Biological Conservation 284 (2023) 110201

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

Protected, cleared, or at risk: The fate of Australian plant species under continued land use change

Vanessa M. Adams[a,*], Nathalie Butt[b], Stuart Allen[a], Robert L. Pressey[c,d], Jayden E. Engert[e], Rachael V. Gallagher[f]

[a] School of Geography, Planning, and Spatial Sciences, University of Tasmania, Hobart, TAS 7001, Australia
[b] Centre for Biodiversity and Conservation Science, University of Queensland, St Lucia, QLD 4072, Australia
[c] ARC Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, QLD 4811, Australia
[d] Faculty of Science, Queensland University of Technology, Brisbane, QLD 4000, Australia
[e] Centre for Tropical Environment and Sustainability Science, James Cook University, Cairns, Australia
[f] Hawkesbury Institute for the Environment, Western Sydney University, Locked Bag 1797, Penrith, NSW 2751, Australia

ARTICLE INFO

Keywords:
Land degradation
Land clearing
Protected areas
Agricultural land capability
Conservation priorities
Proactive conservation
Reactive conservation

ABSTRACT

Land clearing and protected area provision are two contrasting forces shaping the persistence of species in the landscape. Using Australia's flora as a case study, we characterize the three possible states of species persistence: protected, cleared, or at risk of future loss based on agricultural capability, using a comprehensive suite of plant distributions and traits. We test the assumption that plant species, assemblages, and growth forms are adequately preserved in protected areas in Australia, and contrast this result with historic and future loss driven by trajectories of continued land clearing. We find levels of protection and clearing are inversely related, with both bioregions and species with high levels of clearing having low protection. We find only one third of Australian bioregions meet international protection targets of 30 % of area in formal protection. Similarly, we find that 29 % of plant species have met representation protection targets (with 30 % of their range protected), while similar numbers (33 %) have clearing as the dominant land use across their ranges. Protection and clearing have also unevenly affected species with different growth forms, range sizes, and distributions across agricultural land capability. Narrow-ranged woody species (e.g., trees) are the most at-risk group in relation to clearing, whereas large-ranged non-woody species (e.g., graminoids, herbs) are afforded a high level of protection in reserved lands. We demonstrate that the Australian protected-area network, although theoretically underpinned by sound CAR principles (comprehensive, adequacy, representativeness), falls short in protecting both individual plant species and growth forms.

1. Introduction

Human actions threaten biodiversity, with extinction rates estimated to be 1000 times the background rate (Pimm et al., 2014), and 1,000,000 species facing extinction within decades (IPBES, 2019). Protected areas are a cornerstone of the global conservation strategy to combat this extinction crisis. The centrality of protected areas to meeting global biodiversity goals has been codified in the Convention on Biological Diversity (CBD) biodiversity targets which have included specific area based protection targets since 2002 (Gurney et al., 2023). Over the last two decades global protected area targets have expanded from the original target of 10 % of each of the world's ecological regions effectively conserved, to now specifying 30 % of land and sea by 2030 including specific provisions for ecological representation (Target 3 of the Kunming-Montreal post-2020 Global Biodiversity Framework; CBD, 2022).

Despite significant growth in the global protected area network, achievement of representation targets for protection of all ecosystems and species has lagged due to systematic biases in the placement of protected areas (Adams et al., 2021; Kuempel et al., 2016; Venter et al., 2017). These systematic biases result in over-representation of some environments, commonly those associated with remote or relatively unproductive land, and under-representation of others potentially more suitable for agricultural land uses, which are a dominant global driver of habitat loss and in particular for plants (Devillers et al., 2015; Joppa and Pfaff, 2009; Kuempel et al., 2019; Pressey, 2002; Venter et al., 2017). Similarly, landholders make rationale extractive land use decisions based on the underlying capability of land, thus biasing production land uses such as agriculture to higher capability lands (Adams and Engert,

---

[*] Corresponding author.
E-mail address: vm.adams@utas.edu.au (V.M. Adams).

https://doi.org/10.1016/j.biocon.2023.110201
Received 6 December 2022; Received in revised form 31 March 2023; Accepted 11 July 2023

2023). These biases in land uses can consequently leave some species or ecosystems at elevated risk of loss to outright conversion or modification (Montesino Pouzols et al., 2014; Pressey et al., 2017).

Global plant diversity is particularly under threat from human-induced pressures (Gallagher et al., 2023), with habitat loss resulting from agriculture the primary driver of decline (Antonelli et al., 2020). As of March 2023, 24,194 plant species are considered threatened in the IUCN Red List (Vulnerable, Endangered, Critically Endangered), with 33 % of these affected by habitat loss from agriculture (Antonelli et al., 2020). For many widespread plant species, the impact of agricultural-related habitat loss can be pernicious, resulting from a gradual erosion of distributional range and shifting of suitable growth conditions, which creates an appreciable extinction debt (Helm et al., 2006; Reside et al., 2017). The entire distribution of some narrow-ranged endemic plant species may be impacted in a single land clearing event, as is likely to have occurred for several now extinct species in the Avon-Wheatbelt bioregion of southwest Western Australia (e.g., the shrubs *Tetratheca fasciculata* and *Acacia kingiana*) (DCCEEW, 2023). Plant growth forms (i.e., trees, shrubs, grasses, herbs) are also likely to differentially experience habitat loss due to differences in their perceived utility to landholders. For instance, trees may be targeted for wholesale removal from landscapes subject to the use of mechanized or precision agriculture (Fischer et al., 2010). Conversely grasses, herbs and forbs, are often initially retained as fodder within native vegetation grazing systems, but over time may be gradually replaced by selective grazing and shifting soil conditions (Lunt et al., 2007).

Here, we first construct a qualitative narrative of post-colonial land use history in Australia as the basis for quantitative analyses of patterns of protection, clearing, and at-risk areas for future agricultural expansion for plant species and their relationships in a path analysis. We specifically ask: What are the spatial patterns of three land use fates at a continental scale across bioregions and the distributional ranges of plant species?; and, What is the relationship between level of protection, clearing, and at-risk areas for future agricultural expansion for bioregions, species, and growth forms? We aim to understand the extent to which current protection adequately represents individual plant species and, for species without protection, understand to what extent does having distributions outside protected areas put species at risk from habitat loss due to agriculture. Our analysis at the species level adds to traditional tracking of patterns of protection at bioregional levels.

2. Methods

2.1. Case study

We use Australia – a global land clearing hotspot – as a case study for exploring our questions. Australia has approximately 26,000 plant taxa, the majority of which (88 %) are endemic (Gallagher et al., 2023) (Fig. 1). Australian plants occur across strong spatial and climatic gradients, in particular precipitation, which varies in both amount and predictability across the continent, shaping species and functional composition (Andrew et al., 2021). Several of the world's major vegetation types and biomes are present in Australia, including desert, alpine, rainforests, savanna and arid/semi-arid groups.

We focus our analyses on species-level distributions, traits (growth form), range size, as well as vegetation groups and bioregions. Plant species provide a direct link to the most common surrogates for conservation planning: ecosystems and biomes, where they are the foundations of primary production. Plants also form critical habitats and provide essential food resources on which other species depend. The ranges of plant species have been extensively documented in herbarium collections which are taxonomically verified and increasingly digitized, forming an important source of occurrence information.

2.2. Australian land use history narrative

We first reviewed and summarized the narrative of Australian land use history, and in particular, choices in the landscape to clear or protect. This narrative is the basis for developing a conceptual model as the key first step in model specification for quantitative path analysis and model testing (Fig. 2) (Fan et al., 2016).

The narrative of post-colonial land use history is as follows. Although there had been a long history of widespread fire management and stewardship of vegetation and country by Australia's First Nations people (‘firestick farming’; Fletcher et al., 2021), the post-colonial history of land use and associated clearing in Australia meant that production landscapes were prioritized as a land use over sovereign rights for indigenous people and long before the first National Park was declared (Royal National Park, NSW, in 1879; the second such in the world). The *Crown Lands Alienation Act* of 1861 drove previously unseen large-scale vegetation clearing, as new landowners were financially penalized for not ‘developing’ (i.e., clearing) their land (Braithwaite, 1996). Thus, land use choices, both sequentially and in parallel, were largely that: land was cleared; land in potentially productive landscapes was maintained as available to ensure future production potential, and; land was formally protected. Opportunities for protection were displaced due to historical clearing alongside choices that biased protection to less productive landscapes. This bias has been documented extensively in Australia (Benson et al., 2010; Bryan, 2002; Mendel and Kirkpatrick, 2002; Rundle, 1996; Sharafi et al., 2012), as well as globally (Joppa and Pfaff, 2009). The dominance of production-oriented decisions over decisions to protect should result in the proportion of a species' range that is cleared being a direct predictor of the proportion of species range protected, with an expected inverse relationship.

The choice of where to clear, according to the above rationale, is based on whether land is suitable for agriculture or has high agricultural capability. Thus, we expect that land with high agricultural capability would be targeted for clearing and intensive land use first, and therefore be at highest risk of future clearing. Woody vegetation is the vegetation type most often cleared for agriculture, while herb and grass dominated vegetation is often used for grazing. On this basis we expect that woody growth forms should show a higher proportion of clearance. Lastly, the larger a species' range, the more exposed it is to clearing, other things being equal, and thus we would expect a positive relationship between range size and proportion cleared. We acknowledge that land capability is not the sole predictor of where land will be developed; other factors are likely to be proximity to markets and infrastructure, such as irrigation and broader networks for processing and moving products. Thus, some spatial patterns of land classed as high capability but remaining available could reflect historical absence of infrastructure or large distances to markets. Our model does not consider these predictors of spatial variability but rather uses land capability as a strong indicator for individual landholder's choices for land use.

Where land is not cleared, and is thus available for protection, choices about where to locate protected areas are biased towards residual or areas with low agricultural productivity. Thus, the proportion of a species' range that is of low agricultural capability would positively predict the amount protected. Lastly, under the systematic conservation approach to expanding the national reserve system, species targets have followed advice to scale targets based on percentages of range sizes, such that lower protection targets are set for larger species ranges, while higher targets are set for narrow-range species (e.g., Adams et al., 2011; Watson et al., 2009). Given this relationship we would expect range size and proportion protected to be negatively correlated.

This narrative is captured in a path model in Fig. 2. In our path model the endogenous variables are proportions of a bioregion or species that is cleared and protected; exogenous variables are proportion of range that is high capability, proportion of range that is low capability, whether the bioregion or species is a woody growth form, and range extent (Fig. 2). The path model for proportion protected is mediated – the exogenous variables act both directly upon protection but also through an intermediary endogenous variable, in this case proportion cleared.

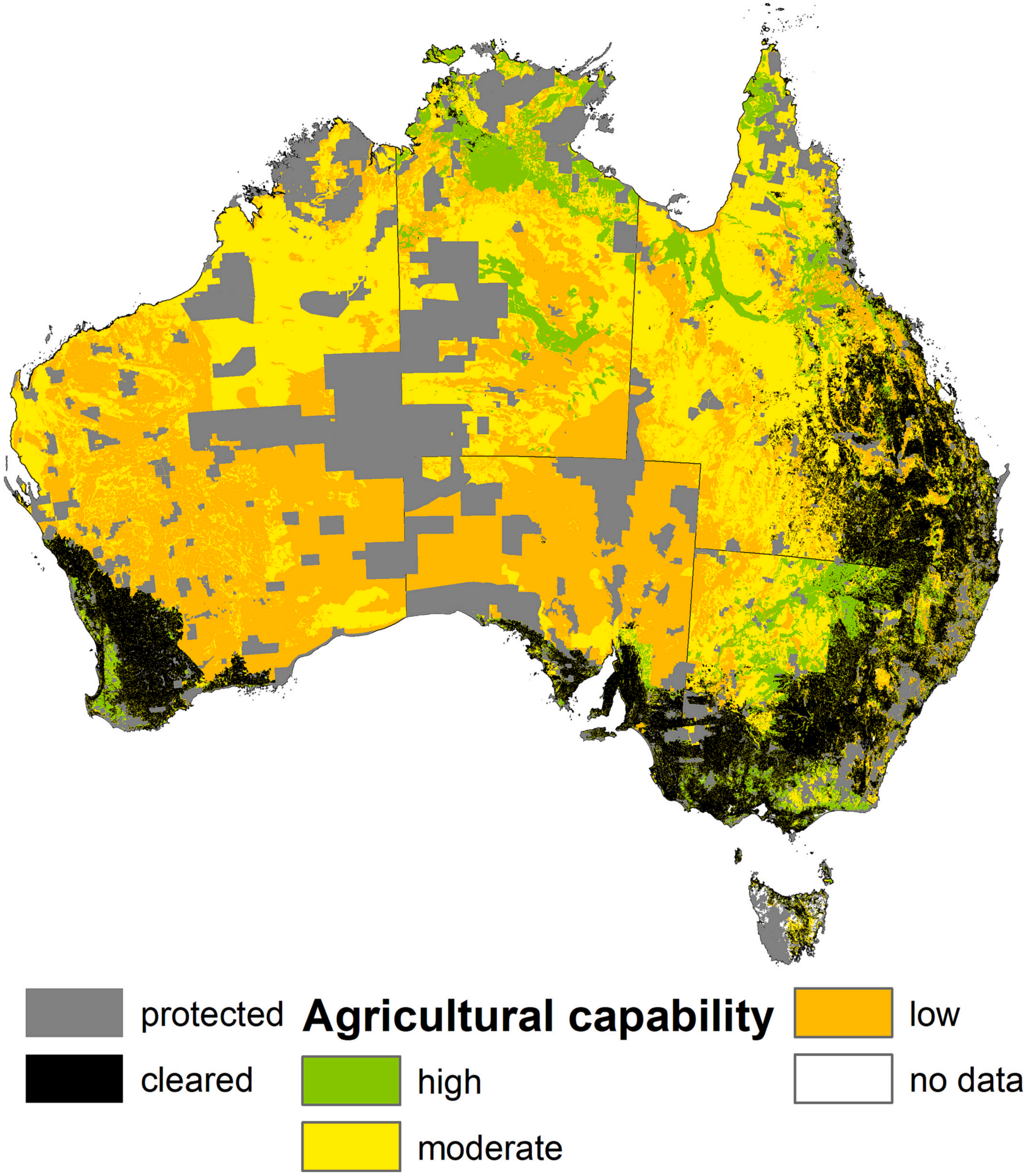

Fig. 1. Australian protected and cleared lands. Agricultural land capability (high = classes 1–4, moderate = 5–6, low, =7–8 (Adams and Engert, 2023)) shown for land that is available (not protected or cleared).

2.3. *What are the spatial patterns of land use at a continental scale across bioregions and the distributional ranges of plant species?*

Reflecting our narrative analysis, we considered that the landscape could be divided into three fundamental categories: protected, cleared, or available (neither protected nor cleared) (Fig. 1). Within available land, future clearing may occur but the variable levels of risk within this land will be driven in part by agricultural land capability (Adams and Engert, 2023). To consider the spatial distribution of those areas that are most likely to be exposed to future clearing, we further segment available land into land 'at risk' defined as both available and with high capability for agricultural land uses (see Table 1 for definitions and data for each land class).

Table 1
Data terms, associated definitions, and data sources.

	Definition	Data reference
Protected	Declared protected areas (IUCN I-VI) recognized as part of the national reserve system	Collaborative Australian Protected Areas Database (CAPAD) 2020 (Commonwealth of Australia, 2021)
Cleared	Land areas that have been cleared	Cleared vegetation as mapped in National Vegetation Inventory System (NVIS) data (Australian Government, 2021)
Bioregions	Land areas characterized by broad, landscape-scale, natural features and environmental processes that influence the functions of entire ecosystems; 89 bioregions in total but we restrict our analysis to the 85 that intersect with our land capability layer	Interim Biogeographic Regionalisation for Australia (IBRA) bioregions (Department of Agriculture, 2020)
Major vegetation groups	Vegetation groups representative of distinct vegetative environments; they can extend over large areas and often contain more than one vegetation association or community	NVIS major vegetation groups (MVG) (Australian Government, 2021)
Plant ranges	Plant species ranges (presence, absence) (n = 24,780) derived from thresholded modelled species distributions developed from Poisson Point Process models, range bagging and area of occupancy; model type chosen based on availability of occurrence records.	Plant distributions (Gallagher et al., 2021)
Growth form	Plant growth form (herbs, grass, tree, shrub, crawlers) used to identify those that are woody or not (binary variable)	AusTraits (Falster et al., 2021)
Agricultural capability	Agricultural capability measures the extent to which land is capable of supporting agricultural activity such as cropping, grazing, and forestry, given sufficient irrigation. The rating system is a ranking of 1–8 where a value of 1–4 is rated as high capability (can host all cropping types with only minor to moderate limitations), 5–6 is rated as moderate capability with land being primarily suited only to grazing and some forestry activities, and low capability where only non-extractive conservation-oriented activities are recommended.	Australian agricultural land capability layer (Adams and Engert, 2023)
At risk	Areas at risk of clearing from agriculture; defined as land that is available (not protected or cleared) and also high capability (classes 1–4)	Derived product based on CAPAD, NVIS, land capability
Moderate risk	Areas at moderate risk of clearing or intensified agricultural land use (grazing), defined as land that is available (not protected or cleared) and moderate capability (classes 5–6)	Derived product based on CAPAD, NVIS, land capability
Low risk de facto protected	Areas at low risk of clearing and thus de facto protected, defined as land that is available (not protected or cleared) and low capability (classes 7–8)	Derived product based on CAPAD, NVIS, land capability

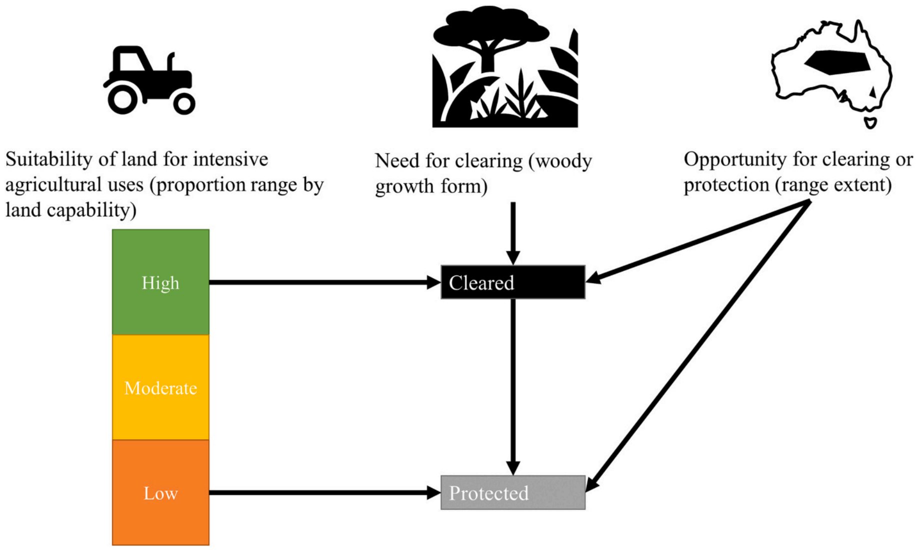

Fig. 2. Conceptual model of patterns of clearing and protection for species. At a species level the proportion of range that is cleared or protected is ultimately a function of location in the landscape relative to land capability, growth form, and range extent. The conceptual model represents the path analysis in which protected and cleared are endogenous variables and suitability for land use, woody growth form, and range extent are exogenous variables and arrows indicate direction of influence.

To explore continental patterns of historic colonial land use decisions (since the mid-1800s), we summarized the proportion of each IBRA bioregion that is: protected, cleared, available. We mapped the dominant (defined as the highest proportion) land category and then further mapped proportion of bioregion at risk. To do so, we intersected a spatial layer of IBRA regions with the 2020 protected area data (Commonwealth of Australia, 2021), the National Vegetation Information System Major Vegetation Groups and national scale agricultural capability data (Adams and Engert, 2023) to estimate protected, cleared and available land, respectively. We excluded the IBRA regions Pacific Subtropical Islands and Subantarctic Islands from the analysis.

For species analyses we used distributional ranges of 24,780 Australia plants (as described in Andrew et al., 2021), and for each range then calculated proportion of that is: protected, cleared, available. We further considered the proportion of each species' range that is at risk. The distributional ranges of the Australian plants were defined based on climatic and soil conditions using three approaches (Poisson point-process modelling; range bagging; area of occupancy) with method choice being defined by availability of occurrence records. Range maps were intersected with spatial data on protected, cleared and available land as for IBRA regions (see Table 1 for full data details and definitions). We appended data on growth form (woody vs. non-woody) to each species based on information in the AusTraits database (Falster et al., 2021). After joining all spatial and trait data, we had a complete data set for 24,592 plant species. All spatial analyses were completed based on a 1 km grid and conducted in R v. 4.2.1.

To visually explore similarities in spatial patterns of land use, we mapped species richness in bioregions using only those species that have a majority proportion of range cleared and are also exposed to further risk of clearing (identified as species with a large proportion of remaining range available at risk) and compared to bioregional patterns of dominant land use (protected, cleared, available). Similarly, we identified those species that have a dominant proportion of range available and mapped those which, within the available land, are

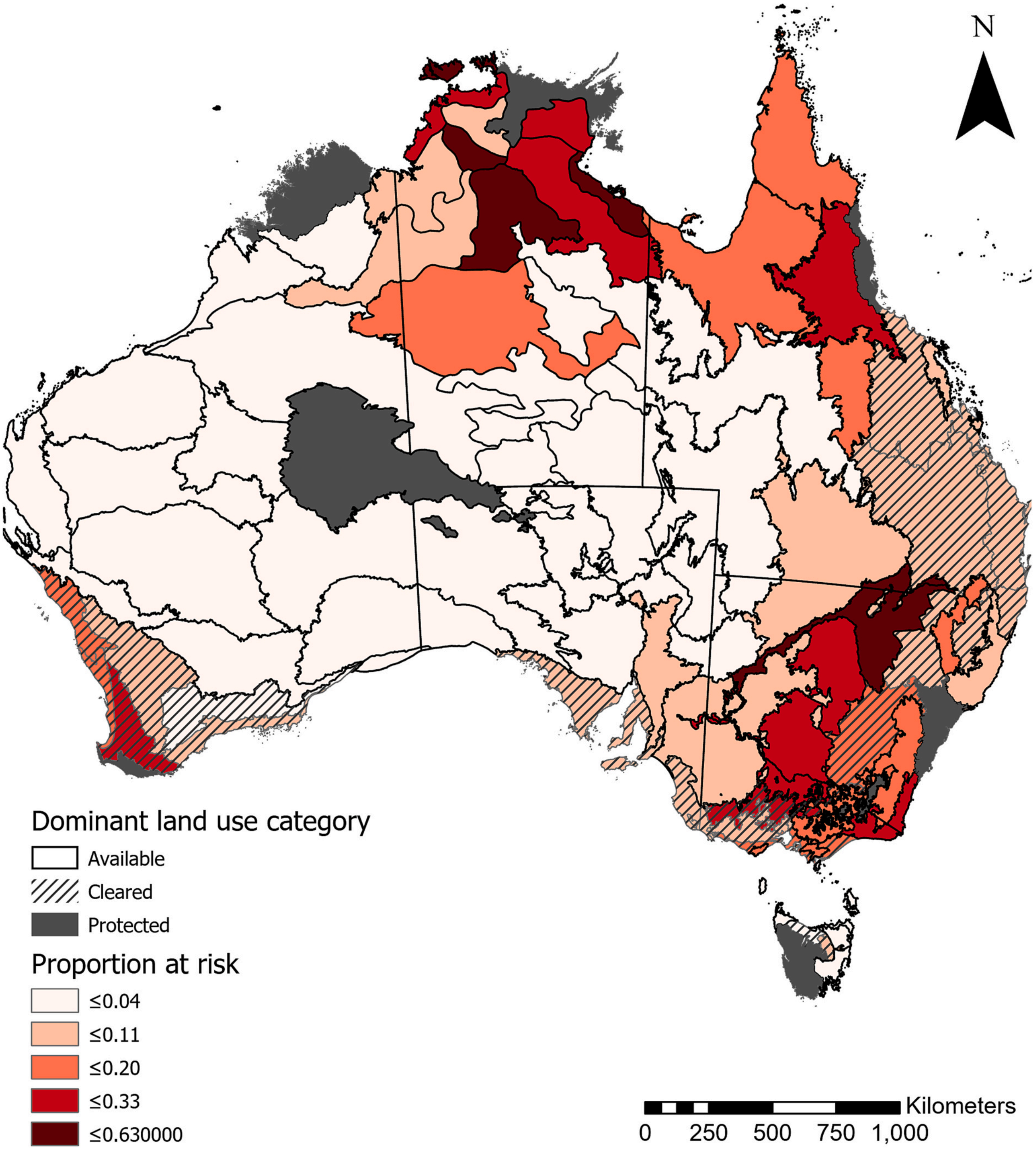

Fig. 3. Map of dominant land category (protected, cleared, available) and proportion of region at risk by IBRA bioregion. Areas at risk of clearing from agriculture are defined as land that is available (not protected or cleared) and also high land capability.

predominantly at risk and compared them to bioregional patterns of dominant land use.

Lastly, we considered levels of protection and the extent to which global protected area targets at bioregion and species level have been met. Thus, for bioregions we considered the number of bioregions that have met the current protection target of 30 % of area protected, and for species we calculated how many plant species have met this target based on range area protected. For species we further considered the number of species that have not met this target and thus have protection shortfalls and whether it is possible to meet the 30 % protection target considering available range area for future protection.

2.4. What is the relationship between level of protection, clearing, and at-risk area for species?

To test the relationship between land use types at a species level we used the land use narrative to construct a path regression analysis and test whether this system model is accurate. The first step in path analysis is to specify the model structure and expected relationships between endogenous and exogenous variables. This was completed based upon the narrative. The second step is to prepare data matched to the model specification, as detailed in our data selection and collation. The third step is model fitting. We completed this step within SPSS. Given our path model is relatively simple, we chose to use standard regression based path analysis models and report her on standardized path coefficients, R^2, and standard errors (Fan et al., 2016; Streiner, 2005). Collectively

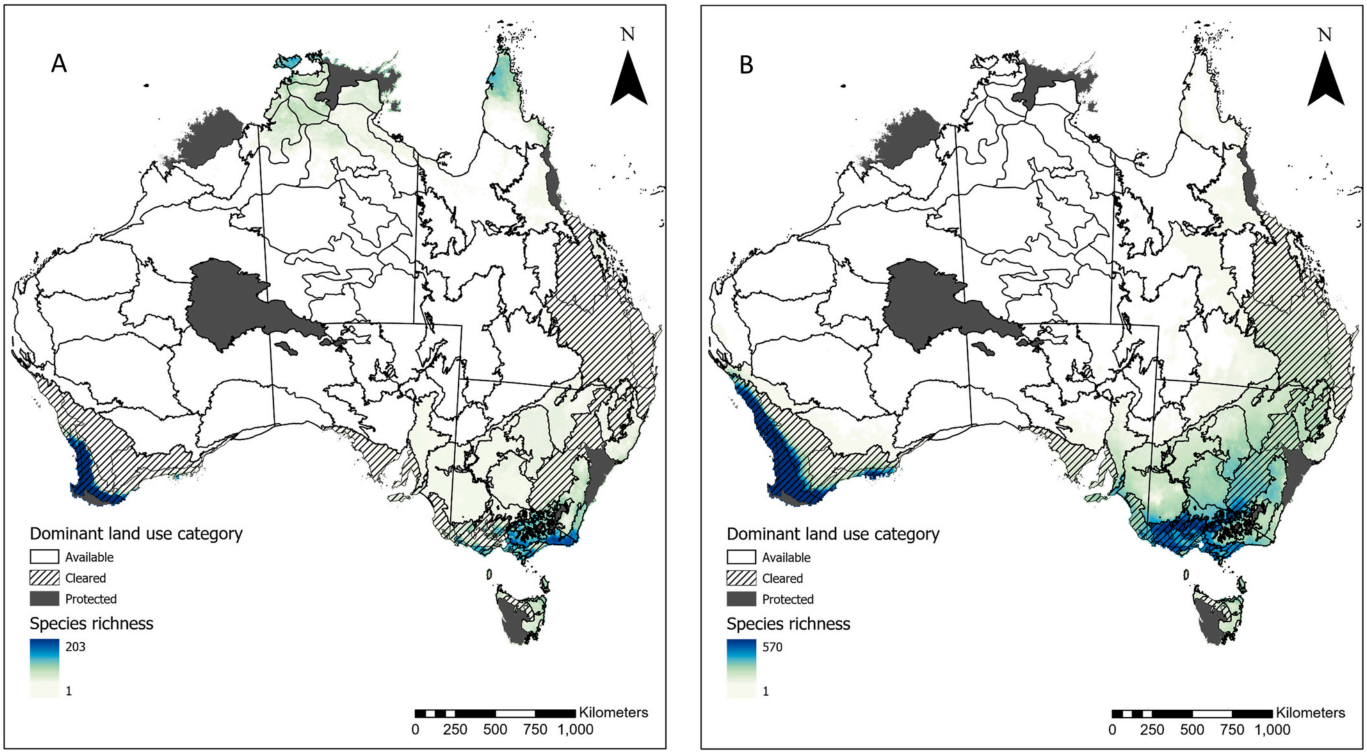

Fig. 4. Richness of species in bioregions with large proportions of their ranges at risk. A. Species with the dominant category of their ranges available (n = 530). These are species for which proactive conservation would be beneficial as they are largely available for protection but exposed to future clearing. B. Species with the dominant category of their ranges cleared (n = 1703). These are species for which reactive conservation is needed to secure remaining parts of ranges. For context, bioregions are displayed including dominant land category (available, cleared, protected).

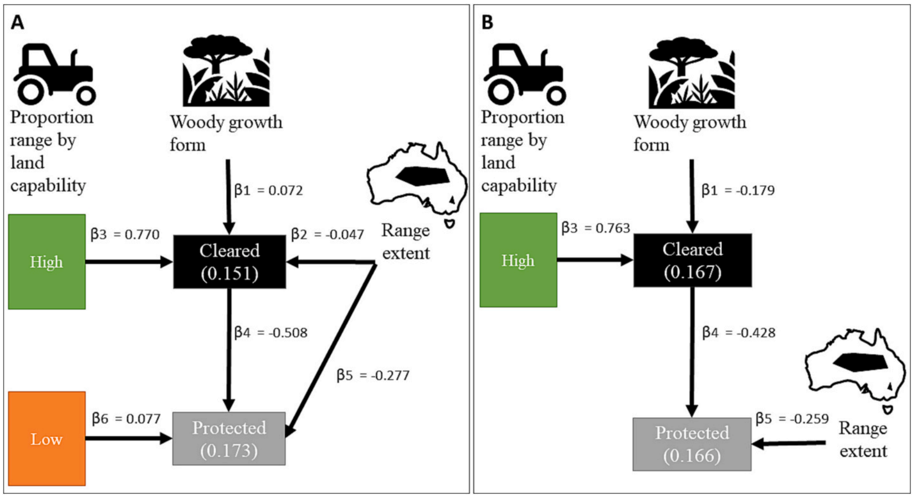

Fig. 5. Path analysis for proportion protected of A) species range, with an R^2 of 0.310 and B) bioregions, with an R^2 of 0.156. Standardized path coefficients are displayed and significant. Standard errors for the endogenous variables are shown within the boxes.

these allow assessment of the validity and reliability of each path in our path analysis (Fan et al., 2016). All variables in the path analysis for species were significant and were thus retained in the final path regression analysis. Variables that were not significant in the path analysis for bioregions were excluded.

2.5. Robustness tests

We note that, for species with small ranges, the entire extent could be cleared or protected with a single property or landholder making land use choices. Thus, restricted range species can be entirely protected or entirely cleared in a single pixel resulting in a bi-modal relationship with modes at 0 and 1 for proportion of ranges cleared or protected. We tested the robustness of our model inferences to this by running the analyses with and without small-range species.

3. Results

3.1. Patterns of protected, cleared, and at-risk lands across bioregions

In 66 % of bioregions (58 of 87 bioregions examined) the dominant land use category is ‘available’ (neither cleared nor protected) (Fig. 3).

Of these bioregions dominated by available land, those with the highest risk of future clearing, based on mapped high land capability for intensive land use, are in the Northern Territory (Tiwi Islands, Daly Basin, Gulf Coastal, Sturt Plateau), and New South Wales (Riverina) (Fig. 3).

By contrast, 20 % of Australian bioregions have 'cleared' as their dominant land use (18 of 87 bioregions). These are largely in coastal regions but also extend inland in the east and southwest of the continent. Within these cleared bioregions, those with the most 'at-risk' area, defined as both available and with high capability for agricultural land uses, are Jarrah Forrest (27 % at risk) and Swan Coastal Plain (16 %) in Western Australia, Victorian Midlands (33 %) and South East Coastal Plain in Victoria (17 %) (Fig. 3).

'Protection' is the dominant land use in 14 % of bioregions which are notable for having large protected area systems, such as the Wet Tropics and Tasmanian West bioregions (Fig. 3). Considering these protection levels, only one third of Australian bioregions (33 %) meet the Kunming-Montreal protection target of having at least 30 % of area in formal protection. However, when considering informal de facto protection due to low agricultural land capability of available land, most bioregions (68 %) would meet the threshold of 30 % protected if converted to formal protected areas (Appendix Table S1).

3.2. *Patterns of protected, cleared, and at-risk area for species*

Similar to patterns of dominant land use category for bioregions, about half of species had available land as the dominant proportion of their ranges (51 % of 24,952 species), of which 530 have a large proportion of at-risk land in their ranges (Fig. 4A). There is some overlap of the spatial distributions of these species with those of at-risk bioregions. For example, species richness is high in the Tiwi Islands and Daly Basin. However, there are also key differences. The Cape York and South East Corner bioregions also have high richness of species at risk. Within highly cleared bioregions, there are also species with the majority of their ranges still available but at risk. These bioregions include Geraldton Sandplains, Jarrah Forrest, and Swan coastal plain in Western Australia and in, Victoria and New South Wales, the Victorian Midlands, South East Coastal Plain, and South East Corner.

Thirty three percent of species (8137) are cleared as a dominant proportion of their ranges. Of these, 1703 have a large proportion of their ranges at risk (Fig. 4B). Richness of these species is matched to those bioregions identified as having high levels of clearing alongside large portions of remaining at-risk land: Jarrah Forrest and Swan coastal plain in Western Australia, Victorian Midlands and South East Coastal Plain in Victoria.

Protection is the dominant land use in the ranges of 16 % of species. Considering level of protection across all species, we found that 29 % (7092) meet the formal protection target of 30 % of range area. Of those with less than 30 % protection, the average split across land use categories was: 15 % protected, 35 % cleared, 50 % available. While the majority of species with less than 30 % protection could meet protection targets with available land, a small number could not; these were 1409 species with more than 70 % of their range cleared, indicating they require restoration.

3.3. *What is the relationship between level of protection, clearing, and at-risk area for species?*

Our path analysis for species had an R^2 value for proportion cleared of 0.63 with all three exogenous variables being significant (Fig. 5A). The regression analysis for proportion of species ranges protected had an R^2 value of 0.31 with all variables being significant. Range size had both a direct and indirect (via proportion cleared) negative influence on proportion protected. Woody growth form and proportion high land capability had indirect effects on the proportion of range protected as well via proportion cleared. Proportion cleared had a negative direct effect on proportion protected ($\beta = -0.508$). Proportion low agricultural capability had a positive direct effect on proportion protected ($\beta = 0.077$).

For bioregions the path analysis excluded area of bioregion as an exogenous variable influencing proportion cleared as well as proportion of bioregion low capability as an exogenous variable for proportion protected. All other exogenous variables were significant. The model had an R^2 value for proportion cleared of 0.57 with woody vegetation and proportion high land capacity being significant (Fig. 5B). Our regression analysis for proportion protected had an R^2 value of 0.19. Woody growth form and proportion high land capacity had indirect effects on proportion protected via proportion cleared. Proportion cleared had a negative direct effect ($\beta = -0.428$) and range extent had a negative effect ($\beta = -0.259$) on proportion protected. The direction of the coefficients for the exogenous variables were similar to the species path model with the exception of woody growth form, which was negative for bioregions ($\beta = -0.179$) in contrast to positive for species level ($\beta = 0.072$). It is worth noting that, at a bioregion level, the dominant growth form for dominant vegetation was used to characterize whether a bioregion was largely characterized by woody vegetation as opposed to the more precise delineation of growth form at species level.

4. Discussion

Levels of protection and habitat loss via clearing are key determinants of the overall health of the environment and biodiversity (IPBES, 2019). Less than a quarter of the Earth's land remains free from substantial human impact (Brink et al., 2018) and extensive further loss is predicted over the next decade (Arneth et al., 2020; Taylor, 2015). In this context it is essential to understand patterns of protection and clearing at a species level to detect whether there are spatial biases in either, or both, of these. Our analyses identified patterns of protection, clearing, and areas at risk for bioregions and species in Australia, a continent with notable endemism (Gallagher et al., 2023) and a global deforestation hotspot (Taylor, 2015). While spatial patterns were largely the same between species and bioregions, when considering the relationship between clearing and protection the path analysis and inferences they support varied slightly between bioregions and species.

Our post-colonial land use narrative captures key elements of historic choices to clear and develop land in Australia, which reflect global (Joppa and Pfaff, 2009) and local literature (Pressey et al., 2000) on biases in protection. Our quantitative analysis of the path model reflecting this narrative provides support for key aspects including: 1) that landholders make rational choices to develop high capability land, 2) that clearing has crowded out opportunities for protection, 3) that protection choices are biased to lower capability land to leave opportunities for agricultural development open. Both preemption by clearing and resistance to protecting available, high-capability land have contributed to residual protection in Australia (Benson et al., 2010; Bryan, 2002; Recher, 2018; Sharafi et al., 2012). Those two drivers are not independent, of course. Both reflect political and economic forces favoring development over conservation, with resistance exacerbating later preemption.

Importantly, our path model explained more variance at a species level, and in particular found that high capability land was an exogenous variable for clearing, while lower capability land was an exogenous variable for protection. A key finding from the species level path analysis is that narrow-ranged woody species (e.g., trees) are the most at-risk group in relation to clearing, whereas large-ranged non-woody species (e.g., graminoids, herbs) are afforded a high level of protection in reserved lands. This indicates that protection alone is not effective at retaining woody species, in particular narrow ranged ones, in the landscape. Confronting these biases in landscape scale retention of species will require reserve design that avoids loss and thus targets areas that are at risk of clearing due to their innate suitability for production land uses (Pressey et al., 2021), while also designing policies that are effective at halting ongoing clearing of native vegetation (Evans, 2016; Simmons et al., 2018a; Simmons et al., 2018b).

Our analysis of the spatial patterns of land use, can support both reactive and proactive conservation strategies that draw upon both clearing and protection policies. We define reactive protection as targeting species that are identified as threatened or have already experienced large losses in habitat; we define proactive protection as protecting species while their ranges are still intact and where protection is placed to maximise population outcomes by avoiding future loss of habitat (Pressey et al., 2007; Pressey et al., 2021). While the mix of reactionary and proactive conservation will depend on measures of success, considering the likely future loss of habitat allows strategies to minimize loss of species (Visconti and Joppa, 2015; Visconti et al., 2010).

In our analysis, priority bioregions for reactive protection (where extensive clearing has already occurred but there are remaining areas at risk of further loss) included the southeast and southwest of Australia. In contrast, bioregions of priority for proactive protection where there are low levels of both protection and clearing and a high proportion of at-risk land include the Tiwi islands, Daly Basin, and Cape York Peninsula. Given the eastern coastline of Australia is a global deforestation hotspot (Taylor, 2015), prioritizing protection there to combat further loss might be necessary. However, the opportunity to act in intact landscapes could be fleeting. For example, there has been ongoing interest in developing the North with particular emphasis on Tiwi Islands, Daly Basin and Cape York (Commonwealth of Australia, 2015). This interest in development and investment in required infrastructure could be accelerating land use change in these previously intact bioregions (Adams et al., 2016; Hernandez et al., 2021). Considering the optimal mix of where and when to act (Adams et al., 2019; Kuempel et al., 2020) using our analysis can provide advice on how best to further build the Australian protected area network to minimize ongoing biodiversity loss (Adams et al., 2021). This also emphasizes the relative importance of habitat outside of protected areas, and thus highlight the contributions that private and Indigenous lands can make to securing biodiversity. This is consistent with other studies in Australia that highlight the relative importance of engaging these tenures for effective biodiversity conservation (Fitzsimons, 2015; Kearney et al., 2018; Kearney et al., 2022).

5. Conclusions

We use the case study of Australia as a megadiverse country for plant species, globally important for protecting plant endemism (Gallagher et al., 2023), and also a global deforestation hotspot (Taylor, 2015), to test for the relationship between agricultural land capability, clearing and protection. In doing so we highlight important spatial patterns in historical protection and clearing for species and bioregions while also identifying regions that are important for reactive or proactive conservation. While spatial patterns are broadly similar across species and regional analyses, the species-level analysis provides further insight into where there are high levels of richness and endemism that are at threat from future loss, an insight lacking when considering only regional-level patterns. Similarly, our path analysis to test our land use narrative confirms processes of protection bias, which provide key insights around how to design conservation strategies which include, but are not limited to, protection, to ensure that biodiversity is secured. Our findings provide critical insights for protecting plant species in Australia and are also of broader global relevance in considering what structural processes might be driving continued clearing in deforestation hotspots. These processes indicate that protection alone is an insufficient strategy, particularly if structural biases in placement of protection continue. Our analysis also confirmed that woody growth forms are more likely to have experienced clearing in their ranges and are thus more exposed to habitat loss. This is an important insight as it suggests that particular types of plants and functional traits in ecosystems may be exposed to loss. Notably in Australia our results demonstrate that woody vegetation is more likely to have been cleared which has important implications for carbon stocks and highlights the role of halting land clearing to address the twin crises of climate change and biodiversity loss. As reserve design moves beyond species to consider ecosystem function (Cadotte et al., 2011; Flynn et al., 2009), measures of functional diversity based on multivariate trait spaces may prove useful to support reserve design (e.g., Andrew et al., 2021). Ultimately effective conservation will include multiple, interacting interventions which take into account the values of people to combat the complex problem of land clearing (Brink et al., 2018).

CRediT authorship contribution statement

VMA, NB, and RVG conceptualised the study. VMA and SA completed analyses. All authors wrote the manuscript.

Declaration of competing interest

The authors declare no potential conflicts of interest or competing financial interests.

Data availability

All data links are shared.

Acknowledgements

VMA was funded by an Australian Research Council Future Fellowship (220100210). RLP acknowledges the support of the Australian Research Council. The Australian Research Data Commons provided support for AusTraits through their Data Partnerships Scheme.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2023.110201.

References

Adams, V.M., Engert, J.E., 2023. Australian agricultural resources: a national scale land capability map. Data Brief 46, 108852.

Adams, V.M., Segan, D.B., Pressey, R.L., 2011. How much does it cost to expand a protected area system? Some critical determining factors and ranges of costs for Queensland. PLoS One 6, e25447. https://doi.org/10.21371/journal.pone.0025447.

Adams, V.M., Pressey, R.L., Álvarez-Romero, J.G., 2016. Using optimal land-use scenarios to assess trade-offs between conservation, development, and social values. PLoS One 11, e0158350.

Adams, V.M., Iacona, G.D., Possingham, H.P., 2019. Weighing the benefits of expanding protected areas versus managing existing ones. Nat. Sustain. 2, 404–411.

Adams, V.M., Visconti, P., Graham, V., Possingham, H.P., 2021. Indicators keep progress honest: a call to track both the quantity and quality of protected areas. One Earth 4, 901–906.

Andrew, S.C., Mokany, K., Falster, D.S., Wenk, E., Wright, I.J., Merow, C., Adams, V., Gallagher, R.V., 2021. Functional diversity of the Australian flora: strong links to species richness and climate. J. Veg. Sci. 32, e13018.

Antonelli, A., Smith, R., Fry, C., Simmonds, M.S., Kersey, P.J., Pritchard, H., Abbo, M., Acedo, C., Adams, J., Ainsworth, A., 2020. State of the World's Plants and Fungi. Royal Botanic Gardens (Kew); Sfumato Foundation.

Arneth, A., Shin, Y.-J., Leadley, P., Rondinini, C., Bukvareva, E., Kolb, M., Midgley Guy, F., Oberdorff, T., Palomo, I., Saito, O., 2020. Post-2020 biodiversity targets need to embrace climate change. Proc. Natl. Acad. Sci. 117, 30882–30891.

Australian Government, 2021. National vegetation information system (NVIS). Available from, Bioregional Assessments Programme. https://www.environment.gov.au/land/native-vegetation/national-vegetation-information-system.

Benson, J.S., Richards, P.G., Waller, S., Allen, C.B., 2010. New South Wales vegetation classification and assessment. Part 3: plant communities of the NSW Brigalow Belt South, Nandewar and west New England bioregions and update of NSW Western Plains and South-western Slopes plant communities. Cunninghamia 11, 457–579.

Braithwaite, L.W., 1996. Conservation of arboreal herbivores: the Australian scene. Aust. J. Ecol. 21, 21–30.

Brink, B.J.E., Cantele, M., Adams, V.M., Bonn, A., Davies, J., Fernández, M., Matthews, N., Morris, J., Ramírez Hernández, W.A., Schoolenberg, M.A., Berg, M.v.d., Pennock, D., Vuuren, D.P.v., 2018. Chapter 7: scenarios of land degradation and restoration. In: Montanarella, L., Scholes, R., Brainich, A. (Eds.), The IPBES Assessment Report on Land Degradation and Restoration. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), Bonn, Germany.

Bryan, B.A., 2002. Reserve selection for nature conservation in South Australia: past, present and future. Aust. Geogr. Stud. 40, 196–209.

Cadotte, M.W., Carscadden, K., Mirotchnick, N., 2011. Beyond species: functional diversity and the maintenance of ecological processes and services. J. Appl. Ecol. 48, 1079–1087.

CBD, . Kunming-Montreal Post-2020 Global Biodiversity Framework. CBD/COP/DEC/15/4. https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf. Convention on Biological Diversity, Montreal, p. 14.

Commonwealth of Australia, 2015. Our North, Our Future: White Paper on Developing Northern Australia.

Commonwealth of Australia, 2021. Collaborative Australian Protected Areas Database (CAPAD) 2020.

DCCEEW, 2023. Species Profile and Threat Database. http://www.environment.gov.au/cgi-bin/sprat/public/sprat.pl.

Department of Agriculture, W.a.t.E, 2020. Interim Biogeographic Regionalisation for Australia v. 7 (IBRA) (ESRI shapefile).

Devillers, R., Pressey, R.L., Grech, A., Kittinger, J.N., Edgar, G.J., Ward, T., Watson, R., 2015. Reinventing residual reserves in the sea: are we favouring ease of establishment over need for protection? Aquat. Conserv. Mar. Freshwat. Ecosyst. 25, 480–504.

Evans, M., 2016. Deforestation in Australia: drivers, trends and policy responses. Pac. Conserv. Biol. 22, 130–150.

Falster, D., Gallagher, R., Wenk, E.H., Wright, I.J., Indiarto, D., Andrew, S.C., Baxter, C., Lawson, J., Allen, S., Fuchs, A., Monro, A., Kar, F., Adams, M.A., Ahrens, C.W., Alfonzetti, M., Angevin, T., Apgaua, D.M.G., Arndt, S., Atkin, O.K., Atkinson, J., Auld, T., Baker, A., von Balthazar, M., Bean, A., Blackman, C.J., Bloomfield, K., Bowman, D.M.J.S., Bragg, J., Brodribb, T.J., Buckton, G., Burrows, G., Caldwell, E., Camac, J., Carpenter, R., Catford, J.A., Cawthray, G.R., Cernusak, L.A., Chandler, G., Chapman, A.R., Cheal, D., Cheesman, A.W., Chen, S.-C., Choat, B., Clinton, B., Clode, P.L., Coleman, H., Cornwell, W.K., Cosgrove, M., Crisp, M., Cross, E., Crous, K.Y., Cunningham, S., Curran, T., Curtis, E., Daws, M.I., DeGabriel, J.L., Denton, M.D., Dong, N., Du, P., Duan, H., Duncan, D.H., Duncan, R.P., Duretto, M., Dwyer, J.M., Edwards, C., Esperon-Rodriguez, M., Evans, J.R., Everingham, S.E., Farrell, C., Firn, J., Fonseca, C.R., French, B.J., Frood, D., Funk, J.L., Geange, S.R., Ghannoum, O., Gleason, S.M., Gosper, C.R., Gray, E., Groom, P.K., Grootemaat, S., Gross, C., Guerin, G., Guja, L., Hahs, A.K., Harrison, M.T., Hayes, P.E., Henery, M., Hochuli, D., Howell, J., Huang, G., Hughes, L., Huisman, J., Ilic, J., Jagdish, A., Jin, D., Jordan, G., Jurado, E., Kanowski, J., Kasel, S., Kellermann, J., Kenny, B., Kohout, M., Kooyman, R.M., Kotowska, M.M., Lai, H.R., Laliberté, E., Lambers, H., Lamont, B.B., Lanfear, R., van Langevelde, F., Laughlin, D.C., Laugier-Kitchener, B.-A., Laurance, S., Lehmann, C.E.R., Leigh, A., Leishman, M.R., Lenz, T., Lepschi, B., Lewis, J.D., Lim, F., Liu, U., Lord, J., Lusk, C.H., Macinnis-Ng, C., McPherson, H., Magallón, S., Manea, A., López-Martinez, A., Mayfield, M., McCarthy, J.K., Meers, T., van der Merwe, M., Metcalfe, D.J., Milberg, P., Mokany, K., Moles, A.T., Moore, B.D., Moore, N., Morgan, J.W., Morris, W., Muir, A., Munroe, S., Nicholson, Á., Nicolle, D., Nicotra, A.B., Niinemets, Ü., North, T., O'Reilly-Nugent, A., O'Sullivan, O.S., Oberle, B., Onoda, Y., Ooi, M.K.J., Osborne, C.P., Paczkowska, G., Pekin, B., Guilherme Pereira, C., Pickering, C., Pickup, M., Pollock, L.J., Poot, P., Powell, J.R., Power, S.A., Prentice, I.C., Prior, L., Prober, S.M., Read, J., Reynolds, V., Richards, A.E., Richardson, B., Roderick, M.L., Rosell, J.A., Rossetto, M., Rye, B., Rymer, P.D., Sams, M.A., Sanson, G., Sauquet, H., Schmidt, S., Schönenberger, J., Schulze, E.-D., Sendall, K., Sinclair, S., Smith, B., Smith, R., Soper, F., Sparrow, B., Standish, R.J., Staples, T.L., Stephens, R., Szota, C., Taseski, G., Tasker, E., Thomas, F., Tissue, D.T., Tjoelker, M.G., Tng, D.Y.P., de Tombeur, F., Tomlinson, K., Turner, N.C., Veneklaas, E.J., Venn, S., Vesk, P., Vlasveld, C., Vorontsova, M.S., Warren, C.A., Warwick, N., Weerasinghe, L.K., Wells, J., Westoby, M., White, M., Williams, N.S.G., Wills, J., Wilson, P.G., Yates, C., Zanne, A.E., Zemunik, G., Ziemińska, K., 2021. AusTraits, a curated plant trait database for the Australian flora. Sci. Data 8, 254.

Fan, Y., Chen, J., Shirkey, G., John, R., Wu, S.R., Park, H., Shao, C., 2016. Applications of structural equation modeling (SEM) in ecological studies: an updated review. Ecol. Process. 5, 19.

Fischer, J., Zerger, A., Gibbons, P., Stott, J., Law, B.S., 2010. Tree decline and the future of Australian farmland biodiversity. Proc. Natl. Acad. Sci. 107, 19597–19602.

Fitzsimons, J.A., 2015. Private protected areas in Australia: current status and future directions. Nat. Conserv. 10, 1–23.

Fletcher, M.-S., Hall, T., Alexandra, A.N., 2021. The loss of an indigenous constructed landscape following British invasion of Australia: an insight into the deep human imprint on the Australian landscape. Ambio 50, 138–149.

Flynn, D.F.B., Gogol-Prokurat, M., Nogeire, T., Molinari, N., Richers, B.T., Lin, B.B., Simpson, N., Mayfield, M.M., DeClerck, F., 2009. Loss of functional diversity under land use intensification across multiple taxa. Ecol. Lett. 12, 22–33.

Gallagher, R.V., Allen, S., Mackenzie, B.D.E., Yates, C.J., Gosper, C.R., Keith, D.A., Merow, C., White, M.D., Wenk, E., Maitner, B.S., He, K., Adams, V.M., Auld, T.D., 2021. High fire frequency and the impact of the 2019–2020 megafires on Australian plant diversity. Divers. Distrib. 27, 1166–1179.

Gallagher, R., Allen, S., Rivers, M., Allen, A., Butt, N., Keith, D., Auld, T., Enquist, B., Wright, I., Possingham, H., Adams, V.M., 2023. Global shortfalls in threat assessments for endemic flora. Plants People Plant. https://doi.org/10.1002/ppp3.10369.

Gurney, G.G., Adams, V.M., Álvarez-Romero, J.G., Claudet, J., 2023. Area-based conservation: taking stock and looking ahead. One Earth 6, 98–104.

Helm, A., Hanski, I., Pärtel, M., 2006. Slow response of plant species richness to habitat loss and fragmentation. Ecol. Lett. 9, 72–77.

Hernandez, S., Barnes, M.D., Duce, S., Adams, V.M., 2021. The impact of strictly protected areas in a deforestation hotspot. Conserv. Sci. Pract. e479.

IPBES, 2019. In: Brondizio, E.S., Settele, J., Díaz, S., Ngo, H.T. (Eds.), Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES Secretariat, Bonn, Germany.

Joppa, L.N., Pfaff, A., 2009. High and far: biases in the location of protected areas. PLoS One 4, e8273. https://doi.org/10.1371/journal.pone.0008273.

Kearney, S.G., Adams, V.M., Fuller, R.A., Possingham, H.P., Watson, J.E.M., 2018. Estimating the benefit of well-managed protected areas for threatened species conservation. Oryx 1–9.

Kearney, S.G., Carwardine, J., Reside, A.E., Adams, V.M., Nelson, R., Coggan, A., Spindler, R., Watson, J.E.M., 2022. Saving species beyond the protected area fence: threats must be managed across multiple land tenure types to secure Australia's endangered species. Conserv. Sci. Pract. 4, e617.

Kuempel, C.D., Chauvenet, A.L.M., Possingham, H.P., 2016. Equitable representation of ecoregions is slowly improving despite strategic planning shortfalls. Conserv. Lett. 9, 422–428.

Kuempel, C.D., Jones, K.R., Watson, J.E.M., Possingham, H.P., 2019. Quantifying biases in marine-protected-area placement relative to abatable threats. Conserv. Biol. 33, 1350–1359.

Kuempel, C.D., Chauvenet, A.L.M., Possingham, H.P., Adams, V.M., 2020. Evidence-based guidelines for prioritizing investments to meet international conservation objectives. One Earth 2, 55–63.

Lunt, I.D., Eldridge, D.J., Morgan, J.W., Witt, G.B., 2007. A framework to predict the effects of livestock grazing and grazing exclusion on conservation values in natural ecosystems in Australia. Aust. J. Bot. 55, 401–415.

Mendel, L.C., Kirkpatrick, J.B., 2002. Historical progress of biodiversity conservation in the protected-area system of Tasmania, Australia. Conserv. Biol. 16, 1520–1529.

Montesino Pouzols, F., Toivonen, T., Di Minin, E., Kukkala, A.S., Kullberg, P., Kuustera, J., Lehtomaki, J., Tenkanen, H., Verburg, P.H., Moilanen, A., 2014. Global protected area expansion is compromised by projected land-use and parochialism. Nature 516, 383–386.

Pimm, S.L., Jenkins, C.N., Abell, R., Brooks, T.M., Gittleman, J.L., Joppa, L.N., Raven, P.H., Roberts, C.M., Sexton, J.O., 2014. The biodiversity of species and their rates of extinction, distribution, and protection. Science 344.

Pressey, R.L., 2002. The first reserve selection algorithm - a retrospective on Jamie Kirkpatrick's 1983 paper. Prog. Phys. Geogr. 26, 434–441.

Pressey, R.L., Hager, T.C., Ryan, K.M., Schwarz, J., Wall, S., Ferrier, S., Creaser, P.M., 2000. Using abiotic data for conservation assessments over extensive regions: quantitative methods applied across New South Wales, Australia. Biol. Conserv. 96, 55–82.

Pressey, R.L., Cabeza, M., Watts, M.E., Cowling, R.M., Wilson, K.A., 2007. Conservation planning in a changing world. Trends Ecol. Evol. 22, 583–592.

Pressey, R.L., Weeks, R., Gurney, G.G., 2017. From displacement activities to evidence-informed decisions in conservation. Biol. Conserv. 212, 337–348.

Pressey, R.L., Visconti, P., McKinnon, M.C., Gurney, G.G., Barnes, M., Glew, L., Maron, M., 2021. The mismeasure of conservation. Trends Ecol. Evol. 36, 808–821.

Recher, H.F., 2018. Politics, emotion, and ideology: the reality of reserve selection for nature conservation in Australia. Aust. Zool. 39, 257–271.

Reside, A.E., Beher, J., Cosgrove, A.J., Evans, M.C., Seabrook, L., Silcock, J.L., Wenger, A.S., Maron, M., 2017. Ecological consequences of land clearing and policy reform in Queensland. Pac. Conserv. Biol. 23, 219–230.

Rundle, G.E., 1996. History of conservation reserves in the south-west of Western Australia. J. R. Soc. West. Aust. 79, 225.

Sharafi, S.M., White, M., Burgman, M., 2012. Implementing comprehensiveness, adequacy and representativeness criteria (CAR) to indicate gaps in an existing reserve system: a case study from Victoria, Australia. Ecol. Indic. 18, 342–352.

Simmons, B.A., Kerrie, A.W., Raymundo, M.-M., Brett, A.B., Oakes, H., Elizabeth, A.L., 2018a. Effectiveness of regulatory policy in curbing deforestation in a biodiversity hotspot. Environ. Res. Lett. 13, 124003.

Simmons, B.A., Law, E.A., Marcos-Martinez, R., Bryan, B.A., McAlpine, C., Wilson, K.A., 2018b. Spatial and temporal patterns of land clearing during policy change. Land Use Policy 75, 399–410.

Streiner, D.L., 2005. Finding our way: an introduction to path analysis. Can. J. Psychiatr. 50, 115–122.

Taylor, R., 2015. Saving forests at risk. In: WWF Living Forests Report.

Venter, O., Magrach, A., Outram, N., Klein, C.J., Possingham, H.P., Di Marco, M., Watson, J.E.M., 2017. Bias in protected-area location and its effects on long-term aspirations of biodiversity conventions. Conserv. Biol. 127–134.

Visconti, P., Joppa, L., 2015. Building robust conservation plans. Conserv. Biol. 29, 503–512.

Visconti, P., Pressey, R.L., Bode, M., Segan, D.B., 2010. Habitat vulnerability in conservation planning—when it matters and how much. Conserv. Lett. 3, 404–414.

Watson, J.E.M., Fuller, R.A., Watson, A.W.T., Mackey, B.G., Wilson, K.A., Grantham, H.S., Turner, M., Klein, C.J., Carwardine, J., Joseph, L.N., Possingham, H.P., 2009. Wilderness and future conservation priorities in Australia. Divers. Distrib. 15, 1028–1036.