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Butterflies on the brink: identifying the Australian butterflies (Lepidoptera) most at risk of extinction

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Running title

Butterflies on the brink

Abstract

The diversity and abundance of native invertebrates is declining globally, which could have significant consequences for ecosystem functioning. Declines are likely to be at least as severe as those observed for vertebrates, although often are difficult to quantify due to a lack of historic baseline data and limited monitoring effort. The Lepidoptera are well studied in

Australia compared with other invertebrates, so we know that some species are imperilled or declining. Despite this, few butterfly taxa are explicitly listed for protection by legislation. Here we aim to identify the butterfly taxa that would most benefit from listing by determining the Australian butterflies at most immediate risk of extinction. We also identify the research and management actions needed to retain them. For 26 taxa identified by experts and various conservation schedules, we used structured expert elicitation to estimate the probability of extinction within 20 years (i.e. by 2040), and to identify key threatening processes, priority research and management needs. Collation and analysis of expert opinion indicated that one taxon, the laced fritillary (*Argynnis hyperbius inconstans*), is particularly imperilled, and that four taxa (*Jalmenus eubulus*, *J. aridus*, *Hypochrysops piceatus* and *Oreisplanus munionga larana*) have a moderate-high (>30%) risk of extinction by 2040. Mapped distributions of the 26 butterflies revealed that most are endemic to a single state or territory, and that many occupy narrow ranges. Inappropriate fire regimes, habitat loss and fragmentation (through agricultural practices), invasive species (mostly through habitat degradation caused by weeds and rabbits) and climate change were the most prevalent threats affecting the taxa considered. Increased resourcing and management intervention will be required to prevent these extinctions. We provide specific recommendations for averting such losses.

Key words

Anthropogenic mass extinction crisis, biodiversity conservation, conservation management Delphi, expert elicitation, IDEA, insect decline, IUCN Red List, key threatening processes.

INTRODUCTION

Biodiversity is in the midst of a human-driven extinction crisis (Jenkins 2003; Pimm *et al.* 1995; Ceballos *et al.* 2015; Cardoso *et al.* 2020; Pimm *et al.* 2014; Woinarski *et al.* 2019). Modern extinctions have occurred at a rate that far exceeds the background rate estimated from the fossil record (Ceballos *et al.* 2015; Johnson *et al.* 2017), comparable in magnitude to the five previous mass extinctions that have occurred throughout Earth's history (Dirzo *et al.* 2014). Few of these studies have quantified the likely loss of invertebrates which constitute over 99% of global animal species diversity, and consequently, the true rate of biodiversity decline is likely to be severely underestimated (Régnier *et al.* 2015).

Terrestrial invertebrates and their habitats are increasingly threatened by human disturbances (e.g. habitat loss and fragmentation, invasive species, inappropriate fire regimes and climate change; Sánchez-Bayo & Wyckhuys 2019, 2021) leading to an overall pattern of decline in insect diversity and abundance globally (Wagner 2020). Dirzo *et al.* (2014) suggest that the rate of decline in abundance, species extinctions, and range contraction among terrestrial invertebrates are at least as severe as among vertebrates, estimating a global decline of 45% over 40 years (albeit with varying severity among taxonomic orders). van Klink *et al.* (2020) analysed 166 long-term surveys of insect assemblages across 1676 sites (four of which were located in Australia) to investigate geographic patterns of decline, finding that the evidence of decline was strongest for terrestrial insects in North America, and in some European regions. Indeed, in protected areas in Germany, Hallmann *et al.* (2017) estimated a seasonal decline of 76% in flying insect biomass over a 27-year period (between 1989-2016), while in Britain, Thomas *et al.* (2004) measured declines in 71% of native butterflies over a 20-year period (between 1970-1999).

Increasing levels of decline and possible extirpations in terrestrial native invertebrate communities are certain to have adverse effects on ecosystem functioning because invertebrates play a central role in many ecological processes, including pollination, herbivory, detrivory, nutrient cycling, and by providing a food source for higher trophic levels (Hallmann *et al.* 2017; Sands 2018; Taylor *et al.* 2018; Kitching *et al.* 2020). Accordingly, there is an urgent need to determine the cause(s) of these declines, understand the ramifications for ecosystems and ecosystem services, and implement appropriate management actions that aim to halt and reverse declines in those species at greatest risk of extinction (Samways *et al.* 2020).

The International Union for Conservation of Nature (IUCN) Red List of threatened species is the most widely used tool for measuring extinction risk to biodiversity globally (Rodrigues *et al.* 2006). But because it requires robust data on geographic range, population trends, threats, habitat and ecology (which are typically only available for a small minority of invertebrates from well-known groups, such as Lepidoptera and Odonata), the vast majority of the world's invertebrates have not had their conservation status evaluated (Régnier *et al.* 2015; Cardoso *et al.* 2011). Despite some attempts to better represent invertebrates on the IUCN Red List (e.g. by developing a "Sampled Red List Index" for butterflies, Lewis & Senior 2011), less than 1% of the ca. 1.4 million taxa described globally have been assessed for inclusion

(Régnier *et al.* 2015). This is in part because the original categories and criteria were designed explicitly for vertebrates (Mace *et al.* 2008; Cardoso *et al.* 2011), presenting challenges when applying the IUCN Red List to invertebrates. While there has been an extensive effort to increase the applicability of the criteria to other taxa (IUCN 2012), there are still limitations in their suitability for many invertebrate groups (Moir & Brennan 2020; Kwak *et al.* 2020), such as the inability to adequately capture complex plant and ant host interactions that compound the difficulty of conserving many lepidoptera (e.g. Fiedler 2012; Ueda *et al.* 2016). That there have been many documented invertebrate extinctions of species that were not listed on the IUCN Red List (e.g. see Régnier *et al.* 2009; Braby 2019; James *et al.* 2019) suggests that to date such lists have had limitations for identifying and prioritising invertebrates at greatest risk of extinction. Furthermore, because the IUCN threat categories conflate declining populations and small populations, they do not readily distinguish among species on a rapid trajectory towards extinction from those that may persist in small numbers for long periods (Geyle *et al.* 2018; Dirzo *et al.* 2014), so listing a species within a particular IUCN Red List category says nothing about when a species is likely to go Extinct, only that it is at risk of doing so.

Despite recent progress in Australia (New 2010; New & Sands 2002; Harvey *et al.* 2011; Barton & Moir 2015; Braby 2018), many challenges remain for invertebrate conservation and management (Sands 2018; Taylor *et al.* 2018). Invertebrates are generally poorly known and under-studied (Eisenhauer *et al.* 2019), and much of their vast biodiversity remains undescribed (Taylor *et al.* 2018). This, coupled with limited resources (e.g. scientific expertise and funds), has made it difficult to assess and hence address their conservation needs (Sands 2018). Furthermore, recent advancements in conservation assessments (Braby 2018; Braby *et al.* 2018) have not translated into statutory lists. For example, despite being one of the better-studied and more charismatic invertebrate groups (Fleishman & Murphy 2009; Taylor *et al.* 2018), only ten butterflies (species and subspecies) are currently recognised as threatened under Australian environmental legislation (the *Environmental Protection and Biodiversity Conservation Act 1999* [EPBC]) (Taylor *et al.* 2018), equating to ~1.6% of the recognised 614 Australian butterfly taxa (species and subspecies) (AFD 2020). Of those that are formally listed, most are without management or recovery plans (Sands 2018), while several other species that are likely to be threatened have either not been formally evaluated for listing, or there is insufficient information for them to meet eligibility criteria (Sands 2018).

Australian terrestrial invertebrate biodiversity is substantial, highly endemic, and characterised by numerous ancient lineages, relicts and evolutionary radiations (Andersen 2016; Austin *et al.* 2004; Cranston 2010; Raven & Yeates 2007; Kristensen *et al.* 2015). It is also under increasing stress, and likely to be declining rapidly (Sands 2018; New 2018; New *et al.* 2021). To meet commitments made by the Australian Government—along with signatories to the Convention on Biological Diversity—to avoid further extinctions (Department of Environment and Energy 2016; United Nations 2015), we must first identify the species at most immediate risk, and identify actions that should reduce that risk.

Here, we used structured expert elicitation to estimate the probability of extinction in the next 20 years for the subset of Australia's butterflies identified by experts to be at high risk of extinction. We chose to assess extinction risk in butterflies because they are relatively well-studied in Australia (unlike most other Lepidoptera, and indeed most invertebrates; Lewis & Senior 2011), and because there is a large enough group of interested experts with sufficient knowledge to make an informed assessment about their current and future conservation outlook. We acknowledge that this relatively substantial evidence base for butterflies, and the relatively large constituency of experts, renders this group potentially unrepresentative of the plight of invertebrates more generally. However, the factors driving butterfly decline may be typical of those affecting other invertebrate groups (e.g. see Leather 2018), so it is plausible that the rate and extent of declines in butterflies may also be representative of other invertebrate groups, for which comparable analyses would be severely constrained by far greater knowledge gaps.

We mapped the distributions of the most threatened butterfly taxa to identify priority regions for Australian butterfly conservation. We then collated information on likely threatening processes, with the overall aim of identifying key research and management objectives for averting future extinction. Our approach follows estimates of imminent extinction risk among Australian birds and mammals (Geyle *et al.* 2018), freshwater fish (Lintermans *et al.* 2020), and terrestrial squamates (Geyle *et al.* 2020). Note that this assessment preceded the 2019-20 wildfires in Australia, which are likely to have severely worsened the conservation outlook for many species.

MATERIALS AND METHODS

Initial taxon selection

More than 40 experts were invited to participate in this project, selected on the basis of their experience and knowledge of Australian butterflies and their conservation. This included amateurs among whom resides much of the knowledge of butterfly natural history in Australia, as well as experts from academic institutions, state and federal government offices and agencies and non-government organisations. Overall, 28 experts (including representatives from every state and territory) were actively involved in the project (all of whom are co-authors), either by participating in a workshop, taking part in the expert elicitation and/or by providing detailed information about one or more species of Australian butterfly.

We produced a preliminary list of Australian butterflies at high risk of extinction within the next 20 years based on published information and various conservation schedules (e.g. state and federal conservation documents and threatened listing advices). We then undertook detailed email correspondence and workshop discussions with our expert panel to identify a candidate list of species that could be lost to extinction within our 20-year timeframe of interest, with a particular focus on unlisted taxa (i.e. the aim was to consider only those taxa that were candidates for possible extinction by 2040). We chose 20 years as an arbitrary period over which might reasonably be assessed, and which might reasonably be influenced by policy and management changes made today. All experts were given the opportunity to nominate additional taxa for consideration, which they believed warranted inclusion. After several weeks of detailed discussions, a list of 26 species and subspecies was finalised for assessment (Table 1).

Structured expert elicitation

A total of 21 experts participated in a workshop to discuss the conservation of Australian butterflies, to finalise the list of taxa most likely to become extinct in the next 20 years, and to estimate the likelihood of extinction for those taxa. We used structured expert elicitation for obtaining estimates of butterfly extinction probability, using a procedure based largely on the Delphi (Burgman *et al.* 2011) and IDEA methods (Hemming *et al.* 2018). Each of these approaches has been developed in an attempt to reduce the incidence of some commonly encountered biases in expert elicitation processes (Martin *et al.* 2012). Our adapted approach followed five main steps:

1. Before the workshop, experts were provided with a draft conservation account of relevant information on each taxon based on published literature and unpublished information obtained from taxon specialists. Draft accounts included information on biology, habitat requirements, population parameters, geographic range, historical and predicted rates of decline (where available), and threats. The accounts were available on the day of the workshop, and a summary of the information was presented for each taxon. Experts were given the opportunity to provide greater context through discussion of the information, to seek clarification from taxon specialists (if present), and to identify any missing information that might influence the risk of extinction.
2. Based on the information presented in the draft accounts and discussions, experts were asked to provide, for each taxon, an initial estimate of the probability of extinction in the wild within the next 20 years, scaled from 0-100%, *assuming current levels and characteristics of management* ("Round 1" scores). In addition, experts provided a level of confidence in each of their estimates (very low, ≤ 20%; low, 21–40%; moderate, 41–60%; high, 61–80%; or very high, ≥ 80%), and were encouraged to provide justification for their scores. Participants were asked not to discuss their scores with each other (as each individual assessment was to be treated as independent).
3. Individual estimates of extinction probability were compiled during a break in the workshop. We then calculated summary statistics (including mean, median, range), and provided participants with graphs displaying the summary data so that they could see where their estimates conformed or otherwise to those of the rest of the group. Experts were encouraged to engage in a general conversation about the results, and to highlight taxa for which they would consider modifying their estimates of extinction probability based on this discussion. For several taxa, it was noted that additional information from taxon specialists (who were not able to attend the workshop) was required to inform estimates. Detailed minutes were taken during this discussion for later reference.
4. Following the workshop, the individual assessments of extinction probability and their associated confidence were modelled using a linear mixed effects model. We controlled for individual experts consistently underestimating or overestimating likelihood of extinction by specifying their identity as random intercepts. We specified a variance structure in which the variance increased with the level of uncertainty associated with each estimate of likelihood of extinction. Confidence

classes of 'very low', 'low', 'moderate', 'high' and 'very high' were converted to uncertainty scores of 90, 70, 50, 30 and 10% respectively. This model allowed us to predict the probability of extinction (with 95% confidence intervals) for each taxon (as in Geyle *et al.* 2018). Predicted probabilities of extinction and 95% confidence intervals, the summary statistics and the detailed workshop minutes were provided to all workshop participants, and also to additional experts who were unable to attend (but have key knowledge on one or more of the taxa under consideration). All experts were then asked to review the results, while noting any concerns about the spread of estimates given for a particular taxon, or the rankings of extinction probability. Each participant was then given the opportunity to clarify information about the presented data, introduce further relevant information that may justify either a greater or lesser risk of extinction, and to cross-examine new information via email.

5. Participants were then asked to provide a second, final assessment of the probability of extinction (and associated confidence) for each taxon, from which the results were finalised ("Round 2" scores).

Estimating the number of taxa likely to become extinct in the next 20 years

The predicted probabilities of extinction for each of the 26 butterflies (assessed by the experts) were summed to estimate the number of taxa (from this subset of Australian butterflies) likely to become extinct in the next 20 years (as per Geyle *et al.* 2018).

Testing for concordance among expert assessments

We measured the level of agreement among experts in the relative ranking of the most imperilled butterflies using Kendall's Coefficient of Concordance (□) (Kendall & Babinton Smith 1939). This test allows for comparison of multiple outcomes (i.e. assessments made by multiple experts), whilst making no assumptions about the distribution of data. Average ranks were used to correct for the large number of tied values in the dataset, and ranks were compared only for the 16 experts who assessed all 26 taxa.

Geographic distribution of the most imperilled butterflies

We mapped the distribution of the most imperilled butterflies according to their presence in each Interim Biogeographic Regionalisation for Australia (IBRA) bioregion (DAWE 2015) using distributional data (range maps) compiled from Braby (2016).

Key threatening processes

Key threats to each taxon were derived from the published literature, conservation listing advices (where applicable), the Action Plan for Australian Butterflies (BAP, Sands & New 2002) and from unpublished information and observations of taxon experts. All threats were categorised using the IUCN Threats Classification Scheme (Version 3.2, IUCN 2020c). We used this information to determine the number and proportion of taxa threatened by various threat types. Note that this assessment of threats included both ongoing threats, and putative threats that could plausibly impact the species under consideration within the time frame of interest (i.e. 20 years).

Conservation priorities

For each of the butterflies under consideration, we identified relevant research and management actions considered necessary for reducing extinction risk using various published and unpublished sources (BAP, conservation listing advices, published literature and expert opinion). Research included actions that involve seeking improved knowledge of status, understanding of threats, or those aimed at improving management options (i.e. actions required to fill knowledge gaps that reduce uncertainty about which management actions to implement, and how to implement them) (Gillespie *et al.* 2020). Research actions were categorised using the IUCN Research Needed Classification Scheme (Version 2.0, IUCN 2020b). Management actions included those that, based upon current knowledge, are likely to lead, directly or indirectly, to tangible reductions in a species' extinction risk (i.e. evidence suggests that such actions will ameliorate the impact of a threatening process, or increase the number and/or size of populations) (Gillespie *et al.* 2020). Management actions were categorised using the IUCN Conservation Actions Classification Scheme (Version 2.0, IUCN 2020a).

Monitoring is crucial for testing recommendations from research and evaluating whether management interventions are achieving their intended aim (Robinson *et al.* 2018). However, the type of monitoring required will depend upon the target species and specific management interventions (Woinarski *et al.* 2017). Therefore, we assume here that monitoring will occur in conjunction with research and management interventions (i.e. we do not consider actions relating solely to monitoring in the absence of management intervention). Likewise, all of the butterflies considered here would benefit from formal conservation planning (i.e. through recovery plans and/or area-based management plans), and accordingly, actions relating solely to conservation planning are not considered. This should not be taken as discounting the importance of monitoring and recovery planning, as each is a critical component of conserving threatened species.

RESULTS

Only six of the taxa considered had been designated as threatened under the *EPBC Act* (as of February 2020), with a further two nominations in preparation (by some of the authors listed here). A far larger number of species (20) were recognised as threatened under the relevant legislation from one or more of the states or territories in which they are known to occur (Table 1). A small proportion of the remaining 588 recognised taxa were considered to be threatened at either a national or state level in the Action Plan for Australian Butterflies (see Appendix 1, Sands & New 2002); however, these taxa were considered unlikely to go extinct in the next 20 years by our expert panel. Braby and Williams (2016) calculated the number of species likely to be missing from the Australian butterfly fauna (i.e. those that are undescribed, described but not recognised, or known but not yet recorded from Australia), and estimated that 42 butterfly taxa are yet to be discovered.

Expert elicitation, extinction probabilities and the number of species likely to become extinct

Collation and analysis of expert opinion (Round 2 scores) indicated that one of the 26 taxa considered, the laced fritillary (*Argynnis hyperbius inconstans*) is at extremely high risk (likelihood >90%) of becoming extinct within the next 20 years (Table 2); indeed, it may already be so, with apparently no confirmed specimen records of the butterfly since 2001 (Lambkin 2017). The most recent putative record of the species is a sighting of a single male made near Port Macquarie, NSW on 13 April 2015 by A. Moore (pers. comm.). An additional four taxa had moderate-high probabilities of extinction (30-50%) (Table 2). Summing across the extinction risk values assigned by the experts to the 26 taxa assessed, we estimated that five taxa are likely to become extinct by 2040 unless management improves. There was a reasonable and highly significant degree of conformity among experts in their assessments of extinction risk (□ = 0.3, □ = <0.001).

Geographic distribution of the most imperilled Australian butterflies

Of the 26 taxa considered in our assessment, all are endemic to Australia, although two taxa (*A. hyperbius inconstans* and the apollo jewel *Hypochrysops apollo apollo*) have other subspecies beyond the shores of Australia (but note that *A. hyperbius inconstans* may be a distinct species endemic to Australia (Lambkin 2017)). Eighteen of the butterflies are endemic to a single state or territory (Table 1). The remaining eight taxa are known historically from two or three neighbouring states or territories (Table 1), but in some cases are believed to have been locally extirpated. For example the small bronze azure (*Ogyris otanes otanes*) is most likely extirpated in New South Wales (NSW) and possibly Victoria, with extant populations confirmed only from SA, whereas the eastern bronze azure (*O. halmaturia*) has almost certainly been extirpated from a formerly wide area in Victoria and now persists precariously at only three sites in South Australia (Braby & Douglas 2008; R. Glatz, unpublished data). Victoria is home to the highest number of taxa (n = 9), with the majority occurring in the Murray Darling Depression, Victorian Midlands, Naracoorte Coastal Plain and South Eastern Highlands bioregions (Fig. 1). Queensland and NSW each have seven taxa, mostly occurring in the Brigalow Belt (north and south), South Eastern Queensland and Wet Tropics bioregions (Fig. 1).

Key threatening processes

Natural system modifications were the most prevalent threats to the butterflies, affecting 21 of the taxa considered (Fig. 2). Within this broad category, inappropriate fire regimes, including both increases and decreases (suppression or absence) in fire frequency and/or intensity, impacted the most taxa at 19. Four butterflies (three of which were also affected by fire) were impacted by dams and water management, particularly drainage of wetlands and swamps (Appendix S1). Other important threats included agriculture (notably clearance and fragmentation of habitat associated with non-timber crops and domestic livestock, affecting 17 of the taxa considered, and invasive species (particularly introduced grasses, introduced herbivores—namely European rabbits *Oryctolagus cuniculus*—and introduced invertebrates) affecting 14 of the taxa considered (Appendix S1). Climate change is likely to affect almost half of the taxa considered (n = 11) (Fig. 2), with increases in temperature, the duration and frequency of drought, and sea level rise being potentially catastrophic in the future (Appendix S1).

Conservation priorities

All 26 taxa considered are likely to benefit from further surveys, allowing for more precise estimates of occupancy, geographic distribution (extent of occurrence and area of occupancy) and population size (Fig 3a). Likewise, all 26 taxa should benefit from further research to assess the impacts of their known or putative key threatening processes (Fig 3a). Specifically, most of the butterflies considered (n = 18) require a greater understanding of the role of disturbance (e.g. fire) in their ecology, or in the ecology of their attendant ants and host plants (Appendix S2). There is some uncertainty about the ecological requirements for 10 taxa (including their critical habitats, interactions with attendant ants, biology and life cycle), warranting further investigation (Fig 3, Appendix S2). For six of the butterflies considered, further work to clarify their taxonomic status is required (Fig. 3a), as this could have important implications for their conservation. For example, if a taxon is "split" (i.e. where it is found to be two or more species), each new species would have a smaller geographic distribution and population size than previously thought, which may elevate their threatened status Eight butterflies were also identified as possible candidates for research into the feasibility of *ex-situ* conservation (including captive breeding) (Fig. 3a, Appendix S2).

The most important management actions to reduce the risks of extinction were related to education and awareness (a priority for all 26 taxa under consideration), land/water management (a priority for 21 of the taxa considered), and land/water protection (a priority for 18 of the taxa considered) (Fig. 3b). Community engagement, including site visits, installation of signage, and discussions with private landholders and land managers, was considered to be a priority management action for all 26 taxa considered. Within the broader category of land/water management, implementation of an appropriate fire management strategy was the most common action assigned (a priority for 18 of the taxa considered), followed by invasive species control (particularly weeds and invasive herbivores) (a priority for 13 taxa) (Appendix S3). Within the broader category of land/water protection, the most common action assigned was site protection, particularly identifying sites of high conservation value for priority protection (Appendix S3).

DISCUSSION

The abundance and diversity of invertebrates is declining globally (Sánchez-Bayo & Wyckhuys 2019, 2021; Wagner 2020; van Klink et al. 2020). Given increasing concerns of continued decline (Dirzo *et al.* 2014), escalating pressures associated with ongoing threatening processes (Sánchez-Bayo & Wyckhuys 2019; Samways *et al.* 2020), and the ecological importance of maintaining invertebrate biodiversity (Hallmann *et al.* 2017; Sands 2018), it is crucial that extinction risk is recognised in a timely manner to allow for implementation of management responses aimed at preventing extinctions. Here, we used structured expert elicitation to help redress this issue for Australian butterflies, by forecasting which, and how many, taxa are at high risk of extinction.

Overall, experts estimated the butterflies under consideration to have moderate probabilities of extinction within the next 20 years, with an average estimate of 18% across the 26 considered taxa. One butterfly, *A. hyperbius inconstans* was considered to have a very high extinction probability (~94%). Four other taxa, the pale imperial hairstreak (*Jalmenus eubulus*), the inland hairstreak (*J. aridus*), the bulloak jewel (*Hypochrysops piceatus*) and the Marrawah skipper (*Oreisplanus munionga larana*), were estimated to have probabilities of extinction of 30–50%. Although there are no confirmed extinctions of Australian butterflies since European colonisation, the pace of modern insect extinctions is suspected to have surpassed that of vertebrates by a large margin (Sánchez-Bayo & Wyckhuys 2019). However, this is obfuscated by a paucity of historical data on trends in population size and geographical range size in many regions (including Australia). In areas where population trajectories have been assessed, the majority of taxa have declined, including not only specialist taxa (i.e. those with narrow ecological requirements, such as dependence on a single host plant), but also generalist species that were once very common (Sánchez-Bayo & Wyckhuys 2019, 2021). This suggests that there are likely to have been earlier undetected extinctions, and that future extinctions are inevitable without rapid and targeted intervention.

Insects have been declining in many parts of the world for several decades, a phenomenon which is likely to be affecting ecosystem functioning (Hallmann *et al.* 2017). Yet despite their importance, these losses have been largely unreported in the wider community. In Australia, there is little long-term monitoring data to support anecdotal reports of decline (Braby 2019). Few of the taxa considered in this study have had their distributions (extent of occurrence and area of occupancy) accurately mapped, and even fewer have robust data on population sizes or trends. This is primarily due to a lack of resources (including qualified entomologists and butterfly conservation biologists) and funding for conservation activities (Taylor *et al.* 2018; Sanderson *et al.* 2021). Nevertheless, for many of the taxa considered here (and others, e.g. *Ogyris idmo*; Williams *et al.* 2020), there has been a clear contraction in range (attributable to localised extinctions or extirpations of populations). Population monitoring has also been accorded insufficient priority in Australian biodiversity research and management (Lindenmayer & Gibbons 2012; Legge *et al.* 2018), contributing further to a general lack of data on Australian butterfly populations.

The butterflies considered in this study share many common threats, the most prevalent of which are natural system modifications (e.g. inappropriate fire regimes or surface water abstraction), habitat loss and fragmentation for agriculture, invasion by exotic species, and climate change. These threats are largely consistent with those identified to have contributed to the reduction of insect numbers nationally and globally (Sands 2018; Sánchez-Bayo & Wyckhuys 2019). Indeed, many of the taxa considered in this study are associated with habitats that have historically been cleared at a high rate (e.g. old-growth Brigalow woodlands of central Qld and the old-growth mangrove forests of coastal NSW and Qld), and almost all of the taxa considered are suffering from secondary impacts associated with fragmentation and isolation. Notably, four of the five most imperilled butterflies occur in Qld (with two also known from NSW) on the eastern coast of Australia, an area currently undergoing high rates of land clearing. This region has been identified as one of 11 deforestation hotspots by the World Wildlife Fund (Schwartz 2015). This suggests that those species are highly likely to have undergone substantial historical declines (e.g. *J. eubulus*) (Eastwood *et al.* 2008). For several taxa currently persisting in these already highly modified landscapes, land-use change and habitat loss for development is ongoing. For example, extant and potential breeding sites used by the mangrove ant-blue (*Acrodipsas illidgei*) are threatened by further coastal development, particularly so in areas where the butterfly occurs outside of conservation reserves. Similarly, there is still extensive clearing of critical habitat used by the Tasmanian chaostola skipper (*Antipodia chaostola leucophaea*) as a result of increased urbanisation, particularly around Hobart, Tasmania. This current, and any future, loss of critical resources must inevitably cause further declines.

Another key aspect facing the most imperilled butterflies is that all of the taxa are ecological specialists (most are monophagous, being dependent on a single species of host plant or host ant). In fact, 13 taxa considered in this study are co-dependent on a specific species of ant. In addition, almost all of the taxa are narrow-range endemics, with very small geographical distributions. The only exception to this is *J. eubulus,* although this species has lost >95% of its habitat, and so has suffered from substantial contractions to its' area of occupancy (Eastwood *et al.* 2008). Host specificity and ecological complexity, together with limited spatial extent, could be key predictors of vulnerability in Australian butterflies. Thus, using a traits-based approach, it may be possible to identify and prioritise additional taxa which might be of high extinction risk.

We identified many common research and management priorities among the butterflies considered, each of which were largely congruent with the three main recommendations of the BAP: (1) further exploration to detect any previously unknown populations, whose discovery may affect other priorities and needs, (2) acquisition, or conservation measures, to secure critical sites, and (3) aspects of restoration and management of degraded habitats (Sands & New 2002). The most important research actions included further surveys to allow for more precise estimates of geographic distribution and population size to be determined, and further research to assess key threatening processes (particularly relating to climate change and inappropriate fire regimes) and their relative and compounding impacts. For some taxa, more research is required to determine their ecological requirements (including critical habitat types, interactions with attendant ants, biology and life cycle), while others require further research to resolve taxonomic issues.

Many of the taxa considered here are likely to benefit from implementation of an appropriate fire management strategy, invasive species control, and the identification of sites of high conservation value for priority protection. The most important conservation actions, however, were related to education and awareness (identified as a priority for all of the taxa considered) and land/water management and protection. Community engagement has the potential to raise general awareness, to locate additional populations of threatened taxa, to encourage key stakeholders to contribute to the implementation of conservation actions, and to foster community ownership regarding conservation. This engagement is critical, given that much of the work required to recover threatened Australian butterflies, including ecological restoration, management and monitoring falls into the hands of citizen scientists and non-government organisations (Sands & New 2002). Platforms like Butterflies Australia, a smart-phone app and website (https://www.butterflies.org.au) launched recently for citizen scientists (Sanderson *et al.* 2021), provide a great step towards achieving some of the key goals in invertebrate conservation. This initiative was designed specifically to remedy the data deficiency of butterflies in Australian conservation policy and scientific research. It is likely to help increase community awareness, to encourage community participation (where observational data can be collected in a format suitable for scientific analysis), and to increase the availability of scientifically robust observational data on butterflies (which, previously has not been readily accessible) (Sanderson *et al.* 2021). The launch of the app and website was accompanied by a series of workshops around Australia to train citizen scientists on butterfly identification and survey methods, how to use the app and web portal, and to explain how this data can be used to assist in butterfly conservation.

We did not consider actions relating solely to recovery planning and monitoring, as the need for these is influenced by the circumstances of the individual target species and their ecological contexts, and the specific research and management interventions required. We stress, however, that both components are critical for ensuring the ongoing persistence of Australia's most threatened butterflies. Scheele *et al.* (2019) demonstrated for vertebrates that taxa with national recovery plans were more likely to be monitored, and that the monitoring was more likely to be of higher quality. In fact, even taxa with lapsed recovery plans scored highly for monitoring quality. Implementing effective monitoring can be challenging, particularly so for naturally rare species or those that are in rapid decline (and consequently are difficult to detect). Recovery plans (when funded and implemented) provide a useful tool for which clear guidelines on monitoring can be incorporated (Braby 2018). Robinson *et al.* (2018) discuss five key principles requiring consideration when designing monitoring programs for threatened species: (1) engaging people; (2) integrating monitoring with management; (3) planning, designing and implementing a fit-for-purpose monitoring program; (4) ensuring good data management; and (5) communicating the value of monitoring. These principles provide a clear framework in which to implement robust monitoring of threatened species, and should be considered as part of the recovery of each of Australia's most imperilled butterflies.

CONCLUSIONS AND RECOMMENDATIONS

This study predicts that five Australian butterflies may become extinct in the next two decades without immediate and sustained remedial action. To reduce the risk of this happening, the following package of national management and policy responses is urgently required:

1. Implement research and management actions (i.e. those outlined in Appendix S2 and S3). These should not be delayed until the taxa under consideration are formally listed as threatened under the *EPBC Act*.
2. Highly threatened but currently unlisted taxa should be listed formally as threatened under national and state/territory legislative processes, with recovery plans developed, and recovery teams established. The butterfly taxa identified in this study are obvious candidates.

3. Habitat protection is the most important aspect of butterfly conservation. Relevant habitats important to imperilled Australian butterflies should therefore be listed as *critical habitat* under the *EPBC Act*. For the taxa considered here, this includes coastal mangrove communities in Qld and NSW, coastal grasslands and associated paperbark (*Melaleuca*) wetlands in eastern Australia, saline sedgelands in southern Australia and Tasmania, summits of hilltops and of inland sand dunes, inland native grasslands and heathlands, and inland communities of old-growth brigalow.
4. Update the BAP (Sands & New 2002) to assess the current conservation status and trend of all butterfly taxa of conservation concern (not just the most imperilled). Provide the information required for listing, immediate guidance on actions, and enable coordination of recovery efforts for nationally threatened butterflies.
5. Recognising that most of the taxa considered here are narrow-range endemics, and that conservation of Australian biodiversity is a shared responsibility between national and state/territory governments, ensure state governments provide more leadership in the conservation management of imperilled butterflies restricted to their jurisdictions.
6. Promote the amateur study, collection, and sharing of information about butterflies and ensure this is not perversely impeded by conservation policy. In particular, butterfly collecting (i.e. by non-professional lepidopterists) has contributed significantly to the knowledge of the taxonomy, distribution, biology and conservation of butterflies in Australia, and will remain a vital source of information relevant to butterfly conservation and management. As such, prohibition of the collection of listed butterfly taxa is likely to have adverse effects on butterfly conservation. For the exceptionally rare taxa for which over-collecting was identified as a possible threat (included in the category "biological resource use", see Fig. 2), measures must be put in place to ensure maximum responsibility for their conservation. The 'code of conduct' presented in the BAP to facilitate and link the different priorities of collectors and conservation authorities is still relevant and influential today, and should be applied widely across Australia.
7. Ensure that amendments to policy and legislation adequately consider the knowledge and management needs of invertebrate conservation, that regulatory protections of critical habitat are strengthened and that there is adequate support for development and implementation of Recovery Planning.

The probability of further extinctions of Australian butterflies is high, and may have been underestimated here. Our assessment was undertaken prior to the 2019–2020 Black Summer bushfires, and consequently, we do not consider the impacts of the fires on the taxa considered, or on other taxa that were omitted from this study (which may now be at high risk of extinction). It is still too early to determine the impact (both short- and long-term) of the fires at a species level. Nevertheless, and notwithstanding the fire impacts, our results suggest that up to five taxa could become extinct by 2040 under current management regimes. Only urgent action, enhanced policy and planning, increased community awareness and a better-resourced conservation response will prevent future extinctions in Australian butterflies.

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SUPPORTING INFORMATION

Appendix S1**.** Key threats affecting the 26 butterflies at greatest risk of extinction, categorised using the IUCN Threats Classification Scheme (IUCN, 2020. IUCN Threats Classification Scheme, Version 3.2. Available at: https://www.iucnredlist.org/resources/threat-classification-scheme [accessed September 2020])

Appendix S2**.** Priority research actions for the 26 butterflies at greatest risk of extinction, categorised using the IUCN Research Needed Classification Scheme (IUCN, 2020. IUCN Research Needed Classification Scheme, Version 2.0. Available at: https://www.iucnredlist.org/resources/research-needed-classification-scheme [accessed September 2020]

Appendix S3**.** Priority management actions for the 26 butterflies at greatest risk of extinction, categorised using the IUCN Conservation Actions Classification Scheme (IUCN, 2020. IUCN Conservation Actions Classification Scheme, Version 2.0. Available at: https://www.iucnredlist.org/resources/conservation-actions-classification-scheme [accessed September 2020]

TABLES

Table 1. The scientific and common names, state/territory of occurrence (Queensland, QLD; New South Wales, NSW; Victoria, VIC; Tasmania, TAS; South Australia, SA; Western Australia, WA; Northern Territory, NT), and the International Union for Conservation of Nature Red List (IUCN), *Environmental Protection and Biodiversity Conservation Act, 1999* (EPBC), and relevant State/Territory conservation status listings for the most imperilled Australian butterflies (based on structured expert elicitation). Critically Endangered, CR; Endangered, EN; Vulnerable, VU; Threatened, Thr (VIC); Priority 1, P1 (WA); Not listed, NL.

Taxon	Occurrence (State/Territory)	IUCN	EPBC	State/Territory
Acrodipsas illidgei (Waterhouse & Lyell, 1914). Mangrove ant-blue, Illidges ant-blue	QLD, NSW	EN	NL	VU (QLD), NL (NSW)
Antipodia chaostola leucophaea (L.E. Couchman, 1946). Tasmanian chaostola skipper; heath sand-skipper	TAS	NL	EN	EN (TAS)
Argynnis hyperbius inconstans Butler, 1873. Laced fritillary, Australian fritillary	QLD, NSW	NL	CR	EN (QLD), NL (NSW)
Candalides noelkeri Braby & Douglas, 2004. Golden-rayed blue	VIC	NL	NL	Thr (VIC)
Croitana arenaria arenaria E.D. Edwards, 1979. Inland grass-skipper	NT	NL	NL	NL (NT)
Exometoeca nycteris Meyrick, 1888. Western flat	WA	NL	NL	NL (WA)
Hesperilla flavescens flavescens Waterhouse, 1927. Yellow sedge-skipper	VIC	NL	NL	Thr (VIC)^
Heteronympha banksii nevina Tindale, 1953. Banks' brown	VIC	NL	NL	NL (VIC)

Heteronympha cordace wilsoni Burns, 1948. Bright-eyed brown	VIC, SA	NL	NL	Thr (VIC), NL (SA)
Hypochrysops apollo apollo Miskin, 1891. Apollo jewel	QLD	NL	NL	VU (QLD)
Hypochrysops piceatus Kerr, Macqueen & D.P.A. Sands, 1969. Bulloak jewel	QLD	NL	NL	EN (QLD)
Jalmenus aridus Graham & Moulds, 1988. Inland hairstreak	WA	NL	NL	P1 (WA)
Jalmenus eubulus Miskin, 1876. Pale imperial hairstreak	QLD, NSW	NL	NL	VU (QLD), CR (NSW)
Ocybadistes knightorum Lambkin & Donaldson, 1994. Black grass-dart	NSW	EN	NL	EN (NSW)
Ogyris sp. aff. *aenone* (Waterhouse, 1902). Sapphire azure (southern population)	QLD	NL	NL	NL (QLD)
Ogyris halmaturia (Tepper, 1890). Eastern bronze azure	VIC, SA	NL	NL	Thr (VIC), NL (SA)
Ogyris iphis doddi (Waterhouse & Lyell, 1914). Dodd's azure, orange-tipped azure	NT	NL	NL	EN (NT)
Ogyris otanes otanes (C. & R. Felder, 1865). Small bronze azure	NSW, VIC, SA	NL	NL	NL (NSW, VIC SA)
Ogyris otanes sublustris M.R. Williams & Hay, 2001. Western dark azure, small bronze azure	WA	NL	NL	NL (WA)
Ogyris subterrestris petrina Field, 1999. Arid bronze azure	WA	NL	CR	CR (WA)
Ogyris subterrestris subterrestris Field, 1999. Arid bronze azure	VIC, SA	NL	NL	Thr (VIC), NL (SA)
Oreisplanus munionga larana L.E. Couchman, 1962. Marrawah skipper, alpine sedge-skipper	TAS	NL	VU	EN (TAS)

Oreixenica latialis theddora L.E. Couchman, 1953. Small alpine xenica	VIC	NL	NL	Thr (VIC)
Oreixenica ptunarra L.E. Couchman, 1953. Ptunarra xenica, ptunarra brown	TAS	NL	EN	VU (TAS)
Paralucia spinifera E.D. Edwards & Common, 1978. Purple copper, Bathurst copper	NSW	EN	VU	EN (NSW)
Telicota eurychlora Lower, 1908. Southern sedge-darter	QLD, NSW, VIC	NL	NL	NL (QLD, NSW), Thr (VIC)

^As *Hesperilla flavescens*

Table 2. The estimated probability of extinction (EX) by 2040 (in the wild) for the 26 Australian butterflies considered to be most imperilled. Likelihoods of extinction are based on structured expert elicitation (with lower/upper 95% confidence intervals) and are ranked from highest to lowest probability of extinction.

Rank	Taxon	EX	Lower 95% CI	Upper 95% CI
1	*Argynnis hyperbius inconstans* laced fritillary, Australian fritillary	0.94	0.89	0.97
2	*Jalmenus eubulus* pale imperial hairstreak	0.42	0.28	0.58
3	*Hypochrysops piceatus* bulloak jewel	0.37	0.24	0.53
4	*Oreisplanus munionga larana* Marrawah skipper, alpine sedge-skipper	0.33	0.20	0.49
5	*Jalmenus aridus* inland hairstreak	0.30	0.15	0.50
6	*Ogyris* sp. aff. *aenone* sapphire azure (southern population)	0.28	0.16	0.44
7	*Ogyris subterrestris subterrestris* arid bronze azure	0.28	0.16	0.44
8	*Croitana arenaria arenaria* inland grass-skipper	0.22	0.12	0.36
9	*Heteronympha banksii nevina* Banks' brown	0.19	0.10	0.32
10	*Heteronympha cordace wilsoni* bright-eyed brown	0.18	0.10	0.30
11	*Ogyris subterrestris petrina* arid bronze azure	0.15	0.08	0.26
12	*Candalides noelkeri* golden-rayed blue	0.13	0.07	0.23

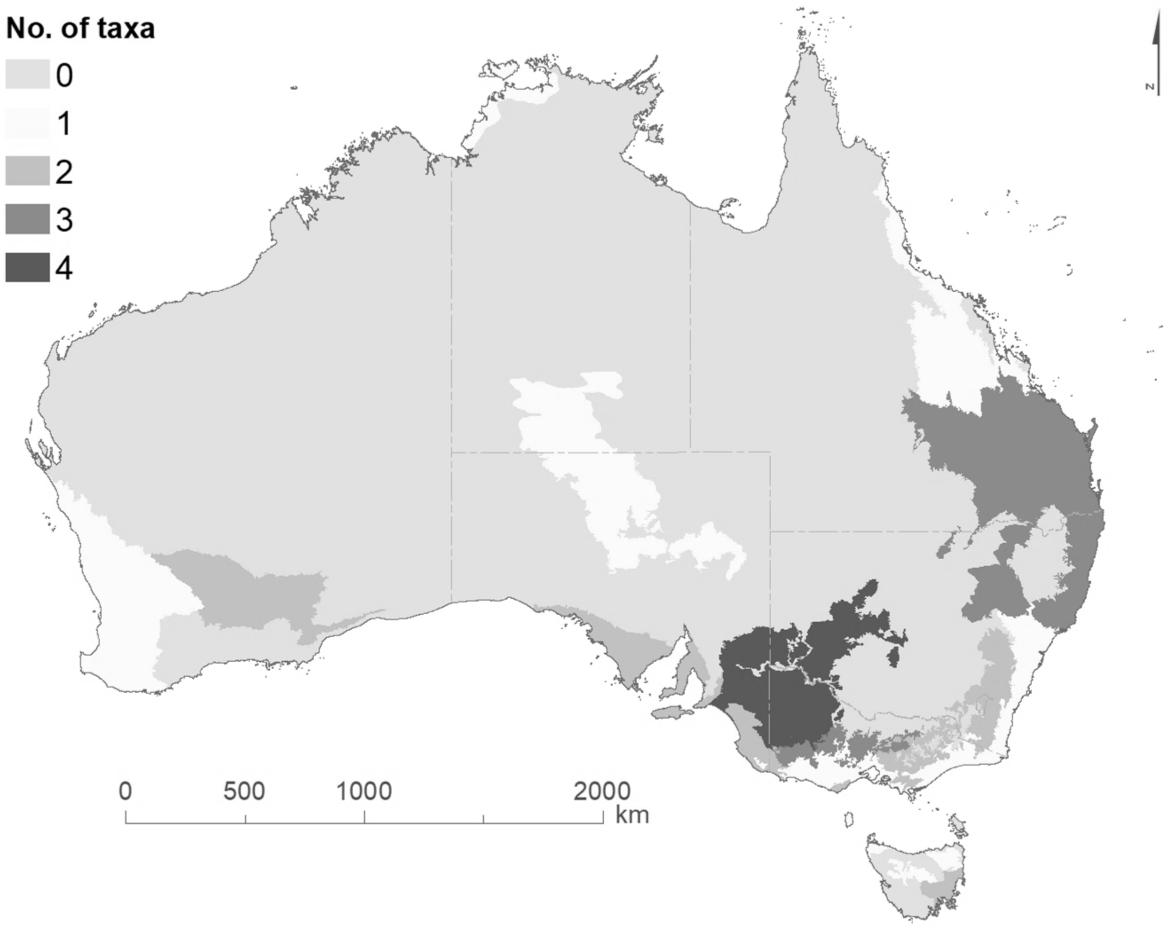
Rank	Taxon	EX	Lower 95% CI	Upper 95% CI
13	*Antipodia chaostola leucophaea* Tasmanian chaostola skipper, heath sand-skipper	0.11	0.06	0.19
14	*Acrodipsas illidgei* mangrove ant-blue, Illidges ant-blue	0.10	0.05	0.17
15	*Oreixenica ptunarra* ptunarra xenica, ptunarra brown	0.09	0.05	0.17
16	*Ogyris otanes sublustris* western dark azure, small bronze azure	0.09	0.05	0.17
17	*Ogyris iphis doddi* Dodd's azure, orange-tipped azure	0.07	0.03	0.14
18	*Hesperilla flavescens flavescens* yellow sedge-skipper	0.07	0.03	0.14
19	*Exometoeca nycteris* western flat	0.07	0.03	0.14
20	*Oreixenica latialis theddora* small alpine xenica	0.06	0.03	0.12
21	*Ogyris halmaturia* eastern bronze azure	0.06	0.03	0.11
22	*Ogyris otanes otanes* small bronze azure	0.06	0.03	0.11
23	*Ocybadistes knightorum* black grass-dart	0.05	0.03	0.10
24	*Telicota eurychlora* southern sedge-darter	0.03	0.01	0.05
25	*Paralucia spinifera* purple copper, Bathurst copper	0.03	0.01	0.05
26	*Hypochrysops apollo apollo* apollo jewel	0.02	0.01	0.04

FIGURE LEGENDS

Figure 1. The total number of imperilled Australian butterflies occurring in each Interim Biogeographic Regionalisation for Australia (IBRA) bioregion (SA Department of Environment, Water and Natural Resources 2015). Data are presented for the 26 most imperilled butterflies (derived using structured expert elicitation). Occurrence data were collated from Braby (2016).

Figure 2. The number of imperilled Australian butterflies affected by different threats types, categorised using the IUCN Threats Classification scheme (Version 3.2, IUCN 2020c). Threat data are provided for the 26 most imperilled butterflies (based on structured expert elicitation). The total number of taxa affected by each broad threat category is provided in parentheses. Note that natural system change includes fire and fire suppression, and weather refers to extreme weather events. See Supplementary Material S1 for a breakdown of the threat categories and for detailed notes for individual taxa.

Figure 3. The number of (a) priority research actions, and (b) priority management actions identified for the 26 most imperilled Australian butterflies (derived using structured expert elicitation), and categorised using the IUCN Research Needed and Management Actions Classification Schemes (Versions 2.0, IUCN 2020b, a). The total number of taxa for which each of the broad research and management action categories were assigned is provided in parentheses. Note that "Other actions" in (a) refers to research to determine how to mitigate particular threats (e.g. whether *ex-situ* breeding is possible). See Supplementary Materials S2 and S3 for a breakdown of the action categories and for detailed notes for individual taxa.



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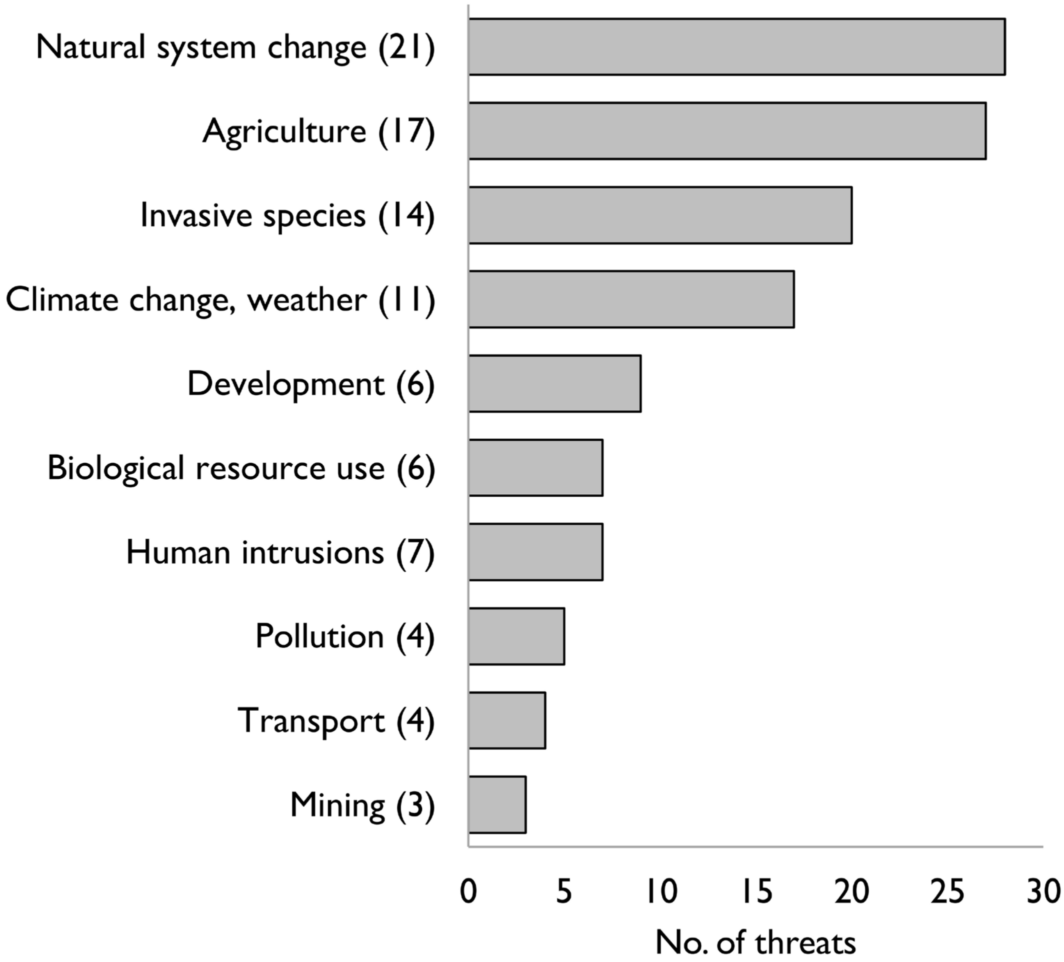

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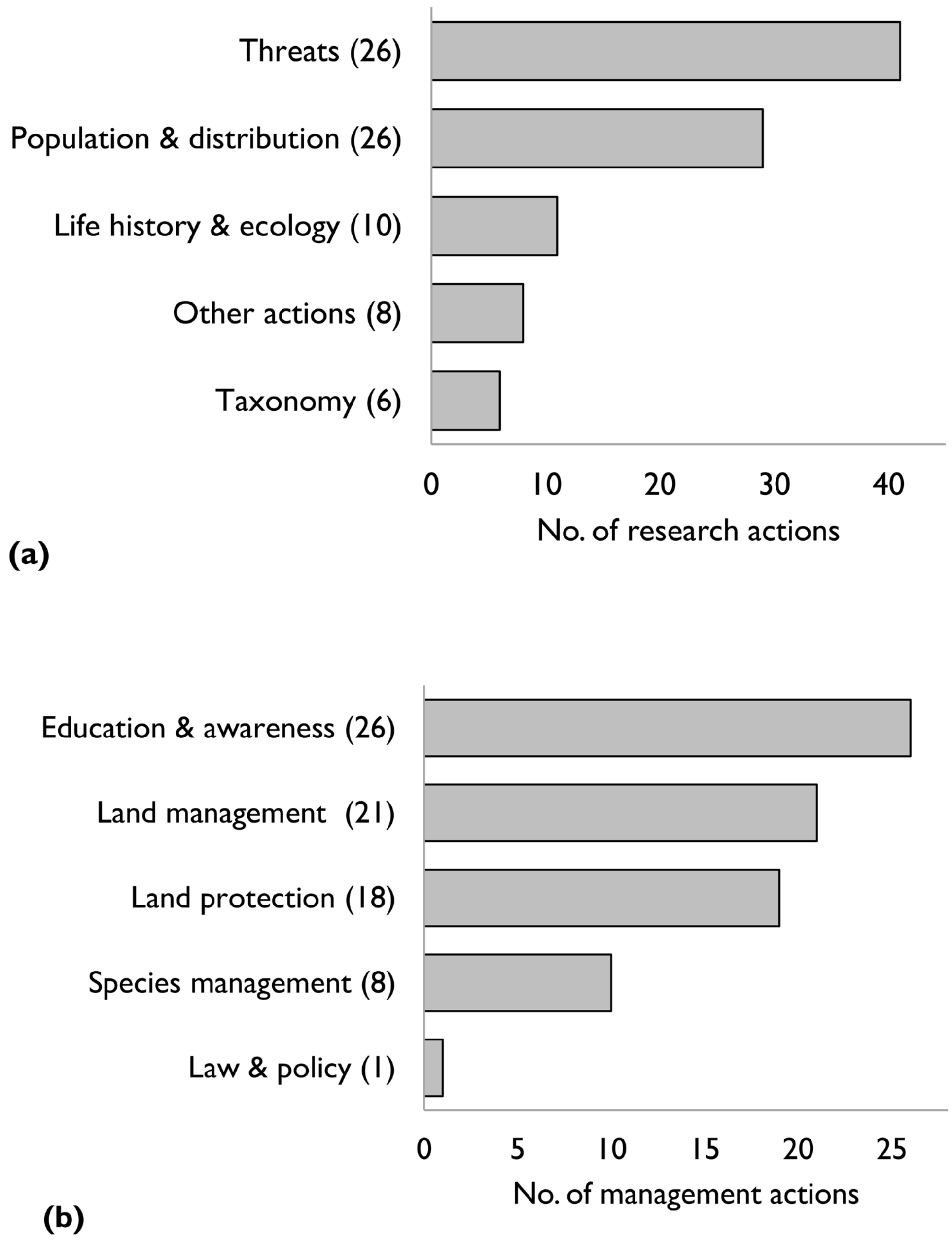

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