. invasive predator management, hydrology management) were composed of a suite of actions to abate the threat (e.g. pre-action office planning, aerial baiting, post-action valuation), and nested within each action were four cost components: labour, travel within site, consumables and equipment (LTCE). Cost modelling was based at the LTCE level. In sum, we assigned a TAS to each biodiversity threat, derived a suite of actions for each TAS, defined a set of standardised actions, described in detail the cost components within these actions, and defined the cost multipliers required.

In the second step we built the cost models based on detailed TAS assumptions. We structured the TAS cost models as a function of action costs, travel to site costs and non-spatial costs (Eq. 1). This step estimated the cost per unit area and travel to site cost per unit area per km distance (Eq. 2 and 3).

$$\begin{aligned} TAS\ cost = & \sum_{actions} (Action\ cost\ per\ unit\ area\ \times\ Action\ area) \\ & + \sum_{actions} (Travel\ to\ site\ cost\ per\ unit\ area\ per\ km\ distance\ \times\ Action\ area \\ & \times 2\ \times\ Distance\ to\ site) + \sum_{actions} Non\ spatial\ costs \end{aligned}$$

(1)

where

$$\begin{aligned} & Action\ cost\ per\ unit\ area \\ & = \sum_{LTCE} Cost\ components\ \times annualisation\ NPV\ factor \times multipliers \\ & \times (management\ grid\ window\ size)^{-1} \end{aligned}$$

(2)

and

$$\begin{aligned}&Travel\ to\ site\ cost\ per\ unit\ area\ per\ km\ distance\\&\qquad = Travel\ cost\ per\ hour \times (transit\ speed)^{-1} \times Number\ of\ trips\ required\\&\qquad \times annualisation\ NPV\ factor \times multipliers\\&\qquad \times (management\ grid\ window\ size)^{-1}\end{aligned}$$

(3)

The action cost per unit area was per km^2 unless specified otherwise i.e. per km of river length or per in-stream structure (Eq. 1). The action areas were determined by the threat extent and were TAS specific (Eq. 1). Distance to site was measured from the closest city or airport to each grid-cell and multiplied by 2 to get a return trip (Eq. 1). Non-spatial costs (if any) are efforts that do not vary with any spatial scale or variables, such as policy change (E1. 1). The cost components are the modelled costs for labour, travel within site, consumables and equipment (Eq. 2). The annualization NPV factor was the standardisation coefficient of different payment frequency cashflows, NPV based on a 4% discount rate and an annuity-due of all payments (Eq. 2 and 3). The multipliers applied were 30% for on-costs, 10% for on-site contingencies, and 30% for uncertainty (Eq. 2 and 3). The management grid window size was assumed to be a standard management area of 100km^2, unless other-wise specified (E1.2 and 3). Number of trips required is based on the trips required for onsite action to be completed in multiples of 21 days of field work (Eq. 3). The travel cost per hour includes vehicle cost and time compensation cost for personnel (Eq. 3).

In the third step we extrapolated the action and travel costs to spatial layers by incorporating the relevant threat, landscape resistance and travel time layers. This process was done for each TAS separately for all management areas that are relevant in Australia. The detail for all costs and assumptions is covered in full in Yong et al (Appendix 4,5 Cost models).

Creating 'action' maps

All spatial analysis was done with spatial data in the projection GDA 1994 Australia Albers. For taxa that all require the same action, we combined their distributions to come up with an area of 'action required' using ArcMap v10.8. The species distributions dissolved into one layer, and the ocean and offshore islands clipped out, to create a final 'impacted species' layer for each action.

There was one exception to the inclusion of "likely to occur" and "may occur" habitat in an allocated action: this was for the "restrict access to critical sites" action. This was restricted to only "known to occur" areas because restricting access was limited to the sites critical to survival of the taxa, and because the other categories of habitat were very large. The data used to create the spatialised cost models that formed the basis of the Threat Abatement Strategy layers are detailed in Appendix 2 Table 3.

To find the area in which the actions were required, we intersected the 'impacted species' layer with the spatial cost model. We calculated the area of each final action map using zonal statistics as table function in ArcMap.

Co-benefits methods

We build on existing work on the co-benefits associated with biodiversity conservation programs to estimate and discuss a preliminary set of 'additional benefits' of implementing threat management strategies targeted at Australia wide threatened species recovery. Where applicable, we apply 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. 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 types of these benefits, which can be created through:

- Restoring the integrity and extent of threatened species habitat in ways that creates additional environmental benefits as well as improving the outlook for threatened species
- Reducing threats that impact upon the economic outcomes of other sectors
- Creating jobs
- Supporting opportunities for cultural management of species and places of value to First Nations Australians, if threat abatement strategies are implemented in culturally appropriate ways where decision making and management is led by Traditional Custodians.

We did not attempt to quantify this these potential benefits – rather we discuss in the discussion section the importance of supporting Indigenous led processes to set local priorities and plans that can care for significant species and places. We provide methods below, and then discuss and quantify examples where possible, and finish by acknowledging the limitations and gaps in knowledge of this preliminary additional benefits analysis for biodiversity threat abatement management strategies across Australia.

Estimating the broader ecological benefits of restoration

We calculated the carbon benefits of the restoring the proposed areas (restorexspp.tiff) we calculated the sum of the maximum potential dry biomass (Roxburgh et al. 2017) of the area to be restored. The total potential dry mass values comes from the Maximum Above Ground Biomass (M) spatial layer (Department of the Environment and Energy 2020). Below ground biomass was assumed to be 26% of above ground biomass following (Mokany et al. 2006). The total potential dry biomass was converted into the equivalent CO2 using the equation:

Total CO2 (tonnes) = (Total dry biomass * .5) * 3.66

Where the weight of the total dry biomass is multiplied by 0.5 to get the total weight of carbon as carbon is assumed to be 50% of dry biomass (Trees for the future 2015). The weight of carbon is converted to equivalent CO2 by multiplying it by 3.66 following (Trees for the future 2015), as the ratio (based on molecular weight) of CO2 to C is 43.999915/12.001115=3.6663.

We also overlayed the map of potential restoration area with current and past native vegetation extents, bioregion extents, protected areas, and threatened ecological communities, to estimate how much area would be added to these. For example, how much area of restored habitat would be added to each of the bioregions, Threatened Ecological Communities, and Bioregions under-represented in the current protected area network (Appendix 7 Table 1).

Costing out full-time equivalent jobs

We calculated total labour cost as the total area managed multiplied by the labour cost/km^2, plus the non-spatial cost. As these are general estimates, we assume the cheaper action labour cost/km^2 when there is potential of double counting actions (i.e. ground and aerial activities), and the most common vegetation type when there are multiple vegetation types.

FTE = Total labour cost/ annual salary, where the annual FTE salary is $110k p.a. ($84k with 30% of on-costs).

In these estimates we have only included TAS that have a spatial element. We have excluded the desktop TAS such as “Biosecurity” and “Policy, education and regulation”; so a final job FTE estimate would be greater than stated here.

Estimating financial benefits to agriculture and other industries

To calculate the benefits of managing invasive predators to industry, we took the extent of the ‘invasive predator management’ Threat Abatement Strategy across Australia in ArcGIS 10.6/Pro (ESRI 2011). We assumed impacts occur across the entire range, and therefore the benefit to agriculture would be the percent of their range in which predators were controlled multiplied by the total cost of those predator species. As these invasive predators can move large distances across landscapes we decided that predator control in all land use types would benefit areas under agricultural land uses. We calculated the percent overlap in the predator management and the current distribution for dogs, foxes, and cats. For cats, we estimated the overlap between grazing land (sheep) and urban areas as these are the places where impacts were costed. For the sheep grazing land we used all grazing that could potentially have sheep across Australia, which includes the land-use categories: Grazing native vegetation (2.1), Grazing modified pastures (3.2), Irrigated pastures (4.2), Intensive animal and plant production (5.1, 5.2), Rural residential and farm infrastructure (5.4.2, 5.4.3, 5.4.4, 5.4.5). The cost of dog and foxes came from the “Cost of Pest Animals in NSW and Australia, 2013-14” report. 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: dogs ($89m), and foxes ($28m). The cost of cats came from (Legge et al. 2020) who estimated the economic costs of cat-dependent pathogens in Australia to be $6 billion per year. Legge *et al.* (2020) 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 dollar value. We estimated that invasive predator management would reduce the impact and cost of dogs by 99.53%, foxes by 98.1%, and cats by 98.74%.

We used a similar approach to estimating the benefit of managing invasive herbivores and invasive birds. We overlaid a map of where invasive herbivore (Invasive grazer management (large herbivore) Threat Abatement Strategy: inv_grazer_cmxsp.tif) and invasive bird management (invasive/problematic bird & bee management Threat Abatement Strategy: bird_actions.shp) was needed, with the current distribution of feral pigs, rabbits, goats, and starlings. The cost of these species also came from “Cost of Pest Animals in NSW and Australia, 2013-14” report and the values include both the cost of management and production loss. We assumed impacts occur across the entire range of each 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: Rabbits ($216m), introduced birds ($69m), then pigs ($14m), and goats ($7m). We used a standard inflation rate of 1.5% to adjust the values in the reports to 2021 dollar value. We estimated that management actions would reduce the impact and therefore cost of rabbits by 91.8%, starlings by 21.9%, pigs by 63.3%, goats by 87.5%.

To estimate the benefit of controlling weeds, we overlaid the map of where weed management is needed, with the broad agricultural and production land uses from Australian Collaborative Land Use and Management Program (ACLUMP 2020) likely to be impacted by weeds. We calculated the benefit of weed management by multiplying the percent overlap in proposed weed management area (Invasive weed Threat Abatement Strategy: inv_weed_cmxsp.tif) and agricultural land uses with the cost of weeds to the agricultural sector. The broad land use categories from ACLUMP used were:

Grazing native vegetation (2.1), Grazing modified pastures (3.2), Dryland cropping (3.3), Dryland horticulture (3.4, 3.5), Irrigated pastures (4.2), Irrigated cropping (4.3), Irrigated horticulture (4.4, 4.5), Intensive animal and plant production (5.1, 5.2), Rural residential and farm infrastructure (5.4.2, 5.4.3, 5.4.4, 5.4.5). The cost of weeds to agriculture and livestock production was taken from the "Economic impact of weeds report in Australia" (Sinden et al. 2003). This report estimated the costs of weeds to be an average of $3,927 million in 2018. The cost value includes the annual cost of weed control, yield losses, loss of economic surplus. We used a standard inflation rate of 1.5% to adjust the values in the reports to 2021 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 weeds cost Australia between $3,583 – 3,737 million per year. Our proposed weeding action would reduce the cost of weeds across 90.66 percent of the agricultural areas impacted by weeds. The average benefit of our proposed weed action would be $3,720 million per year.

Results

The 1,659 species assessed each needed between one and 12 Threat Abatement Strategies, although the majority (n=669) of species required only one (Fig 2.1). There was strong taxonomic bias with the number of Strategies recommended: over 50% of plant species were assigned only one Strategy, compared with 5% of fish and 11% of birds. Birds were assigned the most Strategies, with five bird species requiring more than 10 strategies.

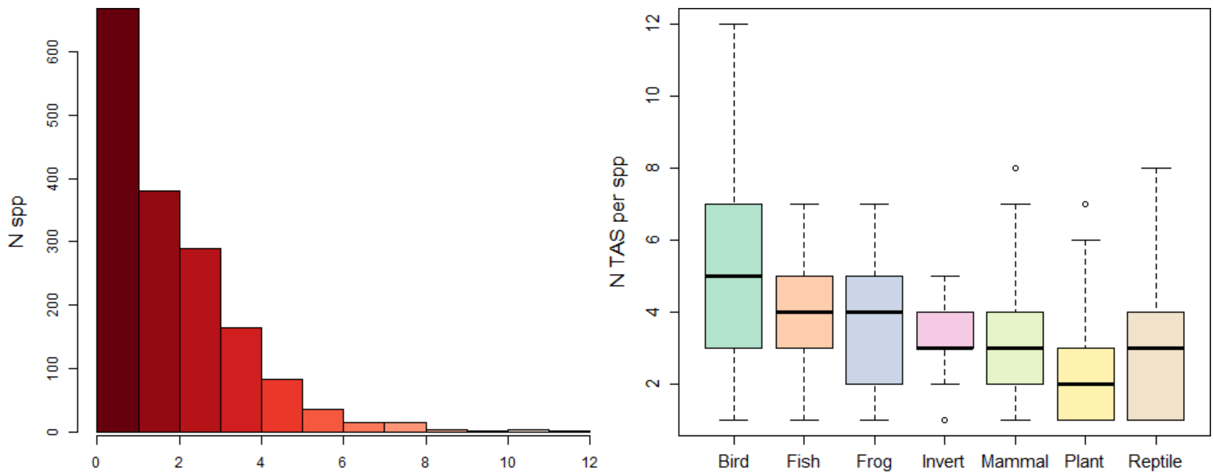

Fig. 2.1. Threat Abatement Strategies required by species and across taxonomic groups. Left: the number of species (y-axis) that require the 12 Threat Abatement Strategies (x-axis), with most species requiring only one. Right: the number of Threat Abatement Strategies required per species compared across taxonomic groups.

We found that habitat restoration was overwhelmingly the most frequent Threat Abatement Strategy required by species (n=1,095, 66%), followed by management of fire (n=676), weed eradication (n=528) and grazing management (n=286) (Figs 2.2-2.3). Habitat restoration was the recommended strategy to address loss of habitat area and quality as a result of agriculture, forestry, mining, urban development, roads and climate change. It was also the best strategy to address other, often related, threats such as salinisation, erosion, water quality, hydrology alteration and in some cases, diseases of freshwater species (Appendix 2 Table 2). In 216 cases, habitat restoration was assigned to address more than one threat per species (Appendix 2 Fig 1).

Table 2.1. Threat Abatement Strategies and their broad objectives. The Code is used for ease for interpreting figures in this chapter.

Threat Abatement Strategy	**Objective of strategy**	**Code**
Aquatic connectivity	Facilitate connectivity of streams to allow waterflow and species dispersal and movement	Aquat conn
Disease management	Prevent spread of pathogens into sensitive areas; Maintain pathogen-free areas	Disease
Fire management	Restore appropriate fire management regimes; prevent catastrophic wildfire	Fire
Grazing management	Grazing management that is compatible with affected species; fence off areas sensitive to grazing	Grazing
Habitat restoration	Restore ecosystem function specific to needs of impacted species	Habitat rest
Invasive fish management	Maintain low densities of invasive fish; prevent invasive fish from entering important habitats	Inv fish
Invasive grazer management (large herbivore)	Eradicate invasive grazers where possible; elsewhere maintain low densities; prevent from entering important habitats	Inv herbiv
Invasive rabbit management	Eradicate rabbits and hares where possible; elsewhere maintain low densities; prevent from entering important habitats	Rabbits
Invasive predator management	Maintain low densities of invasive predators	Inv predator
Invasive weed management	Maintain low densities of invasives, eradicate where possible; prevent spread	Weeds
invasive/problematic birds & bees management	Prevent problematic birds & bees from impacting species' breeding populations	Inv prob birds
Native herbivore management	Protect small vulnerable populations through macropod & possum-proof fencing	Nat herb

Map & protect refugia	Identify areas that could serve as refugia from climate change, have these mapped and protected	Map protect
Restrict access to critical sites	Prevent access to site to avoid hunting, collecting, disturbance	Restrict acc
Policy, Education, Regulation	Create the policy setting that mitigates threats: - Fisheries - Forestry - Herbicide & pesticides - Light pollution - Habitat - Road strikes - Water extraction - Wind	P,E,R
Invasive management (other)	Manage habitat and problematic species to prevent damage to impacted species	
Intensive/ ex-situ	Implement intensive conservation programs to prevent further problematic decline	
Biosecurity		

When all the "policy, education and regulation" Threat Abatement Strategies were combined, they made up the fourth most commonly assigned Strategy. As there were fewer fish species compared with all other taxonomic groups (except frogs), the Strategies specific to freshwater species such as aquatic connectivity and management of invasive fish were required by small numbers of species. Over 73% (n=30) of fish species required habitat restoration (Appendix 2 Table 1).

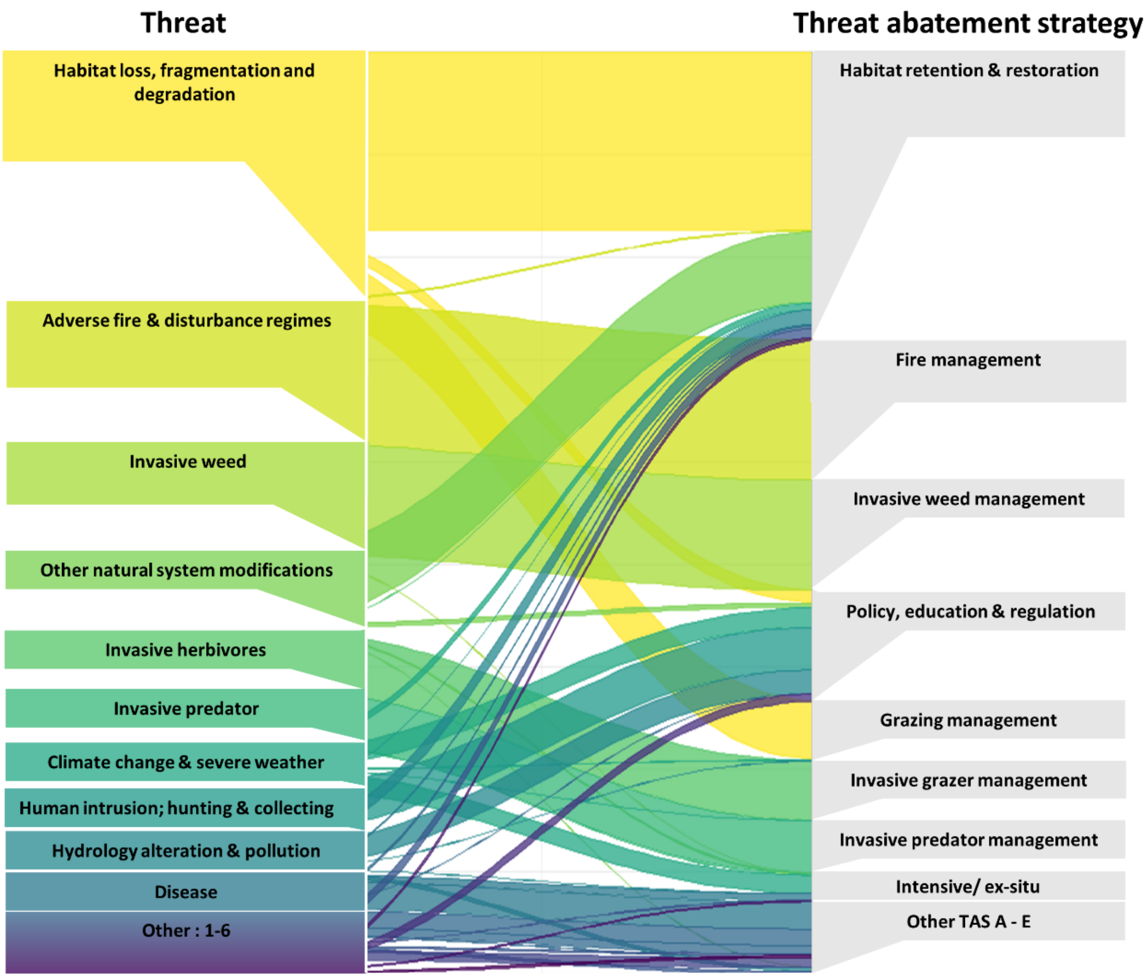

Fig. 2.2. Threats and Threat Abatement Strategies. Left: Threats impacting species. Right: Threat Abatement Strategies assigned to each species to address each threat. Bar widths indicate the relative number of species in the threat and Threat Abatement Strategy categories. Threats in the 'Other: 1-6' category were: problematic native species, invasive animals (not otherwise stated), invasive fish, biological resource use (fisheries, forestry), small/restricted population, invasive/ problematic birds and bees. Threat Abatement Strategies in the 'Other TAS A – E' bar were disease management and biosecurity, native herbivore management, invasive/problematic bird and bee management, invasive fish management, aquatic connectivity, Invasive management (not otherwise stated).

Ten of the Threat Abatement Strategies were required by 151 species or fewer (Fig 2.3); yet multiple Threat Abatement Strategies impacting small numbers of species were still required broadly across Australia: management of invasive predators (n=151), invasive grazers and rabbits (n=128).

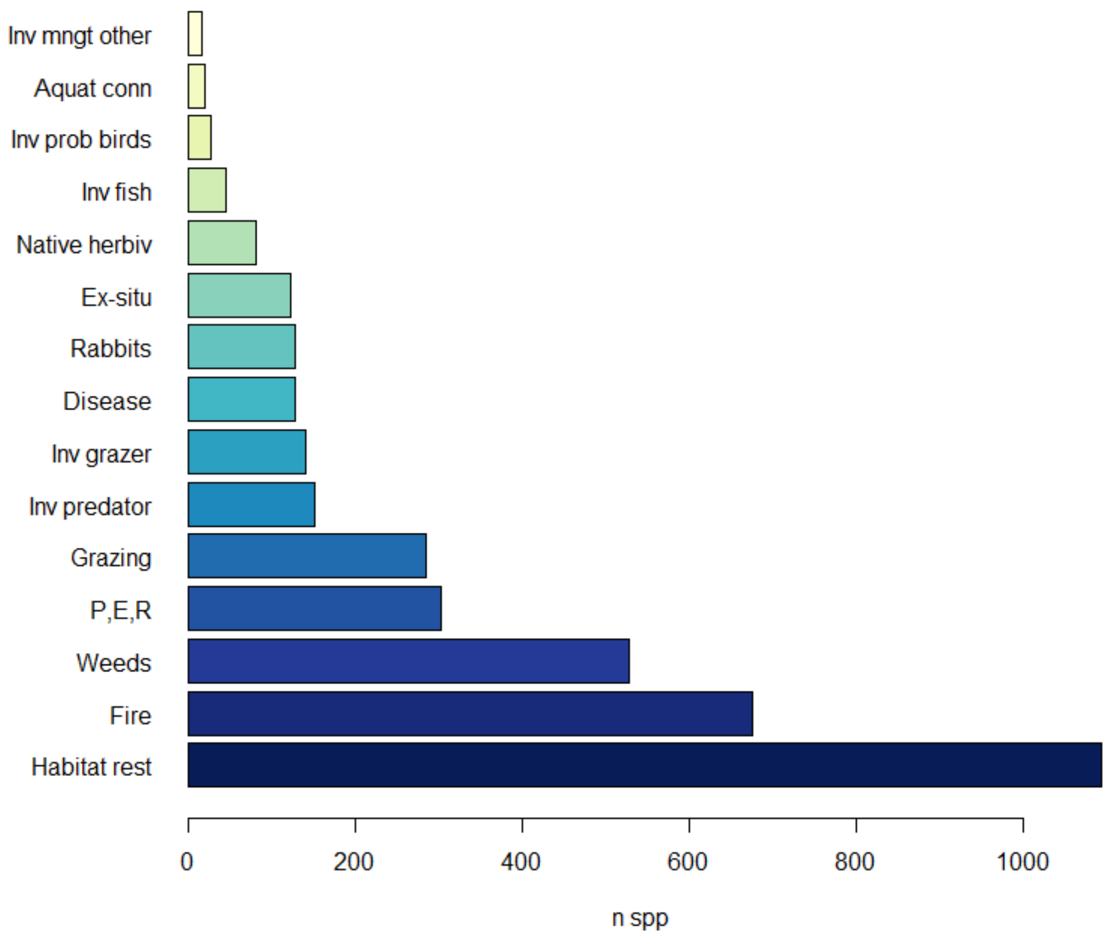

Fig. 2.3. Threat Abatement Strategies, ranked by the number of species requiring each. Refer to codes in Table 2.1 for a full description of each strategy.

We discovered high variation in the cost of each abatement strategy but unsurprisingly, the field-based Threat Abatement Strategies had substantially higher cost than those without the field component. Controlling weeds was the most costly strategy in total (Fig 2.4), partly because it is a labour-intensive action required over a large area (Figs 2.4,2.6), and the next highest total costs were for managing invasive fish, habitat restoration and managing disease. These four Threat Abatement Strategies were labour intensive, and managing invasive fish also required costly infrastructure. The fifth highest total cost was for management of grazing: this predominantly involved fencing to manage the number of stock to reduce grazing pressure, for example, taking cattle or sheep out of sensitive riparian zones, or only allowing grazing at certain times of the year. Likewise for managing the native herbivores that are impacting threatened species, mostly for narrow-ranged plants such as rare orchids, the costs were around fencing out the native herbivores from the tiny populations. The lowest overall cost was for the ‘map and protect refugia’ which was primarily a desktop exercise, with a small budget for on-ground surveys; and predominantly required for species occurring in relatively accessible areas (where the cost of access and travel are lower compared to the remote regions).

Habitat restoration had the greatest cost per area by a wide margin (Fig 2.4).

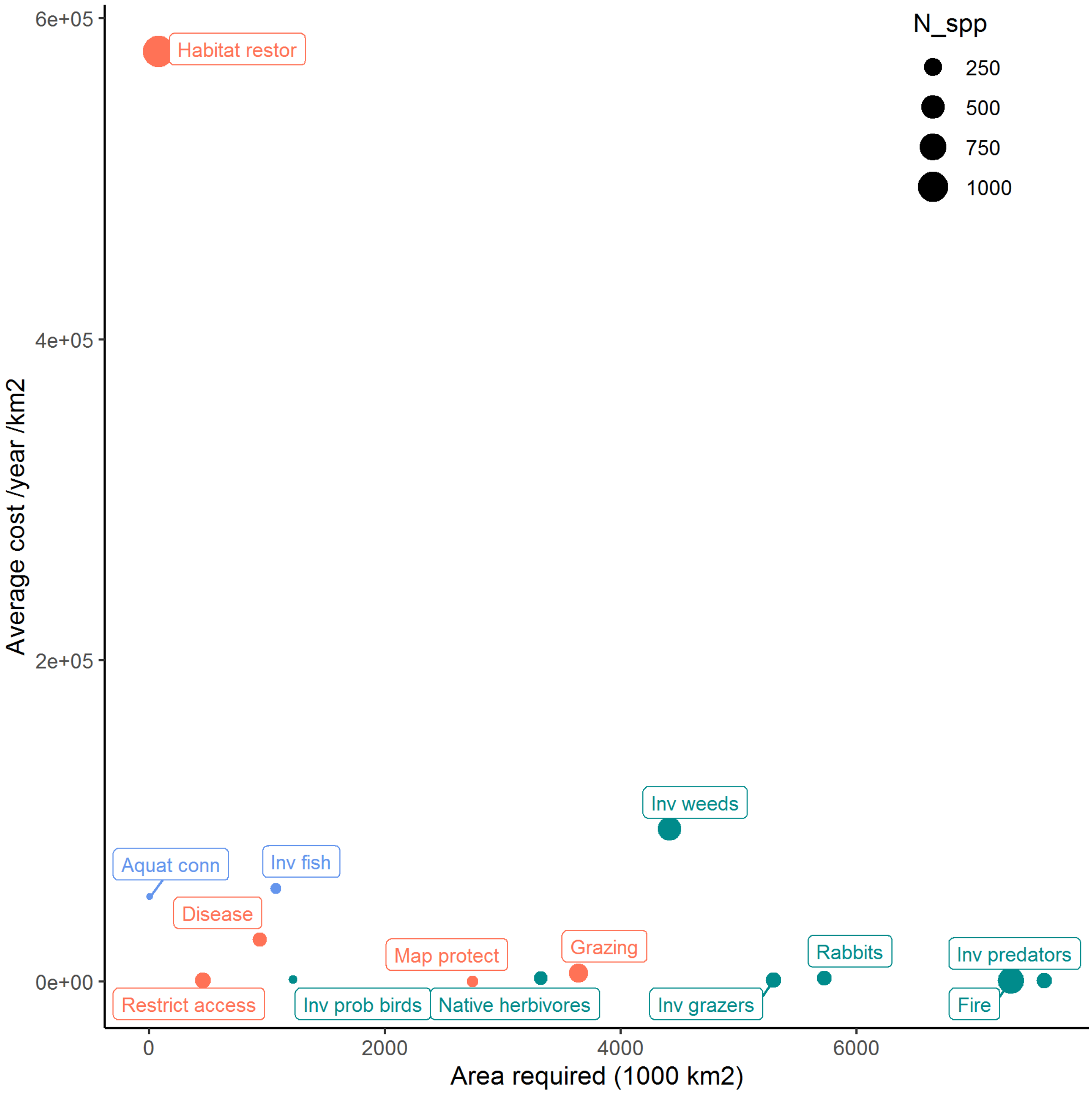

Fig. 2.4. A comparison of the cost per km^2 of each spatially costed Threat Abatement Strategy and its total potential extent. Y-axis shows the average cost per km^2 of each Strategy, the x-axis shows the area over which each strategy is required to address the threat to each species. Relative number of species requiring each strategy is demonstrated by the size of the circle. The colours correspond to whether the species requiring the Threat Abatement Strategy are predominantly terrestrial (green), freshwater (blue) or both (orange). Refer to codes in Table 2.1 for a full description of each strategy.

Eight costs had similar costs per area: restricting access to critical sites, managing problematic native herbivores and problematic birds, managing fire, managing grazing, and managing invasive species such as rabbits, large invasive herbivores, and invasive predators. Managing grazing was required over a very large area (3,643,760 km^2), was required by 286 threatened taxa, had low total cost and has the second lowest cost per area (after 'map and protect refugia').

Taking into account the annualised cost of all Threat Abatement Strategies combined, the total cost of all Strategies was AUD $610,157,764,714 (Fig 2.5). Controlling weeds made up 69% of the total; but there was less variation in costs per km2 across the remaining strategies.

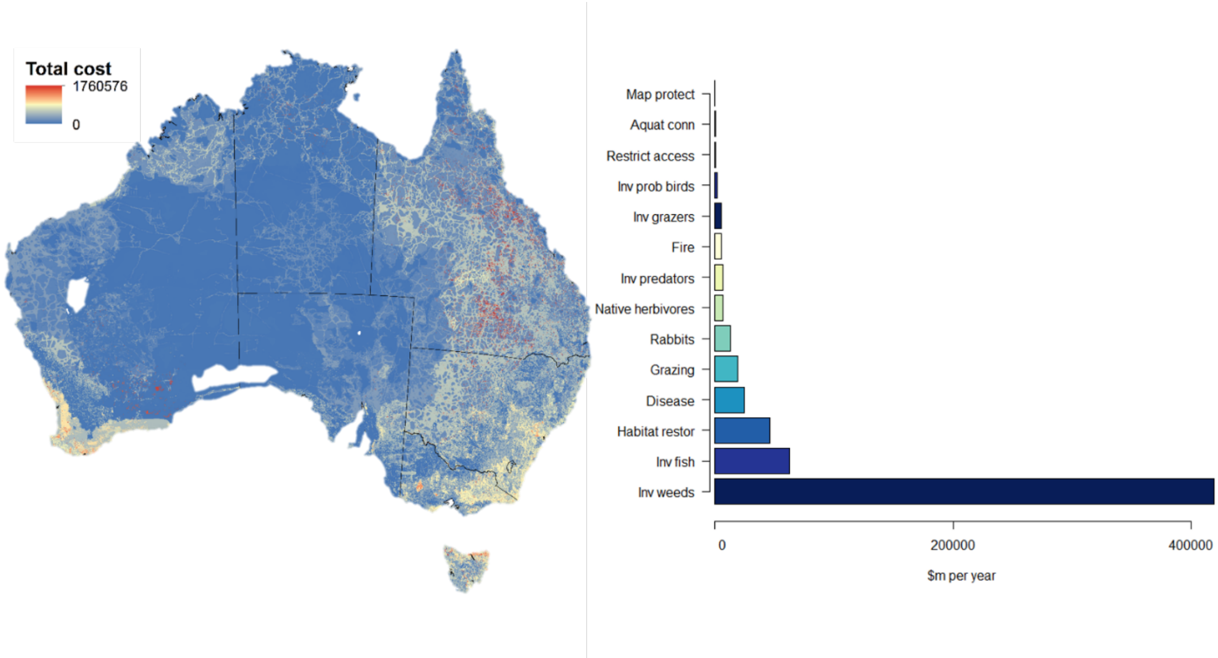

Fig. 2.5. Total cost of all Threat Abatement Strategies. Left: the sum of the costs of all the Threat Abatement Strategies across Australia (legend shows amount in dollars). Right: the total cost of each Threat Abatement Strategy. Refer to codes in Table 2.1 for a full description of each strategy.

Some Threat Abatement Strategies that were required broadly across Australia such as managing fire, invasive predators and rabbits had low overall costs, whereas invasive fish management was the second greatest overall cost but was only required in a small extent. Overall, there was no generalised relationship between the area required and the cost per km^2 across all strategies (Figs 2.4, 2.6).

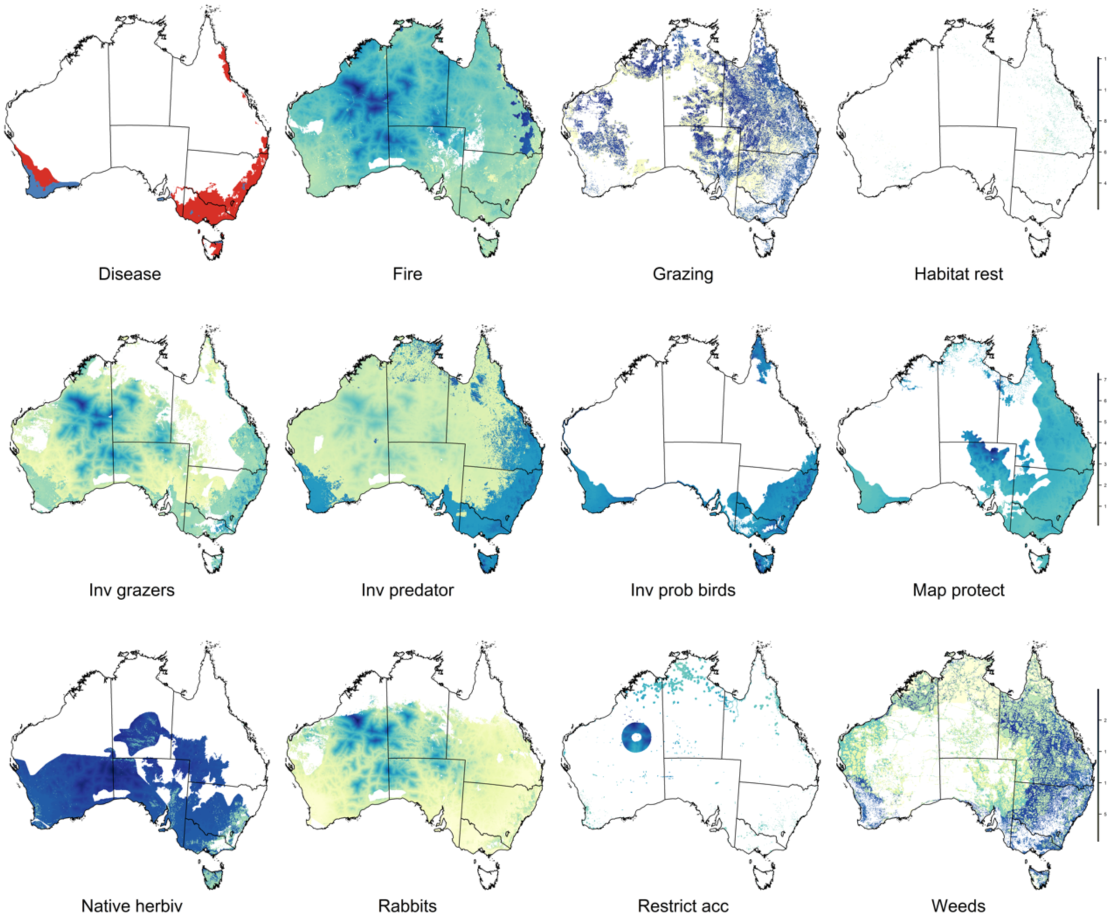

Fig. 2.6. The extent of each Threat Abatement Strategy needed by impacted threatened species. Shown here are the Threat Abatement Strategies required by terrestrial threatened species only, or Strategies that benefit both terrestrial and freshwater threatened species. Refer to codes in Table 2.1 for a full description of each strategy.

The Threat Abatement Strategies required by freshwater species alone, such as increasing aquatic connectivity and managing invasive fish, were required over much smaller areas than actions that benefit terrestrial taxa (Fig 2.7), and also had moderately lower costs per area.

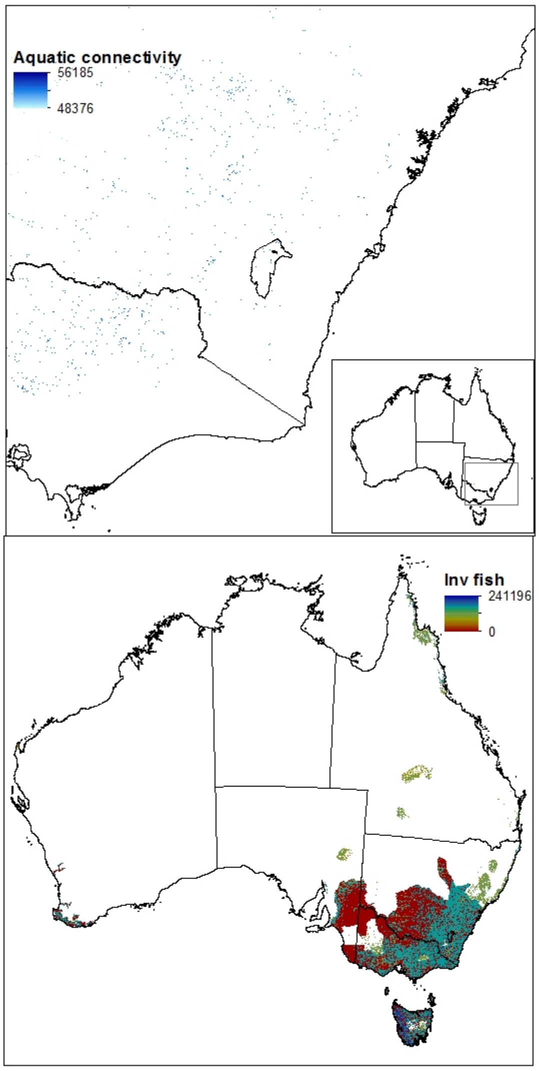

Fig. 2.7. The extent of each Threat Abatement Strategy needed by impacted freshwater threatened species only: aquatic connectivity and managing invasive fish.

By examining the total cost of implementing all Threat Abatement Strategies against the number of threatened species occurring in each area, a pattern starts to emerge (Fig 2.8). The east coast, Tasmania and south-west Western Australia have high costs as well as high numbers of threatened species. Areas that could provide opportunities for high return on investment are those with high numbers of threatened species, and comparatively low cost: these areas can be found across northern Australia, particularly the tropical parts of the Northern Territory and north-west Western Australia. In contrast, parts of the inland, particularly western New South Wales and Queensland which have high implementation costs, but fewer species.

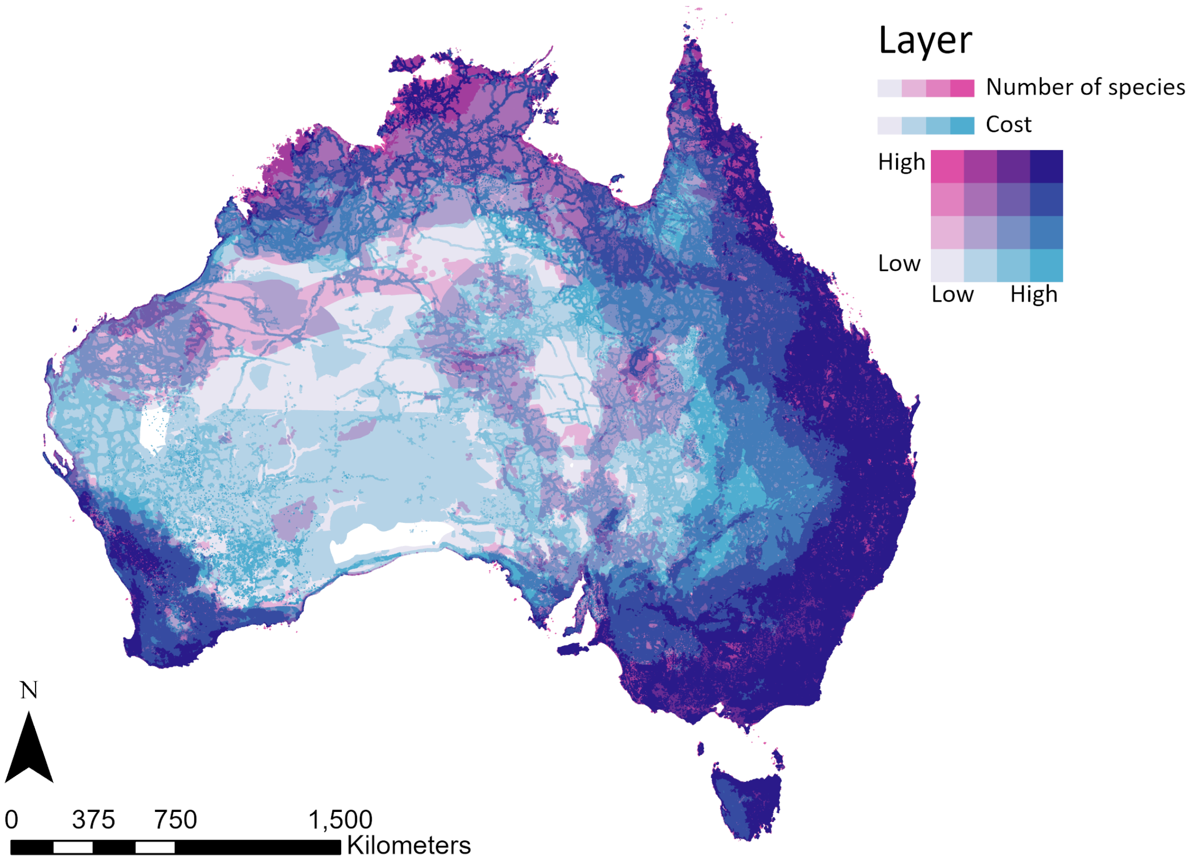

Fig. 2.8. The total cost compared with the number of threatened species occurring across Australia. Paler areas denote lower cost and fewer species, dark purple denotes high cost and greater number of species.

Species recovery outcomes possible with complete and partial funding

We have made the assumption that species need all of their assigned Threat Abatement Strategies to be fully recovered. By doing this we can investigate the species that would not achieve full recovery if all Threat Abatement Strategies were not fully funded (Fig 2.9). We show that without fully funding the three most expensive Threat Abatement Strategies, only a very small proportion (22%) of threatened species could fully recover (if our assumptions hold). This means that an approach that only focusses on specific Threat Abatement Strategies, and ignoring others, will likely lead to a very small number of species being recovered.

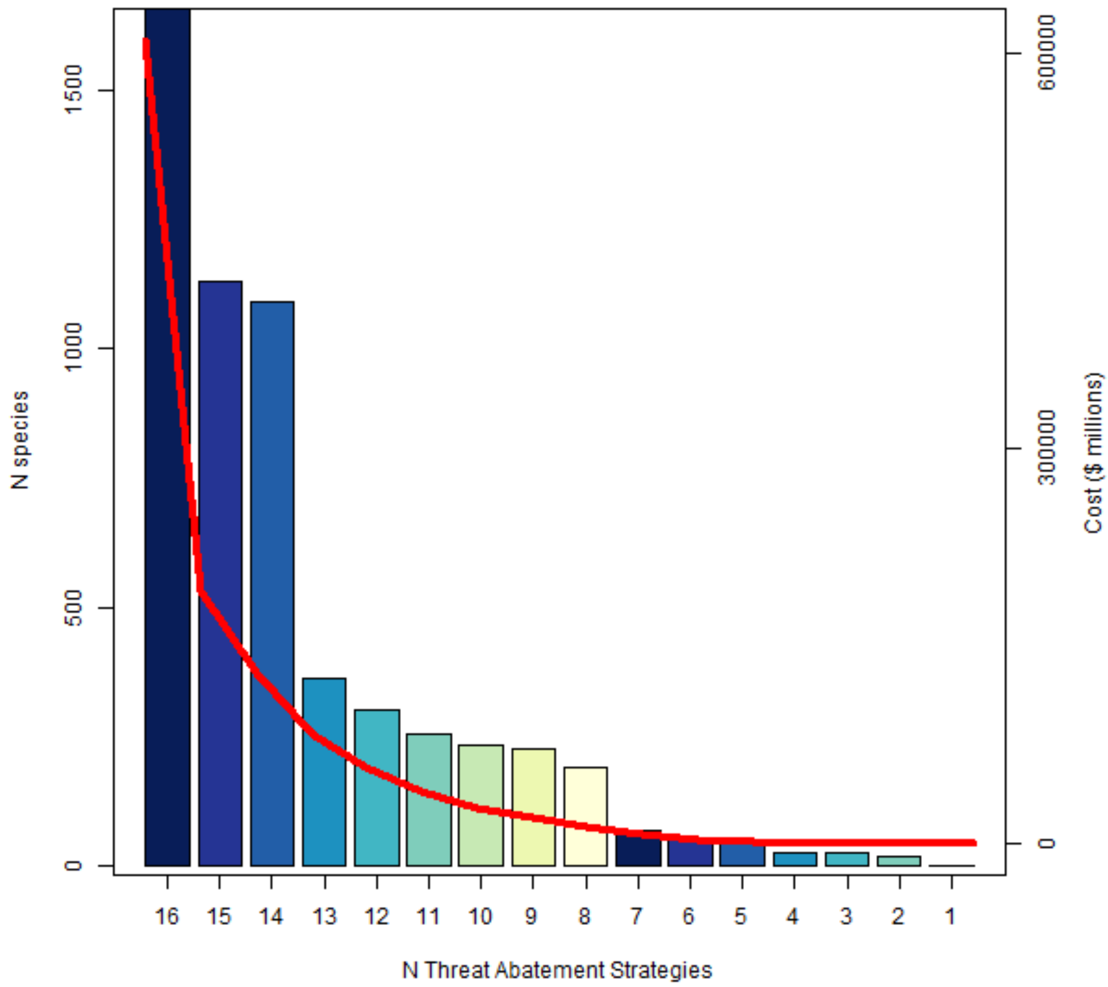

Fig. 2.9. The number of species that could be recovered with complete and partial funding for threat management strategies. Starting from the left: bars show all TAS, then all but the most expensive (weed management), and so on. Red line indicates the cost associated with funding all the TAS (start), then then all but the most expensive, with costs on the right axis, in millions.

Potential co-benefits of implementation

If implemented, the Threat Abatement Strategies likely have far-reaching benefits beyond threatened species recovery. While biodiversity conservation has real and perceived conflicts with other societal priorities and resource use, conservation management can also result in ecosystem services and socio-economic benefits for people (Costanza et al. 1997; Waldron et al. 2017; Waldron et al. 2013). Many of the same threats causing threatened species declines also result economic losses to other sectors, such as agriculture through reduced land profitability. We estimate the likely production savings created by removing threats that impact upon agricultural production is more than AUD$9.9 billion per year, although we recognise other sectors (such as tourism) would benefit from this type of threat management. Collectively, invasive animals and plants cost the Australian economy around AUD$15.3 billion dollars (adjusted for inflation https://www.rba.gov.au/calculator/annualDecimal.html), just in economic loss and control (Hoffmann & Broadhurst 2016) – although itemized costs for all invasive species are not available in this study. Every year, the cost of vertebrate pests such as dogs ($99.1 million), foxes ($31.5 million), starlings ($16.7 million), rabbits ($22.7 million), pigs $16.0 million), and goats ($7.8 million) are immense. These seven pest vertebrates cost the Australian economy between $455.6 – 872.7 million dollars per year adjusting for inflation (McLeod 2016). Recently, cats were found to cost around $6.06 billion per year in agricultural production loss and disease transmission to humans (Legge et al. 2020). Invasive weeds cost the Australian agricultural sector between $5,199 - 6,677 million dollars per year (Sinden et al. 2003).

If we were to manage invasive species (predators, herbivores, and weeds), the benefit to the Australian economy would be enormous. We calculate it conservatively to be at least $9.9 billion. The benefit of invasive predator management is more than $98 million dollars per year for dogs, more than $30 million per year for foxes, and more than $5.9 billion per year for cats. We estimate the benefits of managing invasive herbivores is more than $10.1 million for pigs, $6.7 million for goats, and $16.7 million for starlings. Invasive weed control would result in more than $3.7 billion dollars in benefit.

The benefits of control are likely to extend beyond the avoided costs of management and production losses. Reducing these costs to Australia's economy would free up research dollars ($726 million dollars in grants were awarded research invasive species management), and reduce costs of food for consumers (Sinden et al. 2003). Weed control could benefit indigenous communities, for example the financial costs of weed control on Indigenous land in the Northern Territory is estimated at $4.6 million dollars per year (Sinden et al. 2003).

An important Threat Abatement Strategy in this analysis focuses on improving the integrity of threatened species habitat and extending it through restoration. The most obvious benefits of these actions are generated through increasing native vegetation coverage by more than 79,000 km^2 (Appendix 7) and the resultant improvements in habitat conditions for non-threatened species, soil stability and integrity, decreased run-off, cleaner waterways and oceans, and the maintenance of local microclimate conditions (BenDor et al. 2015). By the time these restored vegetation reaches maturity, they would sequester at least 10.9 million tonnes CO_2 in above and below ground biomass combined, which is equivalent to 2% of Australia's total emissions during 2020 (Australian Government 2021). At a carbon price of $16.55 per tonne, this carbon could be worth $180 million.

These restored habitat areas would also add significantly to Australia's ecosystem retention extents. Currently, 27 bioregions have less than 10 per cent of their area protected under conservation tenure (CAPAD 2018). Efforts to restore vegetation for threatened species would add more than 29,000 km^2 of threatened ecological communities of natural environmental significance, and 77,000km^2 of habitat would be restored outside of protected areas in those bioregions that are under-represented (< 10%). In addition to these increases in the extent of threatened species habitat, areas of extant threatened species habitat would be improved through management of threats and improved in terms of ecosystem integrity. In addition, habitat restoration would also be of benefit to most of the c. 340,000 non-threatened terrestrial and freshwater species across Australia. The cumulative impact of multiples threats has been implicated in ecosystem collapse (Bergstrom et al. 2021), and hence improved threat management is likely to increase ecosystem health and resilience in the face of climate change.

Together, our analyses suggest that implementing these Threat Abatement Strategies would result in 954,275 jobs, ongoing over 80 years, based on the cost models we created for estimating the full-time equivalent jobs required each year for each threat abatement strategy (Table 2.2). The more labour intensive and spatially extensive strategies such as managing invasive fish, disease and rabbits, would likely create the most jobs. As we have not distinguished between jobs that are already in existence and additional jobs, we are unable to claim these as being all additional to the current workforce. It is however worth noting that the jobs created collectively by these Threat Abatement Strategies amount to approximately 70% of current unemployment. Much of this work would be needed in remote and rural Australia, bringing much-needed jobs to struggling regions, particularly for indigenous ranger groups. We recommend that Threat Abatement Strategies to recover threatened species be implemented in ways that support Indigenous cultural values through ensuring First Nations leadership in decision making and management for species and places with Indigenous interests. This would require commitment to culturally appropriate management led by Traditional Custodians and broader recognition of the cultural values of places and species that are significant to Indigenous groups.

Table 2.2. The labour costs and full-time equivalent (FTE) positions required to implement all the Threat Abatement Strategies required to recover all threatened species.

Threat Abatement Strategy	**Total Area Managed**	**Spatial Cost/km^2**	**Total Labour Cost (AUD$)**	**# FTEs**
Aquatic connectivity	2,993	227,370	$ 682,085,744	6,218
Disease management	936,058	9,885	$ 9,252,824,525	84,356
Fire management	7,308,481	323	$ 2,359,617,685	21,512
Grazing management	3,643,760	596	$ 2,172,478,576	19,806
Habitat retention & restoration	79,960	55,593	$ 4,446,789,996	40,541
Invasive fish management	1,072,484	12,258	$ 13,148,440,969	119,872
Invasive grazer management (large herbivore)	5,295,790	241	$ 1,276,318,564	11,636
Invasive grazer management (rabbits)	5,727,081	1,045	$ 5,982,571,886	54,542
Invasive predator management	7,591,786	234	$ 1,778,966,985	16,219
Invasive weed management	4,414,089	13,658	$ 60,289,733,919	549,650
Invasive/problematic birds & bees management	1,216,263	498	$ 605,797,810	5,523
Native herbivore management	3,322,385	748	$ 2,486,798,662	22,672
Map & protect refugia	2,745,020	24	$ 67,463,769	615
Restrict access to critical sites	456,043	265	$ 122,195,393	1,114
Total			**$ 104,672,084,482**	**954,275**

The persistence of threatened species at high enough population numbers to perform their functional roles in maintaining ecosystems and species interactions is difficult to quantify. In this section we have focused on the co-benefits of the management strategies to other industries, rather than attempting to quantify the ecosystems services that are provided by the retention or improved persistence of the threatened species themselves, or their habitats. The protection and management of threatened species habitat also offers an array of additional benefits and ecosystem services, although it is challenging to quantify these in economic terms, and to claim additionality because threatened species habitat is legislatively protected. However as shown elsewhere, the value of extant native ecosystems across Australia is immense, and since threatened species exist across the vast majority of Australia, we can conservatively assume that threatened species coincide with a generous proportion of this value.

Discussion

This first attempt to cost out what it will take to fully recover threatened species at a continental scale across a large megadiverse nation shows that genuine commitment to species conservation targets in the GBF requires significant resourcing. We find that the cost of recovering all threatened species per annum (AUD $61 B) equates to approximately 34% of Australia's 2020 Gross Domestic Product (https://data.worldbank.org/country/AU) and around half of what economists recently estimated what is needed to finance global nature conservation (Deutz et al. 2020). While these numbers should not be used to extrapolate global costs for abating species – as the reasons why Australia's species are threatened are not the same in all places around Earth (Evans et al. 2011; Maxwell et al. 2016) – they should be a cautionary tale of not underestimating the financial costs of species recovery, which nations need to commit to in order to meet their obligations under the GBF (Secretariat of the Convention on Biological Diversity 2021).

Threatened species, as well as their corresponding threatening processes, occur broadly across Australia, and we show that the recovery of all of Australia's threatened species will require action across most of the continent. This is likely the case for most countries, given the degree of degradation across the planet (Halpern et al. 2008; Venter et al. 2016) and pervasive nature of climate change and spread of invasives and disease (Maxwell et al. 2016; Scheffers et al. 2016). This means, for the target set out for species recovery in the GBF (Secretariat of the Convention on Biological Diversity 2021), threat abatement activities are likely to be required across vast swathes of Earth. For many species, changes in current or planned land use would be required to achieve recovery, as many human activities that clear or degrade species habitat are not compatible with a plan to recover those species (Di Marco et al. 2018). But critically, we found that many widespread Threat Abatement Strategies are low cost per km^2, so that their implementation in many places is likely to be viable. Furthermore, undertaking actions to manage these particular threats is compatible with of many land uses that occur across these areas. For example, the management of fire, livestock grazing, and invasive species such as predators, herbivores and weeds, is required across most of Australia. These activities are beneficial across multiple sectors, and if implemented well, will lead to not just species recovery but also better farming and wider land use practices. Moreover, activities that reverse impacts of habitat loss, degradation and fragmentation will have significant positive effects on salinisation, erosion, water quality and microclimate which will be of benefit to multiple industries.

The Australian nation is well-placed to meet the Global Biodiversity Framework 2030 Action Targets, sitting above the 90th percentile for per capita GDP (https://data.worldbank.org/), with comparatively strong governance structures. However, our work needs to be considered in the context that Australia significantly underspends on biodiversity conservation relative to available wealth (Wintle et al. 2019), and federal spending on the environment has decreased by over one third in the last decade (Australian Conservation Foundation 2018). This is despite the fact that the threatened species list is growing (Woinarski et al. 2019), indicating a worsening crisis. If Australia is serious about meeting their Convention on Biological Diversity obligations when it comes to species recovery, it must undertake a steep change in conservation funding, and take a broader view of how landscapes are managed across Australia. In particular, attention is needed on how agricultural lands are managed while retaining and improving threatened species habitat, controlling invasives and managing fire. Over 50% of mainland Australia is under a stock grazing tenure, much of this is grazing of native vegetation, and is home to many threatened species. Constructive partnerships with landholders, with compatible objectives, will therefore be a major determinant of the success of threatened species recovery.

Fortunately, there are substantial opportunities for these recovery strategies to provide far-reaching benefits, for the agricultural industries and for regional communities through employment. Over 900,000 full-time equivalent jobs will be needed per year to implement this work, which will provide $9 billion per year benefit to agricultural productivity. This work will result in the sequestration and storage of up to 10.8 million tonnes of carbon.

We found that habitat restoration was required for over 1000 of Australia's threatened species, to address the impacts of habitat loss, degradation and fragmentation. Over 84% of species listed as threatened nationally in Australia experienced habitat loss through clearing within the government's own species-specific maps of habitat extent in the last two decades (Ward et al 2019). Restoring threatened species habitat is expensive: habitat restoration had the greatest cost per area of any of our Threat Abatement Strategies. Therefore, a genuinely cost-effective (as in, both inexpensive and highly effective) recovery plan must include the proactive prevention of future habitat loss and degradation. High densities of threatened species often coincide with high densities of people: in particular, the productive east coast regions of Australia. This region is in high demand for most of the industries that sustain the human populations, from agriculture to mineral resources, as well as residential infrastructure. Understanding the value of healthy ecosystems, in conjunction with the true of recovering threatened species, and the cost-effectiveness of keeping habitat intact compared with restoration post-clearing, will be instrumental to the social feasibility of this work.

There are species across Australia that are in too perilous a state to rely on landscape scale threat abatement alone, including 138 species requiring intensive or ex-situ action, such as captive breeding, in order to be recovered. For example, both the Southern Corroboree Frog (*Pseudophryne corroboree*) and Northern Corroboree Frog (*Pseudophryne pengilleyi*) species are Critically Endangered and will continue to decline without captive breeding; therefore, maintaining captive colonies is a high priority for the recovery of these species, and is estimated to cost $1.4 million over five years (OEH NSW 2012). Costing out individual species captive breeding programs for each species that required it were beyond the scope of this study. However, cost estimates from individual species' recovery plans indicate that captive breeding can cost over $980,000 per year for one species (Appendix 2 Table 6), and can be a large proportion of overall recovery costs. Therefore, our total cost estimates would substantially increase if captive breeding was included, which would be necessary if zero extinction was the goal. Likewise, some threatened mammal species do not occur in large numbers in the presence of invasive predators such as foxes and cats, and these species need to be maintained in predator-proof places such as islands and fenced exclosures (Ringma et al. 2018; Ringma et al. 2019).

There are other important costs of recovering every threatened species that were beyond the scope of this study, but require a mention here. In particular, monitoring threatened species populations with sufficient granularity to be able to detect changes in populations even of cryptic species is an important, and substantial, undertaking (Scheele et al. 2019). Drawing upon the detailed threatened species recovery and monitoring planning work done by the New South Wales Government, we averaged the cost of monitoring species across taxonomic groups (OEH NSW 2012), then extrapolated by multiplying these costs by the number of threatened species in each group. From this we estimate that it would cost at least $5 million per year to monitor all of Australia's threatened species; and potentially substantially more to account for monitoring in the very remote parts of northern Australia, for cryptic species, and to include fish that were not included in this estimate (Appendix 2 Table 5).

We also excluded offshore islands from our costings, because threatened species recovery on islands will be idiosyncratic to each island's context. This is an important focus for future work because of the importance of islands for threatened species (Moro et al. 2018). There will be substantial costs associated with community consultation and project co-development with Traditional Custodians and other land owners, managers and communities. Additionally, we did not factor in the cost of research to support recovery actions. While important action can be undertaken without further research, such as habitat retention and invasive species management, we acknowledge that more research will be required to effectively manage all threats, accounting for interactions between threats, and how threat abatement actions change these interactions. Great gains in our understanding of interactions between threats have been made in the recent decades (Hohnen et al. 2016; McGregor et al. 2015; Moseby et al. 2021), showing that, in some case, threat management can result in a negative impact to threatened species populations as a result of antagonistic threat interactions (Marlow et al. 2015). In particular, more research will be needed to effectively manage where co-occurring threatened species have conflicting management requirements. For example, while dingoes pose a threat to some threatened animals (one bird and 15 mammal species – seven of these high impact), dingo control can lead to the reduction of other, smaller threatened mammal species, as a result of macropods and other predators that benefit from dingo control (Colman et al. 2014). The effect can be compounding: macropod grazing increases in areas where dingoes are controlled, leading to simplification of the vegetation structure, which in turn renders small native mammals more vulnerable to cat and fox predation; and cats and foxes are in higher densities in the absence of dingoes (Dexter et al. 2013). Likewise, fire has been shown to have important interacting effects with other threats (Geary et al. 2019; McGregor et al. 2017; McGregor et al. 2014). Therefore, understanding optimal fire regimes for all the various components of biodiversity in different ecosystems, how different fire regimes interact with other threats, and how these might all shift under climate change, will require ongoing research efforts.

Here, we costed out habitat restoration only where there was some likelihood of restoring the habitat; this excluded land that is currently under land uses such as intensive agriculture, which is unlikely to be decommissioned and returned to threatened species habitat. Therefore, in reality, to recover many threatened species with insufficient habitat area and quality, substantially greater areas of habitat restoration would be required (Appendix 2 Fig 7), which would equate to far higher total cost and pose more difficult social feasibility challenges.

In this work we do not delve into the issue of responsibility of resourcing threatened species recovery, and indeed much of this work is already being done by a range of different stakeholders. State governments conduct their own threatened species recovery action programs (Chadès et al. 2019; Geary et al. 2021; OEH 2013; Thomson et al. 2020), and some threatened species recovery is resourced and led by non-government organisations such as Natural Resource Management groups, and local and international wildlife NGOs (e.g., Australian Wildlife Conservancy, Bush Heritage Australia, Trust for Nature). Importantly, much of this work is carried out through joint objectives of landscape management and agricultural productivity: in particular landholders that manage invasive predators, herbivores, weeds and fire. However, these efforts need to be scaled up to be commensurate with stopping decline of species, to be done using threatened-species-sensitive methods, and to be externally resourced to ease the burden on private landholders who also need to sustain viable agricultural enterprises. There are emerging funding mechanisms that have great potential, if managed judiciously, to substantially increase recovery work efforts. These include carbon markets, biodiversity accreditation for farms, and funding for increasing water quality in barrier reef catchments. Crucially, important governance needs to accompany these mechanisms to ensure actions undertaken are additional to that already undertaken, so that important funding does not simply maintain business as usual.

Our standardised approach to costing can be adapted for other contexts, to estimate the cost of threatened species recovery in other parts of the world. Delaying action will result in increased costs, and poorer outcomes (Driscoll 2017; McCarthy et al. 2012). Biodiversity loss is a material financial risk at all levels of economic activity (Costanza et al. 1997), yet conservation is sometimes erroneously viewed as only an economic burden. More than half the world’s total GDP - US$44 trillion - is estimated to be at risk due to nature-related dependencies. Such risks include disruptions to operations and asset devaluation faced by sectors such as fisheries, forestry, mining, agriculture, and urbanisation. People spend over US$0.6 trillion per year to visit conservation areas, which contrasts to the less than US$0.2 trillion per year that gets spent on area-based conservation worldwide.

Chapter 3. How to prioritize species recovery after a megafire event

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Abstract

Due to climate change, megafires are increasingly common, and have sudden, extensive impacts on many species over vast areas, leaving decision-makers uncertain about how best to prioritize recovery. Here, we provide a decision-support framework that generates a prioritization of conservation actions needed immediately after a megafire. The framework includes two approaches. The first approach is cell-based, focusing on identifying areas that can cost-effectively recover the most species in any one location, whilst the second approach is broad-scale, selecting complementary locations to extend actions across all impacted species habitats. Using the 2019–2020 Australian megafires as a case study, we show that 290 threatened species have likely been severely impacted and require immediate conservation action. Our framework identified 185 subregions, found mostly in south-east Australia, as key locations to extend actions across all species

habitats. This framework can be utilized to prioritize conservation actions that will best mitigate impacts of future megafire events.

Introduction

Earth's climate is changing and as a consequence many regions are experiencing larger, more frequent (Lindenmayer & Taylor 2020), higher intensity 'megafires' (Mantgem et al. 2013; Stephens et al. 2020), that now often occur within lengthened fire seasons (Jolly et al. 2015). A megafire is defined as fire that burns >400km^2 in extent (Lindley et al. 2019). These megafire events can be disastrous not only for biodiversity (Ward et al. 2020a) but also for people and assets (Jolly et al. 2015). For example, the 2018 'Camp Fire' megafire was one of California's largest megafires in recorded history. It had serious impacts on fauna and flora species, and caused 88 human fatalities, destroying 18,804 societal structures and was 620km^2 in extent (United States Census Bureau 2018). In 2019–2020, megafires occurred across eastern, southern and western Australia, impacting more than 96,000km^2 of fauna habitat (Ward et al. 2020a) – an area bigger than Hungary and more than one hundred times bigger than the 2018 Camp Fire in California.

A range of anthropogenic drivers including climate change, altered land management practices, and invasive species are now shown to be causing these changes in fire regimes (Berry et al. 2011; Zylstra 2018). Native species vary in their ability to cope with changed fire regimes, predominately driven by differences in life histories and functional traits (Whelan 1995; Caturla et al. 2000; Clarke et al. 2015). For example, many woody plant species (e.g., obligate-seeding trees and shrubs in Australia, South Africa, Papua New Guinea and United States of America) need hot fires to disperse and germinate seeds, making fire an essential disturbance for maintaining populations (Regan et al. 2010; Bowman et al. 2016). However, if two fires occur in quick succession, with a shorter gap than the age to maturation, obligate seeders can become locally extinct. Other plant species (e.g., long-lived rainforest trees such as the Wollemi Pine *Wollemia nobilis*, Huon Pine *Lagarostrobos franklinii*), and Marchand (*Protium guianense*) are highly sensitive to repeated fires due to evolving in the absence of fire, wet locations, and requiring long fire-free periods to mature and set seed (Gibson et al. 1991; Balch et al. 2011; Zimmer et al. 2014). Similarly, some animal species tolerate a single fire better than others due to traits such as mobility (to escape the fire front), burrowing, high reproductive capacity (to rapidly recolonize post-fire environments) and opportunistic diets (e.g., allowing post-fire switching of diets to more readily available foods in burnt habitats (Tulloch & Dickman 2007)). While all species are adapted to certain fire regimes, some can suffer declines and possible extinctions if fire events occur more frequently and with greater intensity to which the species and its habitat are adapted (Lindenmayer & Possingham 1995; Bowman et al. 2014; Tulloch et al. 2016).

The long-term consequences of megafires for biodiversity could be dire for many species (Hoegh-Guldberg, O. et al. 2019; Pickrell & Pennisi 2020). Preventative actions such as managing ecosystems to reduce megafire events or be more resilient to fire (Lindenmayer et al. 2020; Driscoll et al. 2021), or identifying those key refugia that must be protected, have become critical. However, when megafires do occur, key post-fire actions must be implemented. In most ecosystems, the first months after a megafire event is the time when fire-sensitive species are at their most vulnerable (McGregor et al. 2014; Lindenmayer et al. 2019; Alexandra & Finlayson 2020). Failing to act during this critical window could allow the impacts of an array of threatening processes to become exacerbated within both burnt and unburnt habitats, further affecting populations of plants and animals that could already be in poor condition due to reduced resources, drought, invasive species, or increased fire competition as a result of burned habitat (McGregor et al. 2014; Souza et al. 2015; Hradsky et al. 2017). For example, fires can provide an opportunity for invasive plants to invade and even dominate vacant space (Vitousek 1990; Brooks et al. 2004); this can create short term issues for ecosystem recovery as well as long term issues, as the dominance of the invasive plant can itself alter the flammability of the site (Buckley et al. 2007), (Berry et al. 2011) and result in increased frequency of megafire events.

To mitigate post-fire impacts and assist biodiversity recovery immediately after a megafire event, conservation scientists, decision makers in governments, and local practitioners require a way of rapidly assessing where and how to reduce known abatable threats to species (Wintle et al. 2020). These decisions must be made in the face of extreme uncertainty about formulating the resource allocation problem, conservation actions required, or data inputs. Decision makers therefore require improved approaches to prioritize resources for preventing severe species declines immediately after megafire events that come from not just the fire event itself, but the cumulative threats that will likely impact fire-affected species populations that are already threatened with extinction.

Here, we use the Australian 2019–2020 bushfire event as a case study to showcase a decision-support framework that specifically assists the prioritization of 22 broad-level conservation actions immediately after a large stochastic conservation disaster. The framework combines species distribution data and threat distribution data, with data on the extent and intensity of the fire event to produce a set of conservation 'features' that are distinguished by their 'risk of severe irreversible decline' post-fire. The framework uses two approaches. The first, called the "hotspot approach", finds the locations where actions deliver the greatest return on investment ignoring spatial considerations with respect to actions and benefits (Mair et al. 2021). It chooses areas that are cost-effective (i.e., have high benefits and low costs (Auerbach 2015)), with the benefit calculated as the weighted sum of the expected threat reduction across all species managed at a cells, and weights determined by extinction risk and proportion of fire-impacted habitat. This approach is best suited to local conservation actors.

The second approach, called the “regional approach”, uses the spatial prioritization decision tool Zonation (Lehtomäki & Moilanen 2013) to find the collective set of locations where actions deliver the greatest return on investment across all affected species. It identifies a set of areas for conservation action that incorporates considerations of complementarity (i.e. managing as many species as possible, without unnecessary overlap (Tulloch et al. 2013; Chadés et al. 2015)), connectivity (i.e., actions that are close by to other actions, which makes them more efficient than widely-dispersed actions (Bektas 2006; Wenger et al. 2018)), and cost-effectiveness (i.e., meeting these objectives at a minimal cost). The benefit of all the actions determined by the regional approach is calculated as an overall value for an entire set of “selected” cells (rather than a cells-based value). The difference between the *hotspot approach*, is that the *regional approach* will find cells and actions that complement each other (by having different species) and hence have a higher combined benefit than cells selected independently – it considers the idea that the whole is different from the sum of the parts. Species are also weighted by their extinction risk and proportion of fire-impacted habitat. Each approach will be useful in different decision-making contexts. For example, the *hotspot approach* that maximizes the number of locally managed species is more likely to appeal to a local non-government agency or set of land managers with a limited budget and/or limited number of locations to work at. The *regional approach* is designed for organizations working to recover as many species as possible, often over large scales (e.g., regional, state or national agencies, Catchment Management Authorities, or Natural Resource Management bodies) (Fig 3.1).

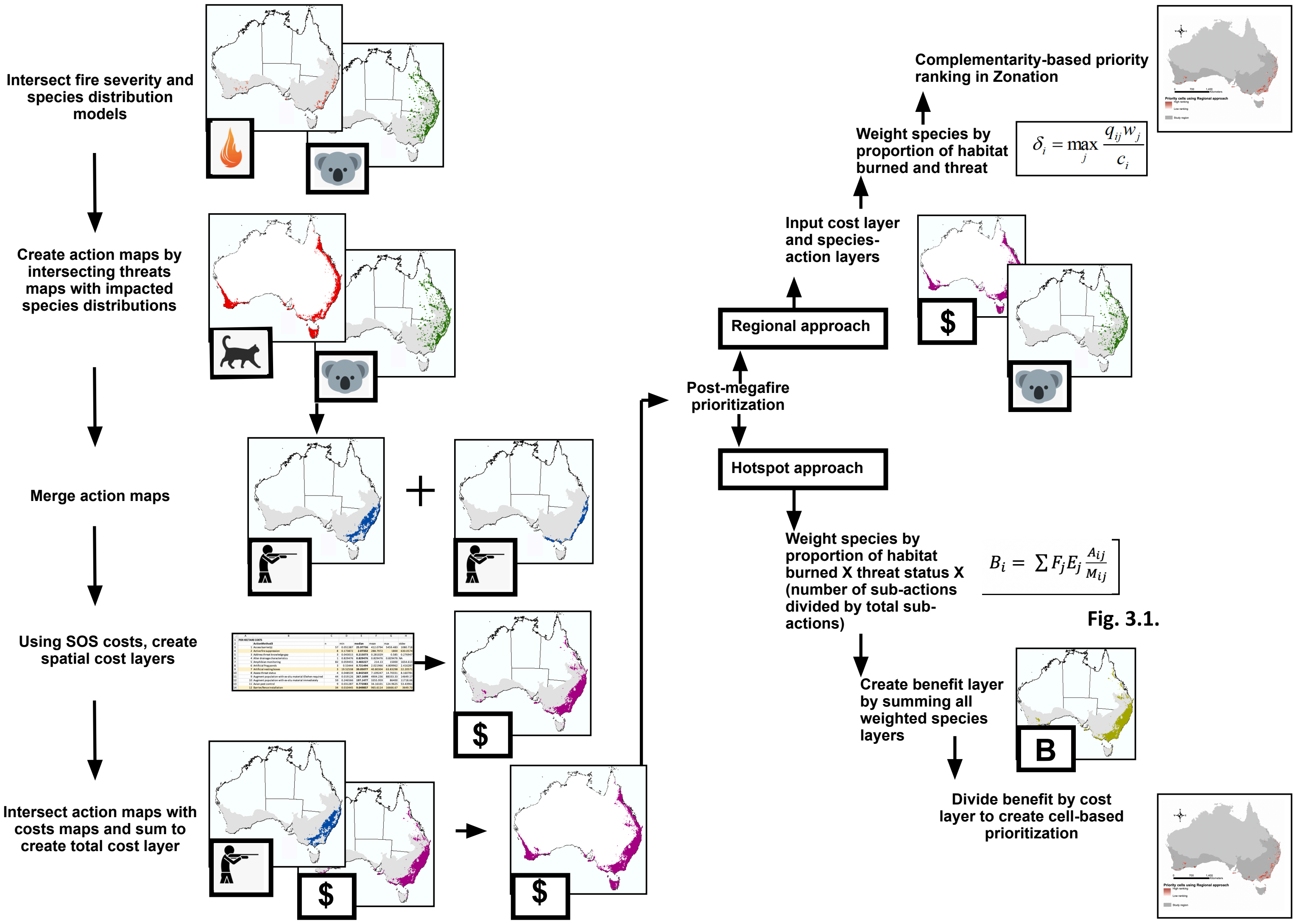

Fig. 3.1.

A methodology for producing the post-megafire prioritization framework using Australia as a case study.

Results

The 2019–2020 Australian bushfires impacted 76,000km^2 - 96,000km^2 with high and very high intensity fires encompassing >36,000 km^2 (46% of all burnt areas within study region), while moderate and low intensity fires encompassed >42,000 km^2 (54% of all burnt areas within study region; Fig 3.2). Using our framework, we identify 290 threatened species that need immediate conservation attention based on their risk rating (Appendix 8). Most species were impacted by all three categories of fire intensity, with 268 threatened species impacted by very high intensity fires (defined by the vegetation in the cell has been clearly consumed), 273 impacted by high intensity fires (defined by the vegetation in the cell has been mostly consumed), and 273 impacted by moderate and low intensity fires (defined by some change or moderate change detected when compared to reference unburnt areas outside the study region) (Commonwealth of Australia 2020a).

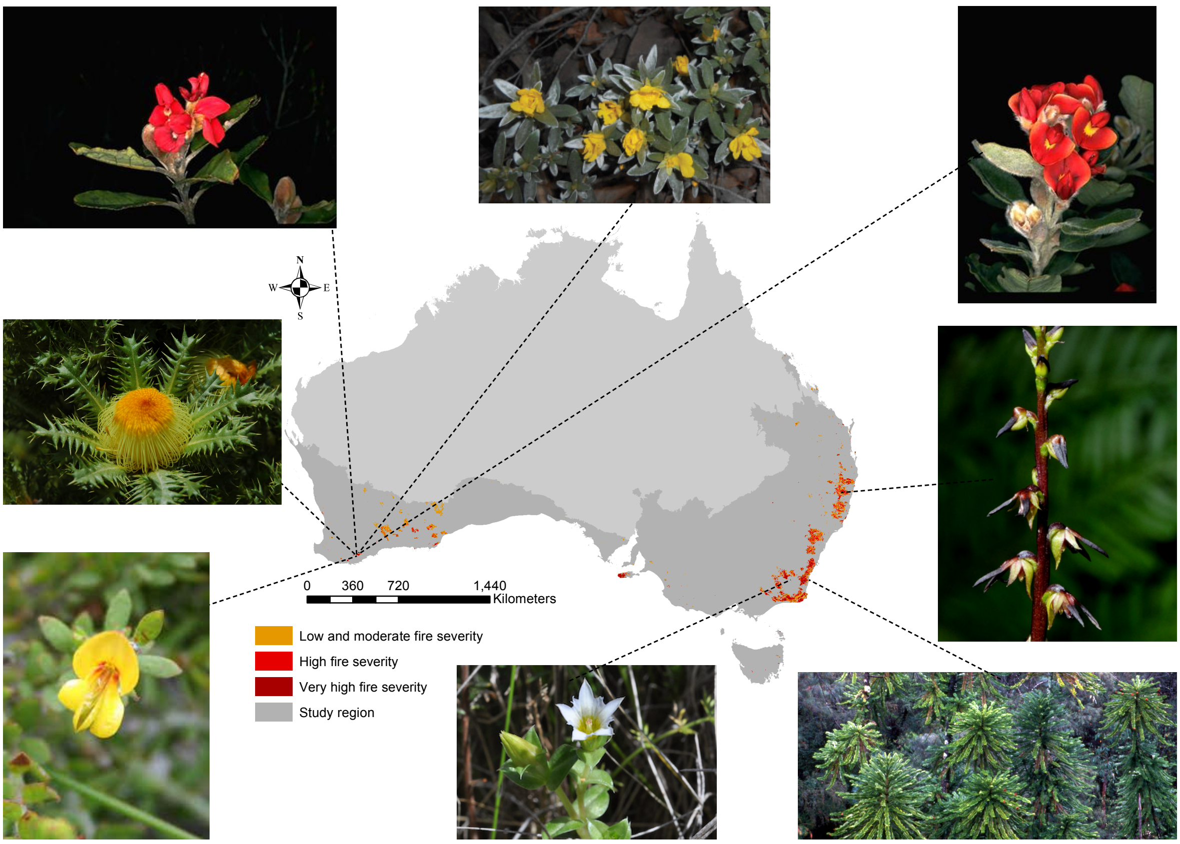

Fig. 3.2. Areas impacted by the 2019–2020 megafires. Dark red represents very high intensity fires, red represents high intensity fires, orange represents moderate and low intensity fires, while dark grey represents the study region. Eight Critically Endangered species that experienced very high and high severity fires across more than 30% of their habitat include (clockwise starting top left): Yellow-leafed Gastrolobium (*Gastrolobium luteifolium*; credit: Crisp, M, a.8858), *Hibbertia barrettiae* (credit: Sarah Barrett*)*, *Gastrolobium vestitum* (credit: Crisp, M, a.8881), Tuncurry Midge Orchid (Genoplesium littorale; credit: Colin Bower), Wollemi Pine (credit: Royal Botanic Gardens Sydney), Bredbo Gentian (*Gentiana bredboensis;* credit: Australian Network for Plant Conservation), Mountain Latrobea (*Latrobea colophona*, credit: Sarah Barrett*)*, Cactus Dryandra (*Banksia anatona*: credit: Australian Network for Plant Conservation).

Twenty-two broad-level actions and 16 sub-actions were identified to mitigate the key threatening processes impacting species and costs of each action were estimated using data from the New South Wales Saving Our Species (SoS) program (NSW Office of Environment and Heritage 2018). Actions were allocated as being needed for each species based on the threatening processes identified as impacting species at a low, medium, or high intensity (Ward et al. In Review). Of the 22 broad-level actions (Appendix 7), each species required, on average, three broad-level actions to mitigate threats (median = 3; range = 1 – 9) (Fig 3.3). The top three actions required by most species were *habitat protection* (100% of all species; n=290), *fire suppression* (57% of all species, n=166), and *invasive weed management* (36% of all species, n=103).

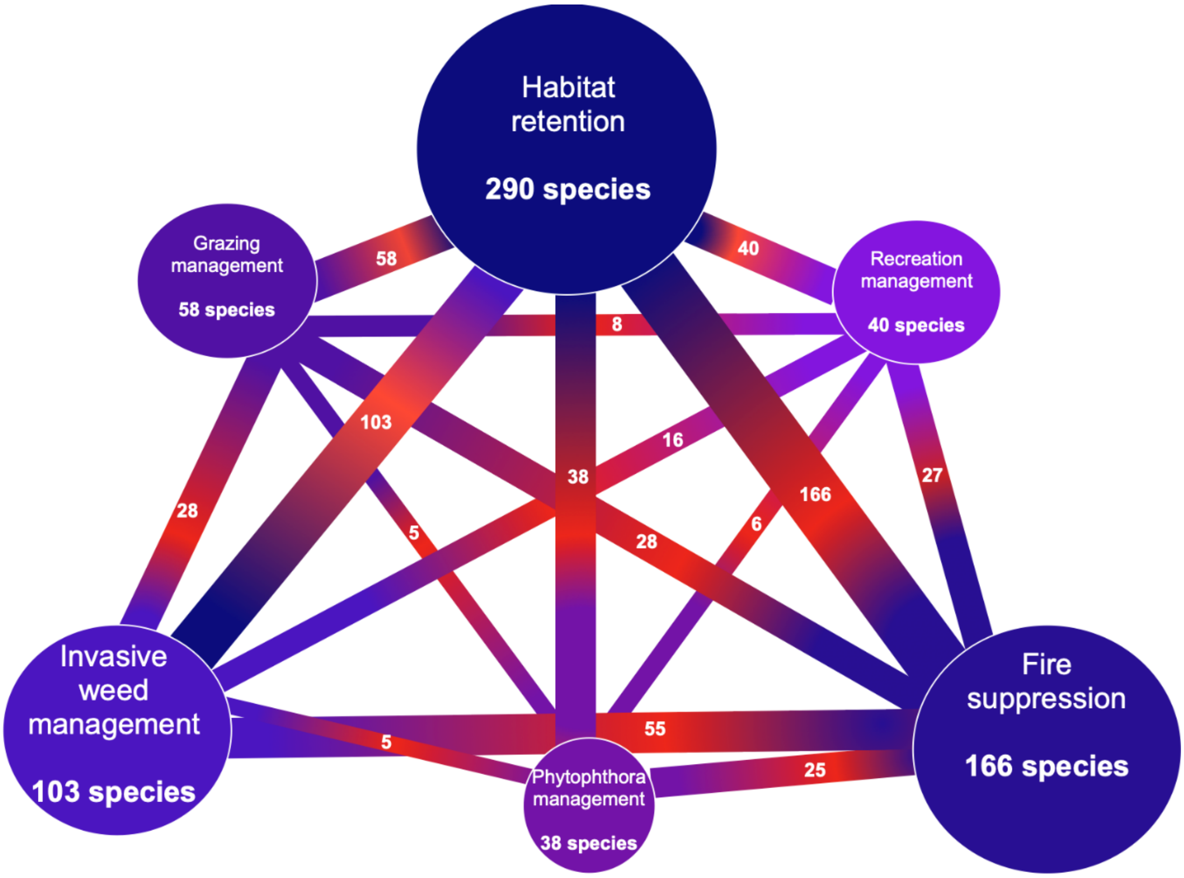

Fig. 3.3. The number of Australian threatened taxa that would benefit from each broad-level action (circles) and the number of taxa that would benefit from each pair of broad-level actions (lines connecting circles). The size of circles and the thickness of lines connecting them are scaled to approximate the number of taxa benefited. Note that only the top six broad-level actions are depicted.

Different taxonomic groups required different sets of broad-level actions. For example, while *habitat protection* and *provision of supplementary resources* were the key actions for mammals (100% and 92% of mammals respectively, with 92% of mammals requiring both), *habitat protection* and *fire suppression* were the most prevalent actions for most birds, plants, reptiles, and insects (with 71%, 53%, 88% and 100% of species in these taxonomic groups requiring both actions, respectively). Frogs however, mostly required *habitat protection* (100% of species) and *chytrid fungus management* (92% of species), with 92% of frogs requiring both actions for recovery.

When we prioritize cost-effective post-fire actions using the *hotspot approach*, our results highlight 42% of subregions (n=178/423) contain the top 30% of the landscape that provide the highest cost-efficiency. Many priority locations were found in the south-west and south-east such as Fitzgerald, South East Coastal Ranges, and Snowy Mountains (Fig 3.4a). Actions in these 180ap subregions deliver the greatest return-on-investment for the highest concentrations of highly susceptible species (i.e., those that have high extinction risk and high proportions of habitat burnt), ignoring complementarity amongst these regions. In contrast, using the *regional approach*, we find that to equitably manage as many species as possible, post-fire recovery action locations were dispersed across 44% of subregions (n=185/423). The most number of cells with the highest ranking occur within subregions in the south-east as South East Coastal Ranges, Monaro, and Wollemi (Fig 3.4b). Interestingly, one key area of interest that emerges within both approaches is Gippsland due to the extensive impact of fire in that subregion in combination with habitat for many threatened species.

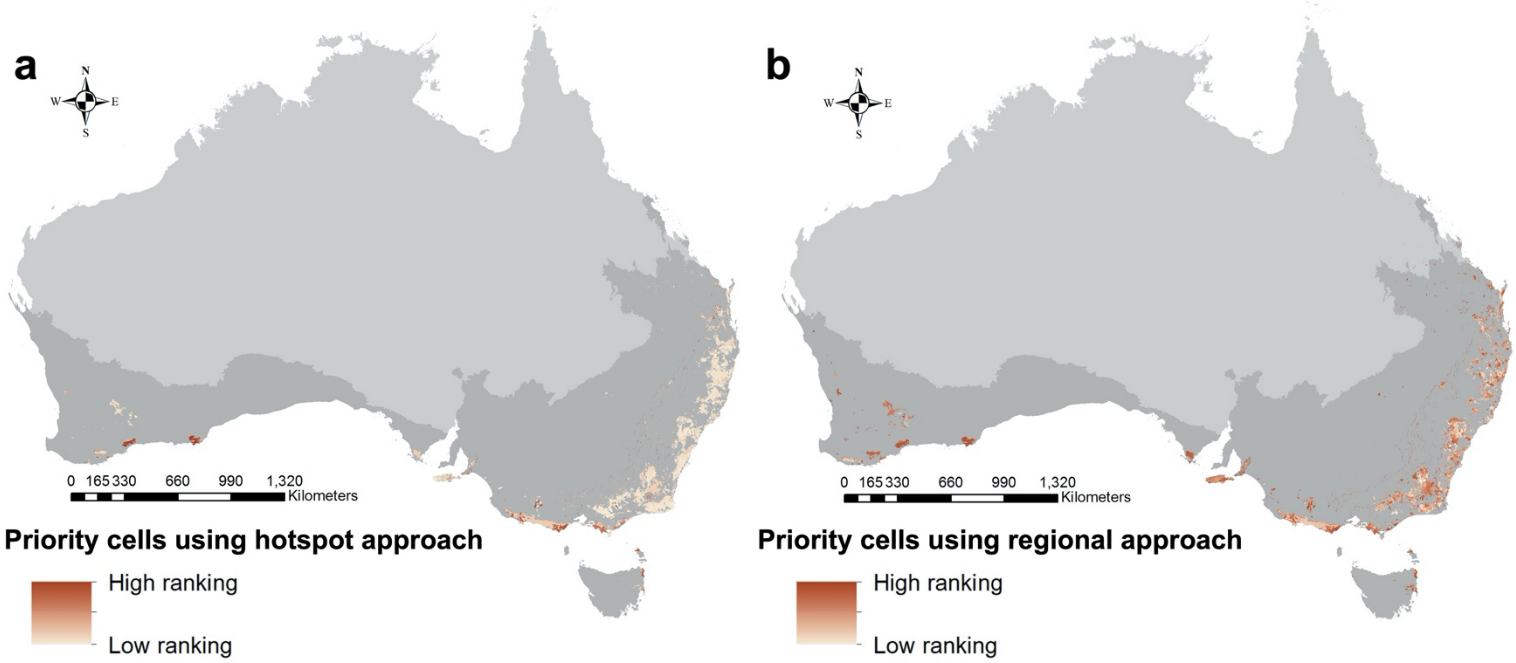

Fig. 3.4. Broad areas for conservation action ranging from high-ranking priority areas (represented in red) to low-ranking priority areas (represented in cream) that maximize threat reduction for highly impacted species. a) Cells containing the top 30% of the landscape that provide the highest cost-efficiency for post-fire recovery actions that maximize the number of highly impacted species. b) Cells containing the top 30% of the landscape that provide the highest cost-efficient, complementary post-fire recovery actions.

Based on the assumptions in our analysis, approximately AUD$3 billion (~AUD$6,406/km^2) is needed to mitigate all post-fire recovery related threats across the entire distribution for all 290 threatened species that were severely impacted by the bushfires (Fig 3.5). Our research found that – depending on the approach taken – between AUD$422 million (*hotspot approach*) and AUD$635 million (*regional approach*) is needed to manage the top 30% (~142,000 km^2) of priority locations for threatened species. The top 30% of ranked cells in the *hotspot approach* managed 288 of the 290 species. There were 2 species not managed with this approach due to not occurring in the most species-rich cells. The proportional average of each species habitat managed was 58% (max = 100%, min = 0%), with an average area of 1,922km^2 (range 0km^2 to 59,000km^2). In comparison, the top priority cells of the *regional approach* managed on average 88% (max = 100%, min = 13%) of every species habitat (mean = 3,500km^2, range 1km^2 to 155,000km^2). This means that the *regional approach* manages more of each species' habitat when the top 30% of priority cells are selected, compared with the *hotspot approach* that misses some species completely and only manages an average area of 58% of every species' habitat.

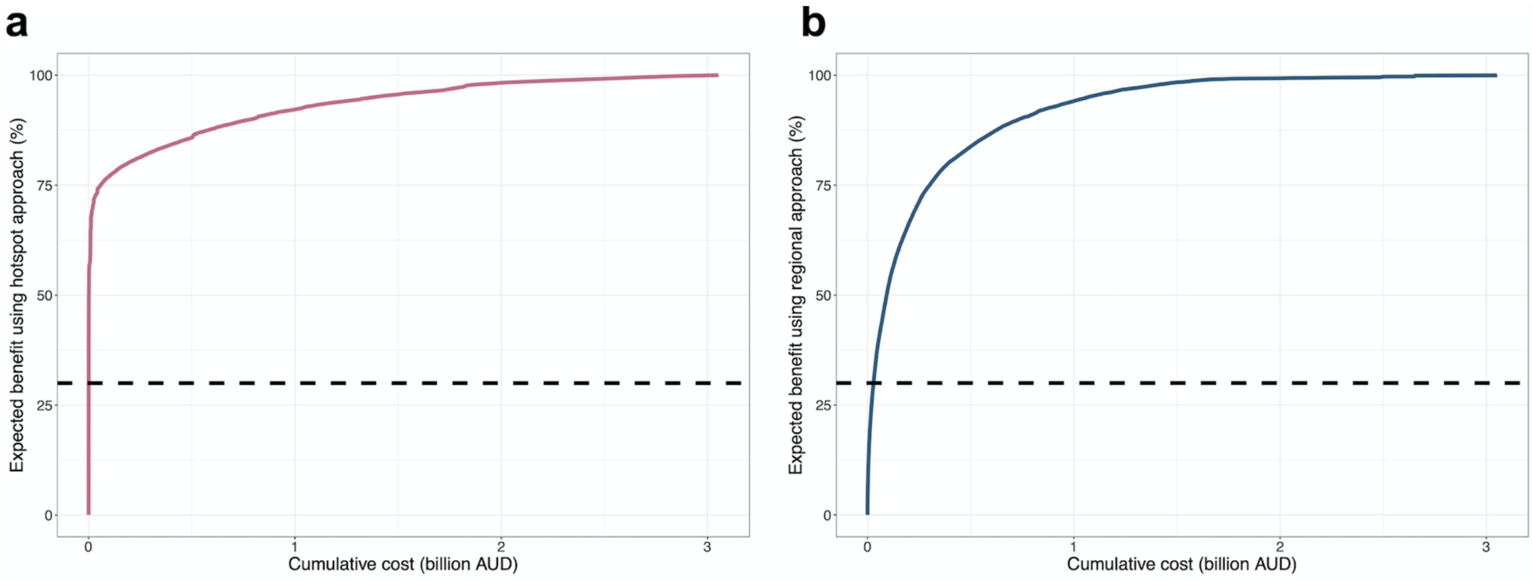

Fig. 3.5. Return on investment curves for the a) *hotspot approach* (red) and b) *regional approach* (blue), highlighting the increase in benefit relative to the increase in spending. The benefit for the *hotspot approach* is a weighted sum of the expected threat reduction across all species managed at a cells, where weights are determined by extinction risk and proportion of fire-impacted habitat. The benefit for the *regional approach* is calculated as the average proportional distribution of each species managed for a given set of priority selected cells. Species are also weighted by their extinction risk and proportion of fire-impacted habitat. The horizontal line indicates the top 30% of ranked cells.

Discussion

Ready-to-use prioritization frameworks that help decision-makers allocate funds to actions post megafire events are critical to ensuring species survive. They also allow for transparent, robust and repeatable decision making processes, ensuring that the limited resources allocated to conservation are spent efficiently and cost-effectively(Joseph et al. 2009; Waldron et al. 2017). Our research fills this knowledge gap by providing a decision support framework that can assist when budgeting and prioritizing conservation actions immediately after fires.

The 2019-2020 Australian megafires burnt the largest area in a single fire season since European settlement, and burned areas that are normally fire resistant, such as wet gullies, riparian strips, rainforest edges, and rocky outcrops (Wintle et al. 2020). Given the uniqueness of this event, governments, conservation scientists and managers had no precedent for designing and implementing a response. Our research found that between AUD422 million (*hotspot approach*) and AUD635 million (*regional approach*) is needed to manage the top 30% of priority locations for the 290 threatened species most impacted by the 2019–2020 bushfires. However so far, only AUD100 million has been dedicated to post-fire recovery actions by Federal and State Governments (Wintle et al. 2020). Currently, 66% of the species in our prioritization are considered low priority in current funding schemes (Brazill-Boast et al. 2018), further highlighting the importance of dynamic prioritizations that respond to large-scale disturbances. The recovery and persistence of species requires additional, consistent, and ongoing resources to be impactful and adequate at the scale it's needed(Garnett et al. 2018). This is due to the many enduring, complex threatening processes that our species faced even before the bushfires, as well as decades after (Bowd et al. 2019).

The megafire was driven by many synergistic processes including anthropogenic climate change resulting in intensified drought (Dale et al. 2001) and inappropriate land use management (Lindenmayer et al. 2020). Without holistic conservation measures, these disastrous events will become worse and more frequent. Reducing these human impacts before fire can also often enhance system recovery and encourages the natural capacities of species to reproduce and survive within the context of natural disturbance regimes (Frissell et al. 1997).

The two approaches will appeal to different decision-makers, working at different scales and will depend on purpose and budgets. The *hotspot approach* maximized the number of locally managed species, yet ignores complementarity, so that disproportionate effort might end up being assigned to species that occur in many hotspots. For Australia, this approach identified areas with high threatened species richness, such as Fitzgerald, South East Coastal Ranges, and Snowy Mountains. We envision that this approach will appeal to a local non-government agency with a limited budget or capacity to work over multiple areas, where the investment is localized and intended to return the biggest local outcome. These local non-government agencies might be looking to distribute philanthropic conservation funds to local landholders, and therefore require a prioritization of single properties that will offer the biggest return-on-investment. The major benefit of this approach is that it is easier to explain and offers insight into 'quick-win' areas, however risks arise if this approach was used in isolation. As such, important, high-risk species outside of hotspot areas may not be targeted for conservation actions. It also risks over-investing and under-investing in some species. The *regional approach* will appeal to organizations working at regional, state or national scales, with the goal of securing as many species as possible (e.g., government agencies). This approach highlighted priority areas such as the South East Coastal Ranges, Monaro, and Wollemi, where many different high-risk species co-occur with many different threats. Interestingly, the areas identified within this analysis have considerable overlap with other national and statewide spatial prioritizations (Chadès et al. 2019; Ward et al. 2019a). The major benefit of this approach is that it offers decision-makers with a set of important areas for recovery the comprehensive list of species impacted by a bushfire season.

Our framework builds upon previous work aimed at mapping the impact of fire on native species (Fonseca et al. 2017; Hughes 2017; Godfree et al. 2020; Ward et al. 2020a), by considering the many other threats that impact species, and developing an approach to guide urgent responses. The initial loss of habitat post-fire can be detrimental for many species, but they also must survive the impacts of a variety of other threatening processes that occur pre-fire and may intensify after a fire. Many plants that regenerate in the post-fire environment are vulnerable to herbivory by native and invasive species, competition from invasive and other native plants, and desiccation (Wintle et al. 2020). Animals may struggle to find food, shelter, and avoid predation from invasive species (McGregor et al. 2014). Many of the animals that try to move across the landscape to recolonise new habitats may find their dispersal interrupted by cleared land, fences, and other human disturbances (Ward et al. 2020b). New habitats may be suboptimal in terms of resources or due to competition by other individuals (Wintle et al. 2020). Our research highlights the number of additional threatening processes that can potentially impact species post-fire, and the importance of multipronged management actions that consider these threats in addition to fire management, to reduce threat impacts and provide the best chance for species survival.

The loss of habitat from the 2019–2020 bushfires occurred on top of decades of land clearing, degradation, and fragmentation (Ward et al. 2019b). Our results indicate that among the species most impacted, the most prevalent additional action needed to recover populations is habitat retention. The retention of habitat post-fire within both the overall fire footprint and outside the fire footprint (i.e. refuge areas) will be critical to species persistence and eventually re-colonisation of burnt areas(Berry et al. 2015). In some locations, unburnt, unprotected habitat is at risk of being thinned, burned and cleared for conversion to agricultural land, or for forestry activities (Lindenmayer et al. 2019, 2020). Loss and degradation of remnant vegetation not only risks declines and possible further extinctions of species (Reside et al. 2019), but it can also create more fire-prone forests (Lindenmayer et al. 2019). The protection of residual vegetation and the species' habitats therein is one of the most fundamental.

The second highest priority action – when considering all impacted species – is the management of invasive species. Many invasive species have long established wild populations in Australia, and some are expected to dramatically expand in numbers and range without effective management strategies (Hone 2002; Zenger et al. 2003; Saunders et al. 2010; Davis et al. 2016). Invasive species can significantly damage soil, elevate erosion, hinder vegetative recovery, contribute to the spread of other invasive species, degrade stream and riparian conditions, increase fire frequency and severity, and delay the recovery of burned areas (Beschta et al. 2004; Berry et al. 2011) . Invasive herbivores are of concern for threatened plants, which make up 84% of the species impacted by the fires in this study; 34% of those threatened plants (n= 44) are impacted by at least one invasive herbivore. Without intensive management of invasive species, especially within burned places, it is likely that some populations of threatened species would decline further post-fire (Gallagher 2020).

While monitoring is a critical component of conservation (Strayer 1986), we did not include a monitoring cost in this study as our approach was to focus on allocating resources towards on-ground conservation actions that could be immediately implemented in burnt and unburnt areas (Possingham, H. P., Wintle, B. A., Fuller, R. A., and Joseph 2012). A similar prioritization to this study focused on post-fire surveys or ongoing monitoring would be valuable after large stochastic natural disasters to ensure that limited funds could be cost-effectively allocated. Immediately after a fire, species may have dispersed or been (at least temporarily) lost from burnt habitats and may only return if areas are well managed and well resourced (i.e. free of invasive species, have sufficient food and cover) (Olsen & Weston 2005; Smith 2013; Robley et al. 2016). Our prioritisation costs actions across the whole year after the fire. Effective monitoring over this time period in key locations would enable managers to track when populations return to areas burnt at different intensities, and enable some actions (e.g. supplementary feeding) to be timed to when they are most useful, thereby potentially avoiding wasted funding on actions for populations that are not present as well as perverse outcomes from feeding non-threatened animals that could increase in numbers and compete with threatened populations trying to return (Kubasiewicz et al. 2016). In some cases, citizen science could be an efficient way of leveraging existing public interest and engagement to survey for threatened species in burnt habitats as well as track the progress of populations as they recover (Kirchhoff et al. 2021).

In this study we used the most current distribution maps of invasive species available at the time of the fire (Pintor & Kennard 2018). It is possible that after a fire, invasive species may move into areas previously unoccupied (Jacquemyn et al. 2005; McGregor et al. 2014). Our prioritization method could be adapted to account for such uncertainties by drawing a buffer around the edges of invasive species ranges, to explore whether an increased range size for invasive species after fire changes the prioritization decision about where to spend limited conservation resources. We also recognise that some species will require ex-situ conservation, such as captive breeding and translocation programs, however we have not included this action because these costs are incredibly variable (Balmford et al. 1996; Mawson 2004) and require detailed specific-specific assessments before implementation. For example, the cost of starting a new captive breeding program is far more expensive than expanding a long-standing breeding program, larger species are more expensive than smaller-bodied species, and some species are difficult to breed in captivity (e.g. Gilbert's potoroo) (Balmford et al. 1996; Mawson 2004). These breeding programs may take much longer than one year to implement, and therefore remain outside of the scope for this study.

With the predicted increases of warming and drying, countries such as Australia, USA, Brazil, and Russia can expect more frequent catastrophic fire events in the near future, highlighting the critical need for prioritized emergency response of conservation actions (Dowdy et al. 2019). While the immediate, direct effect of fire on species are visually profound, the short and long-term indirect effects in the aftermath can be insidious and extend over decades. Our research has illustrated how we can combine current knowledge into a succinct framework to prioritise immediately conservation actions that have the greatest benefits for mitigating post-fire impacts and biodiversity recovery.

Methods

Study region

The study region for this analysis incorporated 43 temperate, Mediterranean, and subtropical bioregions across 2.2 million km^2, as defined in the Interim Biogeographic Regionalization for Australia (IBRA) dataset. We used 100m x 100m gridded resolution species distribution models that were supplied and stored by the Australian Commonwealth Government (Commonwealth of Australia 2020b). These species include all terrestrial invertebrates, mammals, birds, reptiles, plants, and amphibians listed as threatened under the Environment Protection and Biodiversity Conservation (EPBC) Act 1999. In this analysis we excluded all freshwater and marine species due to spatial complexities of these ecosystems and uncertainties in how fire affects such systems. Our analysis focused on Australian threatened species because they have been identified as at risk of extinction in the near future. We recognize that some populations of non-listed species may also be so heavily impacted by an extreme wildfire event that they are also at risk of extinction(Ward et al. 2020a) – our method can be easily adapted to incorporate any list of species regardless of their level of threat.

Fire severity and species impacts

To calculate the area and intensity of the fire's impacts on each species habitat, we first intersected the Federal Government National Google Earth Engine Burnt Area Map (GEEBAM, downloaded on 9th July 2020) (Commonwealth of Australia 2020b) with habitat for each species. We recategorized each species' distribution in terms of total area of habitat burnt with very high, high, and moderate and low severity and total area of unburnt habitat remaining, and calculated the percent of habitat in each category. The GEEBAM dataset included satellite imagery from 1 July 2019 to 13 February 2020 and used Sentinel 2 images. Sentinel-2 (S2) is a wide-swath, high resolution, multispectral imaging mission with a global 5-day revisit frequency. GEEBAM represents the difference between the Normalized Burnt Ratio (NBR) before and after fire, which is formulated:

$$\mathrm{NBR} = \frac{\mathrm{NIR}-\mathrm{SWIR}}{\mathrm{NIR}+\mathrm{SWIR}}, \qquad \text{(eq. 1)}$$

where NIR is near infrared and SWIR is shortwave infrared (SWIR) wavelengths. GEEBAM classes were derived using the change in NBR for each IBRA subregion and each broad National Vegetation Information System vegetation type at 40-meter resolution. The classes presented have been designed for rapid response and were not trained with ground data, therefore do not have confidence interval or accuracy reports.

To identify threatened species that were highly impacted by the megafire, we used three simple decision rules:

(1) All threatened terrestrial species identified by the Commonwealth Government expert panel as requiring immediate actions post fires;

OR

(2) >10% of habitat fire impacted + <2,000km^2 area of occupancy remaining

OR

(3) >10% of habitat fire impacted + <20,000km^2 extent of occurrence remaining

These thresholds were chosen based on Federal Government's guidelines for assessing the conservation status of native species under the EPBC Act (Commonwealth of Australia 2000).

Threats and response actions for impacted species

Using a previously published taxa–threat–impact dataset (Ward et al. In review), we identified the threats impacting the study species, and extracted the corresponding spatial representation of all threatening processes using a combination of Pintor et al. (2018), Public Sector Mapping Agency (2018), and Federal Government datasets (See Appendix 7 for more information). These spatial datasets represent livestock grazing, phytophtora dieback (*Phytophtora cinnamomi*), aerial canker (*Zythiostroma*), myrtle rust (*Austropuccinia psidii*), chytrid fungus (*Batrachochytrium dendrobatidis*), logging, feral cats (*Felis catus*), foxes (*Vulpes vulpes*), rabbits (*Oryctolagus cuniculus*), pigs (*Sus scrofa*), goats (*Capra hircus*), horses (*Equus caballus*), rodents (*Rattus rattus* and *Rattus norvegicus*), and deer (*Rusa timorensis* and *Rusa unicolor*). We converted each threat distribution into an individual 'broad-level action map' for post-fire species recovery, and created an additional five maps of broad-level actions that could be carried out over the entire species distributions (including habitat retention, invasive weed management (only within burnt locations), native species management (only within burnt locations), supplementary resources (only within burnt locations), and other fungal pathogens management, resulting in 22 broad-level action maps in total. Each broad-level action was split into sub-actions, which were then split by land tenure to identify on-ground activities and costs (e.g., the broad-level action of Habitat Protection was split by private and public land, resulting in sub-actions of covenants and protected areas, respectively). In addition, the presence and severity of fire can also change the sub-actions required, therefore sub-actions were also split into burnt, unburnt, and burn severity. For example, action maps for species that are threatened by fire were managed for fire in areas that did not burn or experienced low and moderate severity burns, under the assumption that any areas that experienced very high, or high severity burns would not burn again for a least 12 months (See Appendix 7 for more information).

Cost estimates of actions

For 13 of the 16 sub-actions, we estimated costs using actual cost expenditure recorded for similar activities that have been implemented over the past 5 years through the New South Wales Saving Our Species (SoS) program. The SoS dataset (NSW Office of Environment and Heritage 2018) contains 102 "method level 3" (ML3) actions. For 15 ML3 actions we used the median costs per ha per year, and for 7 ML3 actions, we used "Action Plan Cost" finer resolution data (Appendix 7). New South Wales represents the State with the largest area of habitat burnt in the 2019-2020 fires, hence we assumed that on average, costs per ha would be similar across the fire affected areas. While these costs were vetted through expert consultation (Pullin et al. 2016) with the New South Wales government, the cost data are imprecise estimates of true on-ground costs. While there has been data quality controls completed, errors may exist. It is also important to note that when the "Action

Plan Cost” finer resolution data was used, some actions may be missed. For example, when using 1080 baiting, vehicle hire was not included.

The costs of the other three sub-actions (Protected area management, Lost opportunity cost, and Supplementary feeding) were not identified within the Saving Our Species program – for these we collated reported costs in the peer-reviewed and grey literature to calculate per hectare costs (see Appendix 7). Protected area management was specified as all actions required to maintain a protected area (e.g. staff overheads) except the actions listed in this study (i.e. invasive species management, disease management, and signs), and was estimated to be AUD14.12/ha per year (Taylor et al. 2011; Maggini et al. 2013). Opportunity costs were used only on private land, when species were impacted by grazing. Opportunity costs were calculated using an agricultural profitability layer (Marinoni, Oswald; Navarro Garcia 2018) to identify land owner opportunity costs (i.e. lost income due to agricultural land being repurposed for conservation) for the areas that would be restored for biodiversity. Supplementary feeding was calculated using a variety of supplier costs, under the assumption that we require 1kg per hectare every week for four months (Department for Environment Food and Rural Affairs 2005), resulting in a median cost of AUD340/ha (See Appendix 7 for all actions, costs, and references).

Spatial prioritization framework

We developed a decision support framework that will assist decision-makers in prioritizing conservation actions to implement up to 12 months post a large stochastic conservation disaster. The framework can be split into two approaches. The *hotspot approach* focuses on recovering the most species in any one location, whilst the *regional approach* selects complementary locations to extend actions across all species.

Hotspot Approach: Maximizing local species richness

The *hotspot approach* calculates the cost-efficiency value for each cell, in which the benefit of acting in a location accounts for the number of species being managed there, the proportion of fire-impacted habitat for each species, and the risk of species extinction. The cells are then ranked by their cost-efficiency score, which is the expected benefit divided by the cost of management. The highest cost-efficiency rank indicates the higher benefit to cost ratio, whilst lowest cost-efficiency indicates the lowest benefit to cost ratio.

This approach identifies areas requiring management by setting an approach of maximizing the richness of high-risk species being managed in any location. We prioritize cost-effective (CE_i) cells using the below formula:

$$CE_i = \frac{B_i}{C_i}, \qquad \text{(eq. 2)}$$

where B_i is the benefit of managing all threats to all species within area i, and C_i is the total cost of sub-actions required to mitigate all threats to species present within area i(Auerbach et al. 2015).

The benefit of managing a species at a cell was estimated as the likely magnitude of threat reduction that would be achieved by the actions. Benefits were then summed across all species at a cell, weighted by each species the extent of fire-impacted habitat and extinction risk. We calculate benefit (B_i) by using the following formula:

$$B_i = \sum F_j E_j \frac{A_{ij}}{M_{ij}}, \qquad \text{(eq. 3)}$$

where F_j is the proportion of the habitat of species j that was impacted by fire (a weighting factor to assign higher weight to species with greater proportions of their total distribution burnt), E_j is the risk of extinction of species j (a second weighting factor to assign higher weight to species with higher likelihood of extinction), A_{ij} is the number of sub-actions within cell i for species j, and M_{ij} is the maximum number of sub-actions required for species j. Dividing A_{ij} by M_{ij} ensures that we select cells where the most threat reduction can occur, assuming all threats are equal. The risk of species extinction E_i was determined from the IUCN Red List Guidelines, whereby a species is designated to the category of Critically endangered is the predicted probability of extinction >0.5 in 10 years, Endangered >0.2 in 20 years and Vulnerable is > 0.1 in 100 years(Redding & Mooers 2006; Mooers et al. 2008). If the approach was to be re-applied in cells of different sized areas, the benefits would also need to be weighted by the area over which the benefit is likely to be achieved.

Regional approach: Maximizing regional species recovery

The *regional approach* uses a spatial prioritization decision tool, Zonation (version 4.0) (Moilanen et al. 2011, 2012) to identify a species-balanced set of cells for conservation action, by considering important conservation considerations such as complementarity (that is, we can manage as many species as possible, without unnecessary overlap or redundancy of conservation actions (Tulloch et al. 2013; Chadés et al. 2015)) and connectivity (defined here as actions that are close by to other actions, which makes them more efficient than widely-dispersed actions (Bektas 2006; Wenger et al. 2018)). We prioritized species habitat for broad-level actions at a resolution of 1km^2 using a core-area Zonation cell removal rule (Moilanen & Wintle 2007). Zonation's core-area rule uses a maximum-coverage approach to identify areas that maximize the representation of suitable habitat for multiple species, by iteratively removing cells with the smallest occurrence for the most valuable feature over all biodiversity features in that cell (Moilanen et al. 2012). The benefit for the *regional approach* is calculated as an overall value for an entire set of "selected" cells (rather than a cell-based value), as cells that complement each other (by having different species) will have a higher combined benefit than cells with redundancies. Species are also weighted by their extinction risk and proportion of fire-impacted habitat. In comparison to the *hotspot approach*, where cells only receive a high value if multiple species with high risk are present, a cell in the *regional approach* can receive a high value if even one species has a relatively important occurrence there. The output is an importance ranking of each cell across the region in meeting the spatial prioritization approaches. The prioritization approach was to find a complementary set of cells that can be managed to maximize reduction of threats to all species after the fires. Recognizing that some species were more highly impacted by the fires and are closer to extinction than other species, we weighted each species using a value calculated as the proportion of its habitat burnt multiplied by extinction risk (i.e. *hotspot approach*) using the conservation feature weightings system in Zonation (Moilanen et al. 2012). We do not include the likelihood of response to the management prescribed for either of the two approaches, as for most highly impacted species, this data does not exist.

For each of the two approaches, we identified the top 30% of the most highly ranked cells from each output. To produce the return on investment curve for the *hotspot approach*, we divided the spatial benefit layer by the cost layer (using ArcGIS version 10.8) and reordered cells from highest to lowest based on cost-efficiency. We found the cumulative sum of both cost and benefit (using R version 1.2.5033). Finally, we measured the results for the entire study region and made comparisons for each subregion. For the *regional approach* (Fig 3.4), we used the cost needed for the top fraction (used as the cost) and the average proportion of landscape remaining (used as a surrogate for benefit), both of which are Zonation outputs.

Caveats

This research takes advantage of different spatial datasets including species distribution models, threat distributions, fire extent and severity, and costing estimates. These datasets – while the best currently available – contain known inaccuracies and have been used here to provide indicative areas of interest, rather than definitive locations or costs. It is generally assumed that gathering more accurate monitoring data will lead to better conservation decisions[90]. However, there is now evidence to suggest that waiting on better, more accurate data usually derived from spending time and money on monitoring the conservation feature (i.e., species, threat, or fire), does not necessarily improve or change the overall conservation decision. While more accurate monitoring data is important in conservation in order to inform the public of an issue; learn more about a system to inform a decision support model; or ensure that actions taken have met conservation objectives, we assume more accurate data in this analysis would not change the overall framework.

Chapter 4. Discussion and conclusion

This report attempts to answer the questions: *what are the threat abatement strategies required to ensure threatened species recovery across Australia; and what is the spatial extent, likely cost and co-benefits of implementation?*

To answer this question, our team (with the aid of a network of advisors and contributors from Australian Commonwealth and state governments, NGO's, academic institutions and Indigenous organisations) synthesised information on why each individual species is threatened, where the species is located, which actions would abate those threats, and the cost and co-benefits of implementing these actions, including where possible how costs scale across space and over time.

Importantly, this assessment was intended to inform *where we should recover species.* We provide maps of broad potential areas for threat abatement strategies to benefit threatened species. We have not included the local scale information and contexts that are needed to guide prioritisation and local scale decision making. Rather we aim to provide a systematic rationale and framework to enable rigorous, justifiable budgeting and to support appropriate local scale decision making for threatened species along with other local scale priorities. This includes supporting Indigenous led processes for decision making that can appropriately account for Indigenous aspirations and cross-cultural priorities.

We found that the 1,659 Australian EPBC-listed species that we considered as part of this assessment are threatened due to a myriad of threatening anthropogenically driven processes. By classifying these threats into eight broad-level threat categories and 51 nested sub-category threats, we were able to show that habitat loss, fragmentation, and degradation impact the highest number of species (n= 1,210 taxa), followed by invasive species and diseases (n= 966 taxa), and adverse fire regimes (n= 683 taxa). We identified 18 Threat Abatement Strategies to address the 51 sub-category threats to species. Fourteen of these were costed spatially, the remaining three strategies were policy focused. The total cost of implementing all Threat Abatement Strategies in the locations species required the action was AUD$610 billion, and controlling weeds was the greatest cost, making up 69% of the total. At $55,593/ha, habitat restoration had the greatest cost per area of any Threat Abatement Strategy. However, this is preliminary assessment is subject to change as the cost models are currently being peer-reviewed

To ensure threat abatement is successful, multiple strategies would often be required in the same location – e.g., habitat restored and ongoing threats managed, and additional efforts like translocations may be required in some places.

In addition to helping recover Australia's most imperilled species, the Threat Abatement Strategies have many co-benefits to industry. For example, the control of invasive animals and weeds could save the agricultural industry over $9 billion per year. Restoration of threatened species habitat could sequester and store up to 8.6 million tonnes of above ground carbon, and over 2.2 million tonnes of below ground carbon over our time horizon (80 years). Co-benefits and threatened species benefits need to be considered alongside Indigenous cultural values, especially on Indigenous owned and managed land.

Together, implementing all Threat Abatement Strategies in this analysis would create over 900,000 jobs, ongoing over 80 years. The more labour intensive and spatially extensive strategies such as managing invasive fish, disease, and rabbits, would likely create the most jobs. As we have not separated out jobs that are already in existence, we are unable to quantify additionality to the current workforce, but it is worth noting that the jobs created collectively by these Threat Abatement Strategies amount to approximately 70% of current unemployment.

In additional to our NESP 7.7 project, work within other NESP TSRH Projects will provide additional information on the likely flow-on economic and livelihood benefits resulting from the creation of these positions in regional areas, as employees pay forward their salaries to support local businesses and create additional opportunities for others.

Indigenous leadership in cultural species and places management

The authors of this report recommend that Threat Abatement Strategies to recover threatened species be implemented in ways that support Indigenous cultural values and customary activities through ensuring Indigenous leadership in decision making and management for species and places with Indigenous interests. This would require commitment to culturally appropriate management led by Traditional Owners and broader recognition of the cultural values of places and species that are significant to Indigenous Australians.

A process that identifies the necessary management for cultural species and places, and integrates threatened and cultural species priorities, needs to be Indigenous-led and carried out at appropriate scales. A single species can be valued differently between locations and by Indigenous groups. It is outside of scope and not appropriate for this project to attempt to provide the cultural benefits of threatened species management. However, important initiatives through NESP TSRH and externally provide examples and a basis of information upon which Indigenous led processes can be supported and expanded upon.

Indigenous Australians have rights and responsibilities over significant portions of the Australian continent that include threatened species habitat (Renwick et al. 2017), and already play significant roles in threatened species recovery (Leiper et al. 2018). However, the framing and governance of threatened species focused projects can be a barrier in seeking partnerships to initiate and run these projects (Duncan et al. 2018). To redress this, Indigenous Australians need to be supported in stronger leadership roles, as well as being consulted about cultural values and employed to do on ground management (Robinson et al. 2021). A co-developed approach for supporting Indigenous-led decision making in local scale planning and prioritisation to manage a culturally significant threatened species are provided by (CSIRO et al. 2019). The approach shows how consensus can be built to manage an endangered species as part of its cultural landscape to meet a broader set of cross-cultural objectives than for the threatened species alone, which may be a useful resource for engaging in local scale projects to recovery species in other locations. The project also produced a cross-cultural planning calendar focused around the recovery of a threatened species and its habitat (Bundjalung of Byron Bay Aboriginal Corporation (Arakwal) et al. 2019).

The conservation community can look to the collective findings of NESP TSRH research on healing country for 'significant' (threatened and/or cultural) species (synthesised by Robinson et al. 2021) and endorsed protocols for researchers on Indigenous engage in threatened species projects (https://www.nespthreatenedspecies.edu.au/media/kwfpxdwk/tsr-hub-indig-protocols-report_v6.pdf). This work outlined four key principles for collaborators with Indigenous Australians in significant species management, including that projects should:

- Support recognition of Indigenous rights, activities and interests in species management;
- Recognise and empower Indigenous knowledge to guide actions for species management;
- Balance benefits that arise from species management projects; and
- Ethically collaborate in species management projects.

In all cases, knowledge sharing should be carried out in culturally appropriate ways, as outlined by the NESP Northern Hub's Our knowledge, Our way Guidelines (Woodward et al. 2020).

Respectful and mutually beneficial ways forward are possible through implementation of these guidelines and principles along with a commitment to supporting Indigenous leadership in species recovery and threat management projects. The NESP TSRH Indigenous Reference Group provided crucial coordinated leadership in building national support for the acknowledgement and management of species significant to Indigenous Australians. Building on these initiatives and efforts is required to ensure threatened species recovery occurs in culturally appropriate ways and creates cultural benefits with and for Indigenous Australians, a proposition that is entirely appropriate when threatened species occur on the Indigenous Estate.

Implications of this research

We show that a substantial increase in threatened species recovery funding is required to create a future where our threatened species are no longer at significant risk of loss and can flourish as part of healthy ecosystems across their natural range. Fundamentally, the loss of species habitats poses the biggest risk of failure in achieving this goal, given the vast expense and uncertain outcomes of habitat restoration, and the loss of areas for habitat restoration to intensive land uses. However, much of the management involved in abating threats is compatible and even beneficial to current land use but requires different land management practices. If implemented effectively, fairly, and in culturally appropriate ways the resultant improved habitats, ecosystems, jobs and cultural values could provide unprecedented benefits for Australia's environment and people. Without it, Australia risks continuing its trajectory as the developed nation with the greatest loss of biodiversity on the planet.

Current funds for managing threats to Australia's threatened species are unlikely to achieve an outcome of comprehensive species recovery. There are some emerging mechanisms that have great potential, if managed judiciously, to substantially increase threatened species recovery efforts such as carbon markets, biodiversity accreditation for farms, and funding for increasing water quality in the Great Barrier Reef catchments. Independent governance needs to accompany these mechanisms to ensure actions undertaken are providing additional benefits to those already undertaken, to ensure value for money for threatened species from these initiatives.

How is the information being used?

The information generated by this project is already being used by the Office of the Threatened Species Commissioner to help inform the new Threatened Species Action Plan, where our systematically-defined threats, Threat Abatement Strategies and costs for each species have informed the potential actions and feasibility for assessing priority species. Our ‘species-threat’ matrix has also helped inform the allocation of resources for the national bushfire recovery funds, where high impact threats on species were given a higher priority for funding. The Western Australian Feral Cat Working Group have also used the ‘species-threat’ matrix to make a case for listing cats as a Key Threatening Process in Western Australian, by extracting out the relevant species that are impacted by feral cats in that jurisdiction. Further, the World Wide Fund for Nature have utilised the spatially variable cost layers to cost-effectively prioritise restoration efforts after the 2019-2020 megafire. While it is early days, the framing provided in our project have been part of many inspiring conversations with other governments and organisations to re-evaluate their ability to systematically consider cost in planning tasks.

Beyond these early adoption applications of the data generated in this project, the information we have synthesised and the products we provide can be used to guide coordinated action of threat mitigation and species recovery actions. They can also help inform options to support management of protected areas and other important places, identify priority areas for expansion of the protected area estate to support reserve design, regional planning, investment and strategic assessments, and contribute to frameworks for identifying measures of success in threatened species recovery. It can help inform policy processes across different jurisdictions (e.g., EPBC Act significant impact assessments) and help identify opportunities for investments that benefit multiple species and achieve broader environmental outcomes and assess the likely consequences of land use change on species persistence (and costs of recovery).

Limitations of this research

To achieve an answer to the broad question - which *actions for threat abatement are required to ensure all Australian species recover and what is the likely cost to undertake these actions?* - in the time frame we had available, we had to make a fundamental assumption that all actions could be implemented and would be successful if implemented. However, we acknowledge significant challenges and uncertainty in: (i) the local appropriateness and feasibility of implementing these actions; (ii) the benefit to each species of the action, including under different action intensities (e.g., the intensity of invasive predator control, and how this might need to be different across seasons, years and regions), and, (ii) the costs of the action. Improving our understand of feasibility would affect costs, especially in some regions, and for some actions more than others. We do not assess the responsibility of resourcing threatened species recovery, and indeed actions within the Threat Abatement Strategies we include are already being implemented to some extent by a range of stakeholders. An understanding of where we are at as a nation in abating threats is a critical knowledge gap when devising a plan for recovering threatened species.

There are important costs associated with recovering threatened species that were beyond the scope of this study. Our broad estimate of the total costs of threatened species recovery must be treated as an under-estimate given these omissions. Costs that were not included in this work but should be the focus of future estimates include:

- Ongoing monitoring of threatened species populations and adapting management where needed, in response to findings;
- Intensive and ex-situ conservation (such as captive breeding and seed banking);
- The cost of research to support and improve recovery actions;
- Monitoring threatened species recovery on offshore islands;
- Responding to climate change (although we did consider mitigating climate change impacts through managing other threats and restoring habitat quantity and quality);
- Appropriate processes for engaging communities (this is best carried out with local scale information and will be context specific).

Finally, this assessment focuses on a small portion of biodiversity. Threatened species exist in habitats with other species and ecosystems and important places which would also benefit from improved knowledge and resources, especially those of importance to Indigenous Australians.

All these assumptions and limitations can – and should be – further researched as these will add value to this effort and can help ensure Australia has a biodiverse future.

We note that there are other NESP projects underway in parallel with this project, which we have not had the opportunity to synthesise. Therefore, some of the above limitations and future research questions outlined below are likely to have already been at least partly answered, such as including estimates of the costs of ex-situ conservation, monitoring, and captive breeding, and conservation on islands.

Recommendations for future research

There are a number of important avenues for future research to address the limitations of this work. For example, we need to assess the feasibility of undertaking the actions we have identified, both in terms of what can be achieved (i.e., is there technical 'know how' to do the action) and how likely is it that this will mitigate or manage the threatening process to a level whereby it becomes negligible to the species being impacted. Part of this would be an evaluation of the potential benefit accrued by the actions, and how this differs across different intensities of action. For example, some species might persist with cat baiting alone; other species might need a predator-proof fence; or cat baiting twice a year versus cat baiting 12 times a year. In addition, it would be important to assess how the implementation of these actions benefit non-threatened species. We note that while we did assess total costs of full recovery of species, an assessment on how much of a species' range would need to be managed for the species to be recovered to the point of de-listing (i.e., not threatened with extinction) is important.

Further efforts are also required to bring together information on additional costs outside the scope of our analysis, including comprehensive monitoring of threatened species populations, intensive and ex-situ conservation (such as captive breeding or seed banking), the cost of research to support recovery action, and threatened species recovery on offshore islands. Given the certainty of climate change, we need to assess how these actions need to be refined as climate change progresses in appropriate time horizons for species recovery and consider an adaptive management implementation framework that is responsive to change.

As part of future efforts, we need to undertake spatial assessments of the different land tenures on which threat abatement can benefit threatened species to better understand the social, political and cultural aspirations for implementation. We also need to outline the responsibilities, opportunities and sources of funding for implementing threatened species recovery. Ultimately, we need research and action to determine how to address the drivers of biodiversity loss, such that threat abatement needs do not continually grow for future generations.

Finally, we need to support the commitment of resources and increased leadership opportunities for Indigenous Australians to undertake Indigenous-designed and led research to ensure similarly suitable information is available for species that require attention due to their cultural values, in addition to those which are threatened from a conservation perspective.

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Further information:

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