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Rarity or decline: Key concepts for the Red List of Australian eucalypts

Highlights

- Overall, 193 (23%) of 822 eucalypt (*Angophora, Corymbia, Eucalyptus*) species qualified as threatened using IUCN Red Listing criteria.
- Of these 134 species qualifying under criterion A2, representing a past and irreversible population decline of >30%.
- Habitat conversion to crops and pastures was the cause of decline for most threatened eucalypts.
- With our method, 32 of the 89 eucalypts currently listed as threatened under Australian environmental law are downgraded.
- This assessment of Australian eucalypts emphasises the importance of decline rather than rarity when compared with previous listings.

Abstract

The 822 eucalypt species (*Angophora, Corymbia, Eucalyptus*) within Australia were assessed using IUCN Red List criteria. Overall, 193 (23%) eucalypts qualified as threatened and 36 were considered Data Deficient. One hundred and thirty-four threatened species qualified under criterion A2, representing a past and irreversible population decline of >30%. The remainder were narrow-range species with ongoing threats (mostly mining or urbanisation), or naturally rare. Habitat conversion to crops and pastures was the cause of decline for most threatened eucalypts. Threatened species were concentrated where deforestation and high eucalypt richness coincide, especially south-western Western Australia and the Wimmera of south-eastern Australia. *Corymbia* or *Angophora* species, and relatively few tropical eucalypts are threatened. Fire, timber harvesting and disease were rarely sufficient threats to eucalypts to warrant a threatened status. Sheep grazing limits regeneration in temperate woodlands, but requires further quantification for individual species. Prior to this study, 89 eucalypts were listed as threatened under Australian environmental law. This assessment recommends that 32 of these species be downgraded to Near Threatened or Least Concern. A further 11 species were identified as Data Deficient, while an additional 147 species were proposed for listing as threatened. This systematic assessment of Australian eucalypts emphasises the importance of decline rather than rarity when compared with previous listings, with broad implications for listing long-lived plants in deforested landscapes.

Key words *Angophora; Corymbia;* eucalypts; *Eucalyptus;* Red List; threatened species

1. Introduction

The 'eucalypts' comprise three related genera within the Myrtaceae family; *Eucalyptus, Corymbia* and *Angophora,* which collectively include more than 800 species and define the landscape of an entire continent. Almost all eucalypts are endemic to Australia, where they occupy a near-continuous distribution across almost all habitat types; from mesic forest to semi-desert and mountains. Australia has undergone rapid landscape transformation throughout the 230 years since European colonisation. The consequences of this have been severe for biodiversity, with Australia having the highest rate of mammal extinction globally (Woinarski et al., 2012). Assessing the threat status of eucalypts will further highlight continental-scale conservation issues in Australia, through the lens of the dominant tree genera.

The universally accepted framework for assessing extinction risk of biota is the International Union for Conservation of Nature's (IUCN) Red List Categories and Criteria (version 3.1) (IUCN, 2012). These define extinction risk categories based on quantitative thresholds relating to geographic range, population size and rate of decline (IUCN, 2012; Mace et al., 2008). Currently accepted State and Federal lists for threatened flora have a range of biases and currencies, and often do not align with the IUCN Red List methodologies (Brito et al., 2010). Consequently, the IUCN Red List is misaligned with listings under Australian jurisdictions and only two assessments of eucalypts were included in 2019 (IUCN Red List 2019.2).

The Global Tree Assessment is an initiative led by Botanic Gardens Conservation International and the IUCN Species Survival Commission (SSC) Global Tree Specialist Group that aims to complete conservation assessments for all tree species worldwide by 2020 (Beech et al., 2017; Rivers, 2017). As the third largest tree genus in the world (Beech et al., 2017), an assessment of *Eucalyptus* and its relatives will provide a major augmentation to this effort. In addition, there have been recent advances in conservation assessment procedures within Australia. Foremost, an emphasis has been placed on documenting species that have undergone significant declines relative to naturally rare species that lack conceivable past and future threats (Burgman, 2002; McIntyre et al., 1992; Silcock et al., 2014). However, listing under criterion A has rarely been employed as the time-series data required to undertake these analyses is often limited or unavailable (Brummitt et al., 2015; Le Breton et al., 2019). This tends to result in a preponderance for listing narrow-range species (assessed under criterion B) and species with small population sizes (assessed under criteria C or D) (Collen et al., 2016). This bias may be misleading for conservation decision-makers, as naturally narrow-range species often have pre-adaptations for survival in small populations (Bezemer et al., 2016; Flather and Sieg, 2007; Yates et al., 2007) while widespread but rapidly declining species may be overlooked due to apparent abundance (Lindenmayer et al., 2011b). Emphasis on decline rather than rarity *per se* is reflected in the recent versions of the Red List procedures (IUCN, 2012), but threatened species lists in Australia, typically have not been updated accordingly. There is an urgent need to identify methodologies that quantify past decline for assessment under criterion A and forecast future continuing declines under criteria A, B and C (Brummitt et al., 2015).

Assessing large and related groups of taxa such as the eucalypts, overcomes limitations associated with using variable methodologies over small, species-specific scales (Possingham et al., 2002). A continental assessment also allows regional conservation hotspots to be identified (Brummitt et al., 2015). Many eucalypts are also keystone species that provide the physical framework of the ecosystem where they occur; hollows for nesting and shelter, foliage for herbivores, pollen and nectar, nutrient cycling, and litter and fallen branches for ground-dwelling fauna. The current study aims to (i) provide Red List assessments of all *Eucalyptus*, *Corymbia* and *Angophora* species within Australia; (ii) guide future conservation assessment methodologies emphasising genuine species' declines; (iii) identify the range of threats to the eucalypts; and (iv) identify regional hotspots for eucalypt conservation with recommendations to address conservation issues.

2. Methods

Eucalypts have relatively open breeding systems with considerable gene flow between related species (Potts and Wiltshire, 1997). Hybrids are especially common within subgenera, and species regularly exhibit morphological gradations with intermediate characteristics. It is therefore inevitable that the taxonomic status of the eucalypts will continue to be reviewed. The list assessed here (Appendix 1) includes the 822 described species occurring in Australia accepted by the Australian Plant Census (Australian Plant Name Index, accessed May 2019), excluding clearly erroneous names (n = 24). Infraspecific taxa were not included.

Species' geographic ranges were determined by verifying herbarium specimen records in consultation with herbarium curators, other experts and reference to distribution maps (Brooker and Kleinig, 1994, 2001, 2006; French, 2012; French and Nicolle, 2019; Nicolle, 2006a; French unpublished data, 2013; Williams and Potts, 1996). A 'geographic range' is defined here as the area encompassing the historical distribution of the species. Herbarium specimen data often includes errors associated with misidentified taxa, intergraded/hybrid taxa and erroneous geocoding. Although there are numerous additional data sources (e.g. field surveys), these were not included given the uncertainty when verifying records that are not substantiated by a specimen. Specimen collections are rich for eucalypts, with 215,276 records for 822 species since colonisation in 1788. According to experts, verified specimen records adequately represent historical geographic ranges for most eucalypts. For most species exhibiting decline paddock trees and roadside remnants persist throughout the historical geographic range and the current geographical range is assumed to have not declined substantially. To determine the extent of decline in geographic range would require extensive contemporary survey. Specimen locations were converted to geographic ranges using either a convex polygon or a more-idiosyncratic polygon as guided by geographic features (Appendix 2). For example, the distribution of lowland species often excluded areas that exceeded the highest altitude record. Geographic ranges are smaller than the Extent of occurrence (EOO), which must be a minimum convex polygon, and often larger than the Area of occupancy (AOO), which with adequate data, represents the known area of occupied by the species measured with a 2 × 2 km grid (Red List Technical Working Group, 2018).

2.1 Generation length

Generation length is determined as age of first reproduction + *z* * length of reproductive period (IUCN Standards and Petitions Committee, 2019), where z is a constant between 0 and 1 depending on survivorship and relationship of fecundity to tree age. While the time to seeding has not been quantified for many eucalypts, it can be as rapid as 40 months for species from Western Australia (Nicolle, 2006b) and up to 20 years for the obligate-seeder *Eucalyptus regnans* (Ashton and Attiwill, 1994). The lifespan of tropical eucalypts has been assessed by growth rates, which are reasonably independent of tree size (Cook et al., 2015; Fensham et al., 2017). Growth rates in the order of 1.5 to 2 mm per annum indicate a tree of 50 cm diameter at breast height is 250-330 years of age (Fensham et al., 2017; Murphy et al., 2010). Some *E. regnans* are estimated at 500 years old (Wood et al., 2010) and large lignotubers of other species are of similar age (Lacey and Head, 1988) or older (Kennington and James, 1997; Tyson et al., 1998). Values of *z* for the long-lived tree *Araucaria cunninghamii* have been calculated as 0.33 (Fung and Waples, 2017). Therefore, we assume the minimum value for eucalypt generation length is 4 (minimum age of first reproduction) + 0.33 * 200 (minimum age of large tree) = 70 years. For criterion A, past decline is assessed relative to three generations, which is >210 years for eucalypts. This is prior to 1810 and thus the extensive clearance of eucalypts following European colonisation.

2.2 Assessment of deforestation as a past threat

For assessment under criterion A, a past (A1, A2), future (A3) or past and future (A4) population reduction must be quantified. For Australian eucalypts, past decline (%) is assessed over three generations (the past 210 years), assuming that populations were relatively stable before European colonisation. Deforestation for agricultural crops, livestock pasture and urban development is the most substantial cause of decline in eucalypt woodland and forest (Yates and Hobbs, 1997). This land-use change represents a decline in habitat quality (A2c) because eucalypts are a dominant canopy tree species. The extent of deforestation was determined by intersecting the geographic range of a species with standardised land-use coverages developed for each Australian State and agglomerated for the entire Australian continent (Department of Agriculture and Water Resources, 2019). The land-use categories were assigned as either: 'remnant', deforestation due to 'urbanisation', deforestation due to 'other intensive land-use' or as 'ambiguous deforestation' (Table 1). The 'ambiguous deforestation' land-use categories (Table 1) included a mixture of deforested and non-deforested land and required further examination to determine actual deforestation levels within these areas (see below).

Deforestation does not occur evenly across landscapes. In Australia, areas with fertile soils and subdued topography are highly suitable for agriculture and have been preferentially cleared relative to areas with infertile soils and challenging topography (Fensham and Fairfax, 2003). Eucalypts are associated with certain habitats characterised by particular substrates or soil types. Therefore, in a given area, a eucalypt that occurs on arable soils will have declined more than a species that inhabits rocky hills. Conversely, urbanisation occurs independently of habitat type. To account for these biases, the habitat (soil/geology/topography) for each eucalypt was categorised as 'productive', 'moderately productive' or 'unproductive' (Table 1, Appendix 4).

The following sequence was used to estimate population decline for assessment under A2:

1) The geographic range of each eucalypt (Appendix 2) was intersected with the land-use coverage. The land-use coverage was summarised into 'remnant' (no deforestation), 'unambiguous deforestation' and 'ambiguous deforestation' categories (Table 1). Within the 'ambiguous deforestation' category, random points with 'less than 5% tree cover' were used to estimate the extent of deforestation (Table 1, Appendix 5).
2) A 'preliminary estimate of population decline' was determined for each eucalypt as the sum of 'unambiguous deforestation' and the 'less than 5% tree cover' component of 'ambiguous deforestation' in their geographic range (Table 1, Appendix 4).
    a) For eucalypts occurring in 'productive' habitat, the 'preliminary estimate of population decline' was used as the 'estimate of population decline'.
    b) For eucalypts occurring in 'moderately productive' habitat, the 'estimate of population decline' was determined as 60% of the 'preliminary estimate of population decline'.
    c) For eucalypts occurring in habitat classified as 'unproductive', the 'preliminary estimate of population decline' was not used as an 'estimate of population decline'.
3) For any eucalypt with a significant decline (>8%) due to 'urbanisation', the 'estimate of population decline' was calculated using a modified procedure because decline associated with urbanisation occurs independent of habitat type (Appendix 6).

Any estimate of population decline has an inherent level of uncertainty (IUCN 2019). To avoid 'unrealistically precautionary listings' (p. 23, IUCN Standards and Petitions Committee, 2019), a conservative approach was exercised when quantifying deforestation. Specifically, that (i) deforestation was defined by the low threshold of 'less than 5% tree cover' in the 'ambiguous deforestation' land-use categories, (ii) that deforestation of ‘productive’ habitats was equal to general deforestation, rather than a higher proportion, and (iii) that deforestation of ‘moderately productive’ habitats was equal to 60% of general deforestation, rather than a higher proportion. These assumptions ensured the final ‘estimate of population decline’ tended to underestimate actual population decline due to deforestation, ensuring a high level of certainty that species assessed as threatened meet the criteria thresholds.

2.3 Assessment using criteria B, C and D

Species with ongoing declines, a restricted geographic range and fewer than ten ‘locations’ or showing severe fragmentation can be considered under criterion B (IUCN, 2012). Species with an EOO <20,000 km^2 and AOO <2,000 km^2 were listed as threatened under criterion B if the number of locations was 10 or fewer. Expert elicitation and peer-reviewed literature were used to determine threats, ongoing population decline and population size. While some eucalypts may have ‘severely fragmented’ populations, the viability of these species would require detailed analyses beyond the scope of this assessment (see Fragmentation and genetic integrity below). No eucalypts were found to undergo extreme fluctuations as relevant to criteria B (IUCN 2012).

Eucalypts with <10,000 mature individuals and continuing decline were assessed under Criterion C. Species with <1,000 mature individuals were assessed under Criterion D and D1. Population size was determined using field survey data (Department of Biodiversity, Conservation and Attractions, 2012) or estimates from relevant experts. Criterion D2 was used to assess species with a potential future threat (where current threats are absent), with a very restricted range (AOO <20 km^2 or locations $\leq$5) and future threat that could rapidly drive the species to Critically Endangered or Extinct; for example, a species that occurred on geologies with mineral potential and land tenure that did not preclude mining. The latter was considered to be all tenures excluding conservation reserves (IUCN I to IV reserves, Dudley, 2008). Where available, documentation for existing threatened species listings under Australian Federal and State jurisdictions was reviewed to identify future threats (Department of Biodiversity, Conservation and Attractions, 2012; Department of Environment, 2019; Office of Environment & Heritage, 2015), alongside expert elicitation.

While the fate of any species is uncertain, some IUCN Red List criteria are concerned with future threats and predicting future decline. Generally, current threatening processes can inform future population trends. To manage this uncertainty in this assessment, the responses of eucalypts to past and present threats were used to inform their response to future threats.

2.3.1 Agriculture and pastoralism

All Australian State jurisdictions address native vegetation clearance in legislation and clearing for agriculture has slowed substantially as a result (Evans, 2016). Under certain circumstances native vegetation clearance is ongoing, however vegetation recovery is also occurring in some areas (Lunt et al., 2010). Assuming vegetation clearance for cropping and pastoralism remains regulated, eucalypt population reductions associated with this threat will be relatively insignificant when compared with the past.

2.3.2 Urbanisation

Eucalypts were assessed for decline associated with urbanisation under criterion A2 using the footprint of Australian cities (Department of Agriculture and Water Resources, 2019).

Australian cities will continue to expand and cause ongoing population declines for many eucalypts. This threat was assessed relative to the number of ‘locations’, which were the size of a typical Australian suburb (4 km^2). Widespread eucalypts threatened by urbanisation were not assessed under criteria A3 and A4 given the uncertainty associated with this decline.

2.3.3 Mining

Mining was considered a plausible threat for eucalypts occurring on geology with existing mineral extraction. Where mining was the dominant threat to a species under criterion B, ‘locations’ were scaled as the area of a typical, nearby mining development. Where species occurred on geology with potential for future mining, but no active mining, no continuing decline could be justified, but a potential for future decline was recognised. These species were assessed under criterion D2. IUCN I to IV conservation reserves (Dudley, 2008), including National Park, were assumed to be protected from mining threats.

2.3.4 Climate change

Climate change is an impending threat for biodiversity (Parmesan, 2006) and species with limited capacity for dispersal may be disproportionately affected (Guisan and Thuiller, 2005). Most eucalypts have poor seed dispersal (Booth, 2017) and some have very restricted geographic ranges (Hughes et al., 2006). Species distribution modelling has predicted substantial declines in the climatically-suitable area for many eucalypts (Butt et al., 2013; González-Orozco et al., 2016; Hughes et al., 2006). If the ‘worst-case’ scenario (RCP 8.5) of the IPCC predictions are realised (Stocker et al., 2013), the available ‘climate space’ for 2.4% of species will have no overlap with their current distribution (González-Orozco et al., 2016). However, this modelling approach has limitations (Heads, 2015; Peterson et al., 2018) and is problematic for eucalypts because (i) other factors, notably the soil environment, determine species’ distributions (Booth, 2018); (ii) there is considerable ecotypic variability in many eucalypt taxa (Booth, 2019; e.g. Gauli et al., 2015); (iii) small populations of some rare eucalypts have persisted despite Pleistocene climatic fluctuations (Byrne and Hopper, 2008; Hopper et al., 2016); and (iv) eucalypts have open breeding systems that may allow for gene transfer and confer adaptive-capacity to future climate change (Fensham et al., 2014).

Climate change is likely to intensify drought events (Dai, 2012; Mitchell et al., 2016), which may exacerbate mortality in eucalypt populations. Historical drought-induced mortality data should not be used to assess these potential impacts (Fensham et al., 2019), as the moisture limits of a species’ range can be poorly-related to drought-induced dieback symptoms (Fensham et al., 2014). Moreover, in north-eastern Australia, dominant species appear to be more susceptible to drought-induced mortality than sub-dominant species. These common species apparently trade-off their vulnerability to drought for dominance and the capacity for population recovery (Fensham et al., 2015). Evidently, drought-intensification relevant to individual species will be difficult to predict. Climate change may be detrimental to many eucalypt species in the future. However, the pioneering study identifying these impacts states that bio-climatic predictions cannot be used to reliably predict ‘either the future distributions, the survival or extinction of specific eucalypt species’ (Hughes et al., 2006, p. 27-28) and another recent review stresses the difficulties of. Due to the uncertainties and difficulties for predicting climate change impacts on eucalypts (Booth et al., 2015) this threat was not included in the Red List assessments presented here.

2.3.5 Fire

Eucalypts have evolved in the most fire-prone continent and many have traits that allow them to survive fires. These adaptations include epicormic buds that confer rapid crown re-development if the cambium is damaged (Burrows et al., 2008). Some species do not have substantial capacity for epicormic recovery but possess a lignotuber. This large, woody organ is insulated underground and is replete with buds allowing rapid post-fire recovery (Bowman et al., 2012; Nicolle, 2006b). For some species, fire promotes seed-release from woody capsules that then germinate in the ash-bed (Ashton and Attiwill, 1994; Burrows et al., 1990; Henry and Florence, 1966), while other species regenerate from root suckers (Lacey, 1974).

The Australian monsoonal savannas dominated by *E. tetrodonta* and *E. miniata* have the highest fire frequency in Australia (Bradstock et al., 2013; Russell-Smith et al., 2007). Even in these extremely fire-prone environments, only a very minor proportion is burnt annually (Russell-Smith et al., 1998, 2003b). Long-term experiments have not elicited major changes to stand structure under divergent treatments including annual fires relative to sites unburnt for 23 years (Russell-Smith et al., 2003a). Experimental studies for a range of eucalypts in other environments indicate burning regimes have minimal impact on stand structure (Fensham et al., 2017; Henry and Florence, 1966; Russell-Smith et al., 2003a). A review of the substantial body of research from tropical savanna concluded eucalypts are fire tolerant and unresponsive to reductions in fire frequency and intensity (Murphy et al., 2015). Moreover, there is no peer-reviewed evidence that frequent burning within the range determined by natural fuel accumulation can cause population declines for any eucalypts that re-sprout from stems or lignotubers. However, prolonged extremely frequent fire regimes may result in changes in tree densities over three generations (Werner and Peacock, 2019).

Some eucalypts are ‘obligate-seeders’ with aboveground stems that are typically killed by intense fire and germination from seed is the dominant form of regeneration (Nicolle, 2006b). Theoretically, successive fires could cause significant population declines if the individuals that germinated after a fire were burnt before reaching reproductive maturity (Bowman and Prior, 2018). *Eucalyptus delegatensis* subsp. *delegatnesis* from the Australian mainland is an obligate-seeder that was assumed to require 20 years to produce ‘replacement’ quantities of viable seed (Fagg et al., 2013). In a few areas across its range, successive fires have occurred at intervals <20 years (Doherty et al., 2017) and under these circumstances a reduced rate of regeneration relative to the response after a single fire has been observed (Bowman et al., 2014). However, it has been recently demonstrated that ‘precocious’ individuals can fruit and set seed within 6 years (Doherty et al., 2017) and adults of this subspecies of *E. delegatensis* can survive burning at some sites (Bowman et al., 2014). This indicates that long-term population impacts over the entire range of this and other obligate-seeders from similar high rainfall environments are yet to be understood.

In south-western Western Australia, there is a concentration of obligate-seeders that occur in relatively dry landscapes (Gosper et al., 2019; Nicolle, 2006b). Increased fire frequency, either through ignitions or climate change have been considered a significant future threat to these species (O’Donnell et al., 2011a). Germination occurs *en masse* after fire for these obligate-seeders, which then often form single-age cohorts (Gosper et al., 2018). Germination also occurs sporadically without fire and as individuals senesce stands develop as multi-age cohorts (Gosper et al., 2018). The time to seed production for obligate-seeders in south-western Western Australia varies between 4.5 and 7.5 years (Nicolle, 2006a), although seed volumes increase substantially after this time (Gosper et al., 2018). In low rainfall areas (<1000 mm mean annual rainfall) where some of these obligate-seeder species occur, average fire intervals are ~400 years (O’Donnell et al., 2011b). Fuel loads in *E. salubris* woodlands take 35 years to peak (Gosper et al., 2013), suggesting that fires occurring at intervals substantially less than this are unlikely. While frequent burning could theoretically cause population declines for obligate-seeders, we are not aware of any observations where this has occurred in low rainfall environments. As fire is rare in agricultural landscapes due to fire suppression (Shedley et al., 2018), the species most at risk of fire-related decline are those with restricted ranges occurring outside intensive land-use areas. These species were assessed under criterion D2 with 'locations' as the size of an average fire in the region (Shedley et al., 2018). Other than these species, fire was not accepted as a threat given this high level of uncertainty. Further investigation is required to determine the vulnerability of obligate-seeders to future fire regimes, especially those with small populations and restricted ranges.

2.3.6 Grazing

Cattle and sheep grazing is the primary land-use throughout many areas dominated by eucalypts. The stand structure of eucalypt woodlands is typically represented by a high density of small stems and a lower density of large stems (Burrows et al., 1990; Fischer et al., 2009; Scanlan et al., 1996). Intensive sheep grazing can eliminate regeneration and result in decline in tree density in eucalypt woodlands as mature trees die (Dorrough and Moxham, 2005; Weinberg et al., 2011). In these areas, recruitment is insufficient to replace scattered paddock trees in grazed pastures (Fischer et al., 2009). However, if sheep grazing is not continuous, recruitment does occur (Dorrough and Moxham, 2005; Fischer et al., 2009; Semple and Koen, 2001). In tropical areas, cattle grazing can increase mortality of small trees, however densities remain sufficient for stand replacement (Scanlan et al., 1996). Livestock grazing does not increase the incidence of drought-induced mortality (Fensham, 1998). Clearly, livestock grazing is a threatening process for eucalypt populations in intensively grazed areas. However, the mere coincidence of livestock grazing with eucalypt distributions was not accepted as sufficient evidence of population decline. Intensive grazing was considered a threat where it was observed to impede generation and was the major land-use throughout a species' range. Studies demonstrating the impacts of grazing for individual species are required to ascertain a causal relationship between grazing and future population declines.

2.3.7 Timber harvesting

Timber harvesting has been a pervasive land-use in eucalypt forests, particularly in humid areas of temperate Australia, with species such as *Corymbia maculate*, *E. delegatensis*, *E. diversicolor*, *E. fastigata*, *E. grandis*, *E. obliqua*, *E. marginata*, *E. nitens*, *E. pilularis*, *E. regnans* and *E. saligna* particularly affected. In some areas, native eucalypt forest have been replaced with plantations, often monocultures of a single species. Population decline was assessed under A2 as deforestation in these areas. More generally, harvesting of native forest typically allows canopy trees to regenerate.

2.3.8 Dieback and absence of regeneration

Some species exhibit 'dieback' (death and crown damage) due to unspecified causes. *Eucalyptus gunnii* has exhibited substantial mortality and many populations have little regeneration (Calder and Kirkpatrick, 2008; Sanger et al., 2011). Where this decline was characterised by substantial mortality of adults combined with minimal recruitment, ongoing decline was accepted. This threat was subsequently assessed at the scale of a population or the portion of the population affected.

2.3.9 Disease

Eucalypts can be susceptible to disease including the root pathogen *Phytophthora cinnamomi* (Davison, 2018), *Armillaria* sp. (Kellas et al., 1987), myrtle rust *Austropuccinia psidii* (Berthon et al., 2018) and other galls and cankers (e.g. Paap et al., 2016). These diseases can have localised impacts, particularly in plantations, but there is no evidence these are substantial threats at the species level to naturally occurring eucalypt populations.

2.3.10 Fragmentation and genetic integrity

Fragmentation effects on genetic diversity may be profound for eucalypts with once large continuous geographical ranges (Prober, 1996). Conversely, naturally fragmented species such as those endemic to disjunct habitats like rock outcrops may have evolved genetic mechanisms for surviving in small populations (Bezemer et al., 2016; Byrne and Hopper, 2008; Hopper et al., 2016). Many widespread species have naturally occurring 'outlier' populations that are probably genetically isolated from the core range. These apparently persist without negative effects of a small gene pool, e.g. inbreeding depression. Experimental studies are needed to ascertain the associated threats of fragmentation to genetic integrity, which may reveal unexpected resilience; as has been established for *E. incrassata* (Breed et al., 2015). The reduced genetic variability of *E. argutifolia* has been attributed to events associated with the origin of the species rather than subsequent genetic bottle-necks (Kennington and James, 1998). Therefore, in the absence of evidence, fragmentation effects on genetic integrity were not considered a threatening process.

The above-mentioned procedures adopted here follow IUCN Red List categories and criteria, but are conservative, in that the estimations of generation length and decline are likely to underestimate threat status. This provides a high degree of certainty that the thresholds for threat criteria are satisfied but may have resulted in an underestimation of the threat status for some species under category A2.

3. Results

With our conservative method, 193 of 882 eucalypts were eligible for listing under IUCN Red List criteria as either Critically Endangered (CR), Endangered (EN) or Vulnerable (VU; Appendix 1). No *Corymbia* (93 species) or *Angophora* (10 species) were assessed as threatened, compared to 26.8% of 719 species in *Eucalyptus* (Appendix 1). Thirty-six species of uncertain taxonomic status or geographic status were identified as Data Deficient (Appendix 1). Of the 193 threatened species, 134 qualified as threatened under criterion A2 (Table 2). Of these, 71 have geographic ranges >15 000 km^2, none of which has been included in Federal/State listings. Under category A2, threatened species were concentrated in south-western Western Australia and in other areas with intensive land-use represented by 'unambiguous deforestation' (Figure 1a, Figure 1b).

Twenty-two species qualified under criterion B. These species were largely threatened by ongoing mining (Table 3). Only 17 species qualified under criterion C as there were few species with less than 10 000 individuals and small subpopulations undergoing decline (Table 3). Twenty-seven species qualified under criteria D and D1 due to small populations (<1,000) (Table 3) and 14 of these occur in south-western Western Australia. Nine species qualify under criterion D2, i.e. restricted range and potential future threat, including seven obligate-seeder species from Western Australia that are threatened by unlikely frequent fire (Table 3).

Supporting documentation for current listings under State/Federal legislation is often unavailable. Therefore, an evaluation of how a species met specific thresholds in this study compared with previous assessments was not always possible. Of the 89 species currently listed as threatened under Australian jurisdictions (Appendix 1), 32 species did not meet the Red List criteria as threatened (Table 4). All of these species have a population size of at least 1,000 mature individuals (disallowing them for consideration under criterion D1). The majority of currently listed species were listed due to predicted future decline under putative threats with insufficient evidence (Table 4); most commonly roads and pipelines (13 species), too-frequent fire (12 species), clearing for agriculture (11 species), effects relating to small populations or restricted range (11 species) and grazing (10 species).

4. Discussion

This study emphasises the importance of past decline in threatened species assessments. Eucalypts exhibiting past decline have been overlooked in listings under Australian jurisdictions when compared with narrow-range species that have no clear threat. Many of the species with past decline listed under criterion A2 remain relatively common and widespread, particularly those with large geographic ranges (Table 2). These species are preserved as paddock trees, on roadsides and in other remnants and have not undergone substantial decline in their EOO or AOO. However, habitat characteristics and deforestation indicate 16% of species with ranges >15 000 km^2 have declined by more than 30% within three generations, qualifying as threatened under criterion A2. Eucalypts threatened by past decline occur where cropping ('unambiguous deforestation'; Fig. 1b) is an important land-use (Fig. 1a). Clearing of temperate eucalypt woodland for crops and pastures has previously been identified as the dominant threat to eucalypts (Yates and Hobbs, 1997).

In south-western Western Australia, the coincidence of a high diversity of species (Figure 2a) with intensive land-use (Figure 1b), primarily cereal-cropping, creates a hotspot for eucalypt decline that requires urgent conservation measures (Figure 1a, 2b). Similarly, a second hotspot coincides with the 'wheat cropping' lands in the Wimmera district, straddling the Victoria-South Australia border (Fig. 1a, 1b). The distribution of threatened eucalypts listed under category A (Figure 1a) is similar to the distribution of threatened eucalypts collectively (Figure 2b) due to the large range of the former species combined with the scarcity of species listed under criteria B, C, and D. Despite the relatively high diversity of eucalypts in northern Australia (Fig. 2b), there are almost no threatened species here (Fig. 2a). Intensive land-use is relatively restricted in this region (Figure 1b) and there are few species with restricted ranges associated with mining activity. There were no *Corymbia* or *Angophora* species that qualified for listing under any category. *Corymbia* primarily occur in northern Australia, while *Angophora* are typically associated with relatively infertile soils that have been cleared at low rates for agriculture.

Many currently listed species (32) did not meet the thresholds for threatened status in this assessment. Generally, their populations were greater than 1,000 individuals or there was insufficient evidence that the listed threats were causing population declines. The most common of these putative threats were transport and utility infrastructure, too-frequent fire, clearing for agriculture, grazing and fragmentation (Table 3). Roads and utility infrastructure will continue to expand but generally occur at a small-scale relative to the distribution of most eucalypts. Other threats require further evidence at the species level than is documented (see Methods). For some species, a plausible threat was listed (i.e. active/ future mining) but the number of locations exceeded the threshold of ten (category B) or five (category D2).

The impact of intensive sheep grazing may have been underestimated in this study. Sheep grazing is the dominant land-use alongside cropping through the southern temperate areas of Australia. In these areas, many widespread eucalypts have suffered direct declines with cropping (Fig. 1). Those species with geographic ranges also coinciding with sheep production will probably exhibit future decline due to lack of regeneration. *Eucalyptus blakelyi, E. microcarpa, E. melliodora, E. blakelyi* and *E. albens* are likely candidates (Dorrough and Moxham, 2005; Fischer et al., 2009; Weinberg et al., 2011) and demographic research should be directed to these species.

To account for uncertainty, assumptions that result in a conservative assessment of population decline have been used. In addition to the assumptions for determining deforestation (see Methods), the historical geographic range may be underestimated by specimen records, particularly for eucalypts with small geographic ranges in productive landscapes. There were seven species (*E. carolaniae, E. crenulata, E. dalveenica, E. infera, E. morrisbyi*, *E. purpurata* and *E. yarriambiack*) where the historical geographic range could not be determined. More detailed surveys of paddock trees and roadsides could overcome this deficiency. Potential future decline with grazing was not included in this analysis. Some eucalypts may have been recommended for delisting due to the conservative estimate of deforestation. For example, *E. parvula* is restricted to swamp edges, which may have been preferentially cleared when compared with the wider landscape. These localised habitats were not individually mapped and the more generalised distribution indicated a decline of only 19% (Appendix 2). Furthermore, this species occurs where sheep grazing is the dominant land-use and its regeneration may be disrupted. Again, detailed field survey could inform a more certain conservation assessment for such species.

The imperative to preserve populations of eucalypts within regions that have undergone deforestation is clear. Firstly, recovery effort should focus on permanently protecting populations where natural regeneration is occurring (Yates and Hobbs, 1997). Appropriate management should then be implemented at other locations where natural processes such as regeneration are currently inhibited. Finally, the more challenging objective is to restore eucalypt populations through translocation in reconstructed ecosystems (Cramer et al., 2007) and enhance the health and connectivity of naturally regenerating populations to improve gene flow (Byrne et al., 2008). To maximise conservation outcomes, these strategies should be directed to areas where eucalypt diversity is concentrated (Fig. 2).

Overall, this study has significantly increased the number of threatened eucalypts under the IUCN Red List, from two to 822. A large number of eucalypt species qualified as threatened under criterion A. Excluding species listed only under criterion A, the number of threatened species (65) is less than the 89 species currently listed under Australian jurisdictions (Appendix 1). The extinction risk for widespread species assessed under criterion A has not been previously recognised (Le Breton et al., 2019).. However, these species have undergone a population decline of at least 30%, and with the past trajectory of decline are heading for extinction within ten generations. Many of the species listed under A2 are the key components of Federally-listed Threatened Ecological Communities (Table 2). This highlights that listing taxa that dominate ecological communities such as the eucalypts, may be an alternative to listing ecological communities, overcoming the profound problem of providing a satisfactory classification scheme for communities/ecosystems listing (Boitani et al., 2015).

This study exemplifies that the Red List procedure emphasises decline over rarity. For example, using our assessment of the criteria *E. boliviana* is not eligible while *E. populnea* is proposed for listing as threatened. Both occur in eastern Australia, with the former comprising less than 2,000 mature individuals and an EOO of 2.67 km^2, and the latter represented by many orders of magnitude more individuals with an EOO of 1.1 M km^2. *Eucalyptus boliviana* is confined to a conservation reserve with no perceived threats while *E. populnea* forms widespread woodlands on arable soils that have been extensively cleared.

5. Conclusion

The methodology presented here provides a standardised procedure for assessing a large group of related taxa. The assessment of evidence was underpinned by a review of eucalypt ecology in relation to potential threatening processes (see Methods). Population decline due to deforestation for cropping, pasture and urbanisation is the most important threat to eucalypts. Disease, fire and timber harvesting are not substantial threats to eucalypts collectively, although concerns have been raised about the decline of the forest giant *E. regnans* as a result of timber harvesting and increasing fire frequency (Lindenmayer et al., 2011a). Mining is a potential threat for species with small geographic ranges and suppression of regeneration due to sheep grazing is a pervasive cause of ongoing decline in temperate areas. The quantitative method for assessing decline under criterion A has broad relevance for listing long-lived threatened species with comprehensive collecting records. This assessment suggests that decline has been underestimated compared to rarity as an estimate of extinction risk under Red Listing procedures.

Table 1. Definition of terms used in the text.

Term	Definition
‘remnant’	Relatively intact native vegetation mapped accordingly by the Australian Land-use and Management classification system (Department of Agriculture and Water Resources, 2019)(Appendix 3)
‘urbanisation’	Urban areas mapped accordingly by the Australian Land-use and Management classification system (Department of Agriculture and Water Resources, 2019)(Appendix 3)
‘other intensive land-use’	Intensive land-use (mostly areas converted to agriculture) other than urban areas mapped accordingly by the Australian Land-use and Management classification system (Department of Agriculture and Water Resources, 2019)(Appendix 3)
‘ambiguous deforestation’	A mixture of deforested and non-deforested land mapped accordingly by the Australian Land-use and Management classification system as 2.1.0 Grazing native vegetation, 3.2.0 Grazing modified pastures and 3.2.1 Native/exotic pasture mosaic (Department of Agriculture and Water Resources, 2019)(Appendix 3). Deforestation within these areas was quantified by using random points (Appendix 5)
‘unambiguous deforestation’	The combination of ‘urbanisation’ and ‘other intensive land-use’ (Appendix 5)
‘less than 5% tree cover’	An area of 100 m diameter where deforestation has occurred and tree cover is less than 5% (Appendix 5)
‘productive’	Refers to habitat that has been typically or preferentially subject to deforestation in any given area and is defined by a range of descriptors in Appendix 4

‘moderately productive’	Refers to habitat that has been subject to deforestation, but at a lower rate than for ‘productive’ habitat in any given area and is defined by a range of descriptors in Appendix 4
‘unproductive’	Refers to habitat that may or may not have been subject to deforestation, but at a lower rate than for ‘moderately productive’ habitat in any given area and is defined by a range of descriptors in Appendix 4
‘preliminary estimate of population decline’	The proportion of any given area subject to ‘unambiguous deforestation’ and the proportion of the area of ‘ambiguous deforestation’ represented by random points of ‘less than 5% tree cover’
‘estimate of population decline’	For species occurring in ‘productive’ habitat this is equivalent to the ‘preliminary estimate of population decline’. For species occurring in ‘moderately productive’ habitat this is equivalent to the 60% of the ‘preliminary estimate of population decline’ (Appendix 4). For species occurring in the urban context a modified procedure using ‘urbanisation’ and ‘other intensive land-use’ was used (Appendix 6)
‘other deforestation	‘Other deforestation’ includes ‘other intensive land-use’ areas (see Appendix 3) and the ‘ambiguous deforestation’ land-use areas assigned as ‘less than 5% tree cover’ using random points (see Appendix 5)

Table 2. Eucalypts listed under IUCN Criterion A and relevant parameters including geographic range (GR), estimated percentage of decline (EPD), habitat type (Appendix 4) as 'productive' habitat (P); 'moderately productive' habitat (M); or 'unproductive' habitat (U) and listing under the Environment Protection & Biodiversity Conservation (EPBC) Act, 1999. Species are listed under Category A2 according to their decline over three generations: CR, >80% decline; EN, 50-80% decline, VU; 30-50% decline. Current listings for each species and threatened ecological communities (TEC; Commonwealth of Australia, 2019) under the EPBC Act, 1999 and relevant state jurisdiction are listed, with Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Threatened (T) and Not Listed (NL). TECs are Banksia woodlands of the Swan Coastal Plain[1], Brigalow (*Acacia harpophylla* dominant and co-dominant) ecological community[2], Buloke woodlands of the Riverina and Murray-Darling depression bioregions[3], Central Hunter Valley eucalypt forest and woodland ecological community[4], Coastal swamp oak (*Casuarina glauca*) forest of New South Wales and South East Queensland ecological community[5], Cooks River/ Castlereagh ironbark forest of the Sydney Basin bioregion[6], Coolibah – black box woodlands of the Darling Riverine Plains and the Brigalow Belt South bioregions[7], *Corymbia calophylla – Xanthorrhoea preissii* woodlands and shrublands of the Swan Coastal Plain[8], Cumberland Plain shale woodlands and shale-gravel transition forest[9], Eucalypt woodlands of the Western Australian wheatbelt[10], *E. ovata – Callitris oblonga* forest[11], Eyre Peninsula blue gum (*E. petiolaris)* woodland[12], grey box (*E. microcarpa*) grassy woodlands and derived native grasslands of south-east Australia[13], Hunter Valley weeping myall (*Acacia pendula)* woodland[14], Illawarra and south coast lowland forest and woodland ecological community[15], Kangaroo Island narrow-leaved mallee (*E. cneorifolia*) woodland[16], Lowland grassy woodland in the south east corner bioregion[17], Natural damp grassland of the Victorian coastal plains[18], New England peppermint (*E. nova-anglica*) grassy woodlands[19], Peppermint box (*E. odorata)* grassy woodland of South Australia[20], Poplar box grassy woodland on alluvial plains[21], Proteaceae dominated Kwongkan shrublands of the southeast coastal floristic province of Western Australia[22], River Murray and associated wetlands, floodplains and groundwater systems, from the junction with the Darling River to sea[23], Southern Highlands shale forest and woodland of the Sydney Basin bioregion[24], Swamp tea-tree (*Melaleuca irbyana)* forest of south-east Queensland[25], Tasmanian forests and woodlands dominated by black gum or Brookers gum (*E. ovata/ E. brookeriana*)[26], Tuart (*E. gomphocephala*) woodlands and forest of the Swan Coastal Plain ecological community[27], Warkworth Sands woodland of the Hunter Valley ecological community[28], Weeping myall woodlands[29], Western Sydney dry rainforest and moist woodland on shale[30], White box – yellow box – Blakely's red gum grassy woodlands and derived native grasslands[31]. All species were listed under criterion A2c except *E. gunnii*, *E. morrisbyi* and *E. ornans* that were listed under A2a, where decline was directly observed. Species marked (*) are listed under other criteria (Table 3).

Species	**GR (km2)**	**EPD %**	**Habitat**	**IUCN listing**	**Listing (EPBC, State)**	**TEC**
E. absita	207.40	58.83	P	EN	EN, CR	
E. aequioperta	32718.30	56.76	P	EN	NL, NL	
E. aggregata	13625.90	43.62	P	VU	VU, VU	
E. albens	280142.10	30.97	M	VU	NL, NL	4; 31

E. albida	43766.60	46.70	M	VU	NL, NL	
E. alipes	28322.90	41.82	P	VU	NL, NL	10
E. angulosa	20162.50	32.01	M	VU	NL, NL	
E. angustissima	4601.90	49.93	P	VU	NL, NL	
E. annulata	13470.60	37.77	M	VU	NL, NL	10
E. arenicola	2286.00	37.36	M	VU	NL, NL	
E. armillata	22300.90	48.50	M	VU	NL, NL	10
E. aromaphloia	10288.50	39.18	M	VU	NL, NL	
E. baueriana	9551.40	32.05	P	VU	NL, NL	
E. behriana	52008.10	77.62	P	EN	NL, NL	
E. blakelyi	183581.10	30.17	M	VU	NL, NL	4; 28; 31
E. bridgesiana	149927.10	40.05	P	VU	NL, NL	31
E. buprestium	8498.70	31.36	M	VU	NL, NL	22
E. burracoppinensis	39720.90	33.14	M	VU	NL, NL	
E. cadens	94.50	46.39	P	VU	VU, T	
E. calycogona	213075.70	54.89	P	EN	NL, NL	10
E. cambageana	203020.60	33.91	P	VU	NL, NL	2
E. camfieldii	486.90	32.88	M	VU	VU, VU	
E. captiosa	4189.20	46.24	M	VU	NL, NL	
E. cephalocarpa	25870.80	42.72	M	VU	NL, NL	10
E. cladocalyx	7121.10	31.89	M	VU	NL, NL	12; 20
E. clivicola	19140.80	30.23	M	VU	NL, NL	
E. cneorifolia	1795.10	34.32	M	VU	NL, NL	16
E. conica	161306.30	49.23	P	VU	NL, NL	31
E. cretata	5093.80	75.74	P	EN	NL, NL	
E. cuprea	3525.00	78.15	P	EN	NL, EN	
E. cyanophylla	9657.00	34.12	M	VU	NL, NL	
E. dawsonii	20350.40	37.89	P	VU	NL, NL	4; 14
E. dielsii	20814.70	36.75	P	VU	NL, NL	
E. diminuta	8048.70	39.15	P	VU	NL, NL	
E. dissimulata	15837.40	60.00	P	EN	NL, NL	
E. diversifolia	50172.40	37.69	M	VU	NL, NL	16
E. dolichorhyncha	1939.30	65.15	P	EN	NL, NL	
E. dumosa	275008.50	45.70	P	VU	NL, NL	
E. erythronema	27236.90	53.00	M	EN	NL, NL	10
E. extensa	66876.70	38.59	P	VU	NL, NL	10
E. falciformis	10570.60	48.59	P	VU	NL, NL	
E. fasciculosa	29474.90	42.57	M	VU	NL, NL	16
E. flocktoniae	161060.30	31.24	M	VU	NL, NL	10
E. foliosa	1267.40	80.23	P	CR	NL, NL	
E. forrestiana	3998.50	55.42	P	EN	NL, NL	
E. froggattii	992.30	71.20	P	EN	NL, T	
E. fulgens	1507.70	62.06	P	EN	NL, NL	
E. gittinsii	25514.90	35.05	M	VU	NL, NL	10

E. glaucina	3235.00	39.04	P	VU	VU, VU	4
E. gomphocephala	5732.90	31.38	M	VU	NL, NL	1; 27
E. goniocalyx	106195.50	31.33	M	VU	NL, NL	
E. goniocarpa	376.60	68.32	P	EN	NL, NL	
*E. gunnii**	13193.90	70.00	P	EN	NL, NL	
E. haemastoma	6065.10	37.90	U	VU	NL, NL	
E. halophila	2906.40	32.08	M	VU	NL, NL	
E. hawkeri	104.70	35.95	M	VU	NL, NL	
E. hebetifolia	10923.60	45.71	M	VU	NL, NL	
E. ignorabilis	6636.40	41.73	M	VU	NL, NL	
E. indurata	13481.50	37.74	P	VU	NL, NL	
E. kartzoffiana	90.90	38.62	P	VU	VU, VU	
E. kessellii	14228.60	34.03	M	VU	NL, NL	
E. kitsoniana	3542.50	56.18	P	EN	NL, NL	
E. kochii	70683.10	39.45	M	VU	NL, NL	10
E. kondininensis	23808.10	71.96	P	EN	NL, NL	10
E. lane-poolei	2798.20	35.45	M	VU	NL, NL	
E. largiflorens	517812.00	43.20	P	VU	NL, NL	7; 21; 23; 29
E. latens	38627.90	47.36	M	VU	NL, NL	
E. leptophylla	265441.10	33.22	M	VU	NL, NL	
E. leucoxylon	117729.00	42.56	M	VU	NL, NL	20
E. litoralis	46.30	48.53	M	VU	NL, NL	
E. longicornis	170442.30	52.59	P	EN	NL, NL	10
E. longifolia	16483.50	30.03	P	VU	NL, NL	5; 6; 15
E. loxophleba	300390.20	40.70	P	VU	NL, NL	10
E. luehmanniana	1249.30	40.70	U	VU	NL, NL	
E. macrocarpa	24731.30	49.05	M	VU	NL, NL	
E. mckieana	9174.00	35.71	P	VU	VU, VU	
E. melliodora	425282.30	44.95	P	VU	NL, NL	17; 31
E. merrickiae	2602.00	38.07	P	VU	VU, VU	
E. microcarpa	242583.00	67.75	P	EN	NL, NL	3; 13; 20; 21; 31
E. mimica	556.10	78.01	P	EN	NL, NL	10
E. moderata	120880.60	43.55	P	VU	NL, NL	10
E. moluccana	315219.70	31.15	P	VU	NL, NL	4; 6; 9; 25; 30; 31
*E. morrisbyi**	107.20	51-95	N	CR	EN, EN	
E. myriadena	93446.90	74.54	P	EN	NL, NL	10
E. neutra	34136.70	70.56	P	EN	NL, NL	
E. nicholii	9189.10	31.91	M	VU	VU, VU	
E. nova-anglica	20934.80	30.95	P	VU	NL, NL	19
E. obtusiflora	69607.10	30.14	M	VU	NL, NL	10
E. occidentalis	74702.50	54.50	P	EN	NL, NL	10
E. odorata	44839.40	78.26	P	EN	NL, NL	12; 16; 20

*E. ornans**	0.00	90.00	P	CR	NL, T	
E. orthostemon	41655.70	51.53	M	EN	NL, NL	10
E. ovata	159344.80	47.59	P	VU	NL, NL	11; 18; 24; 26
E. peninsularis	4700.10	79.71	P	EN	NL, NL	
E. petiolaris	4974.10	77.73	P	EN	NL, NL	12
E. phaenophylla	59842.60	37.10	M	VU	NL, NL	10
E. phenax	188548.20	38.63	M	VU	NL, NL	10; 16
E. pileata	92437.90	33.94	P	VU	NL, NL	
E. platypus	32820.70	58.62	P	EN	NL, NL	
E. pleurocarpa	42037.80	30.35	M	VU	NL, NL	22
E. pluricaulis	97796.40	46.96	M	VU	NL, NL	
E. populnea	859188.90	36.14	P	VU	NL, NL	2; 21; 29
E. porosa	244740.40	31.98	M	VU	NL, NL	20
E. pyriformis	31785.70	49.42	M	VU	NL, NL	
E. quaerenda	673.20	42.52	P	VU	NL, NL	
E. recta	90.00	52.50	M	EN	EN, VU	10
E. rhodantha	229.90	50.31	M	EN	VU, NL	
E. rigens	2070.10	55.28	P	EN	NL, NL	
E. risdonii	200.50	49.30	U	VU	NL, NL	
E. sabulosa	8418.90	30.83	M	VU	NL, NL	
E. salmonophloia	287718.30	36.50	P	VU	NL, NL	
E. sargentii	35045.50	52.28	M	EN	NL, NL	10
E. sheathiana	44085.60	49.21	M	VU	NL, NL	10
E. silvestris	1700.50	94.21	P	CR	NL, NL	10
E. spathulata	17748.50	76.21	P	EN	NL, NL	10
E. splendens	47.00	50.68	P	EN	NL, NL	
E. sporadica	69764.60	37.46	M	VU	NL, NL	10
E. squamosa	7021.50	31.00	U	VU	NL, NL	
E. strzeleckii	6479.00	66.71	P	EN	VU, T	
E. subangusta	113962.80	38.83	M	VU	NL, NL	
E. suggrandis	33241.10	31.67	M	VU	NL, NL	
E. thamnoides	39126.80	44.17	M	VU	NL, NL	10
E. tumida	24808.10	44.94	P	VU	NL, NL	
E. uncinata	93976.50	35.58	M	VU	NL, NL	
E. valens	10652.90	50.49	P	EN	NL, NL	
E. varia	10899.50	37.40	M	VU	NL, NL	
E. vegrandis	8988.80	41.58	M	VU	NL, NL	
E. vesiculosa	67.60	35.01	P	VU	NL, NL	
E. wandoo	92897.30	39.11	M	VU	NL, NL	10
E. wimmerensis	9163.10	45.80	M	VU	NL, NL	
E. woollsiana	178502.50	56.19	P	EN	NL, NL	8; 10
E. wubinensis	17988.60	50.95	P	EN	NL, NL	
E. xanthonema	22012.40	43.17	M	VU	NL, NL	2; 21

E. yarraensis	13669.70	62.81	P	EN	NL, NL	10

Table 3. Eucalypts assessed as threatened under IUCN Criterion B, C, D, D1 and D2 including Extent of occurrence (EOO), Area of Occupancy (AOO) and other relevant parameters; proposed listing under IUCN and current listing under the *Environment Protection & Biodiversity Conservation (EPBC) Act*, *1999* and relevant state legislation as Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Threatened (T) and not listed (NL). Species were listed under Category B if subject to continuing decline as CR with one location; EN 1-5 locations; or VU 6-10 locations. Species were listed under Category C where subject to continuing decline, as CR with <250 mature individuals and ≤50 in each subpopulation, EN with <2500 mature individuals and ≤250 in each subpopulation, and VU with <10 000 mature individuals and ≤1000 in each subpopulation. Species were listed under Criterion D as CR with <50 mature individuals, EN with <250 mature individuals or D1 as VU with <1000 mature individuals. Species were assessed as threatened under Criterion D2 where there was a plausible future threat that could drive the species to CR or EN in a short period of time, and an AOO of <20 km^2 or <6 locations. Species marked (*) are also listed under criterion A (Table 2).

Species	**EOO (km^2)**	**AOO (km^2)**	**Mature individuals**	**Largest sub-population**	**Accepted threats**	**Locations**	**Criteria**	**Category**	**Listing (EPBC, State)**
*E. absita**	209.03	24	208			na	D	EN	EN, CR
E. annettae	41.68	12	na		Obligate-seeder with fire	1	D2	VU	NL, NL
E. arcana	8.44	12	200-300			na	D	EN	NL, VU
E. argophloia	357.61	80	na		Recruitment	1	B	EN	VU, VU
E. articulata	224.96	8	270		Future mining	2	D1; D2	VU	VU, EN
E. aurifodina	1029.72	48	1200	<250	Urbanisation	na	C	EN	NL, NL
E. beardiana	10238.00	108	<250	20-50	Roadsides; goats (recruitment)	na	C	CR	VU, EN
E. bensonii	932.49	72	250-800			na	D1	VU	NL, NL
E. benthamii	1110.49	92	na		Dams	5	B	EN	VU, VU
E. brandiana	160.04	16	700		Obligate-seeder with fire	1	D1; D2	VU	NL, NL
E. brevipes	2950.63	44	239			na	D	EN	EN, EN
E. calcicola	22430.34	96	500			na	D1	VU	NL, NL
E. carolaniae	0.17	4	na		Urbanisation	1	B	CR	NL, T
E. cerasiformis	528.43	52	na		Active mining	6	B	VU	NL, NL

E. conferta	3.50	12	700			na	D1	VU	NL, NL
E. conglomerata	951.51	132	1100	20-50	Urbanisation	na	C	EN	EN, EN
E. crenulata	44.22	12	400-600		Dieback	1	B	CR	EN, EN
E. crucis	32457.77	232	500-999			na	D1	VU	NL, NL
E. dalveenica	4.09	0	240	50-249	Urbanisation; recruitment	na	C	CR	NL, NL
E. desmondensis	709.14	68	1000-2000	50-200	Active mining	na	C	EN	NL, NL
E. dolorosa	13.07	4	5			na	D	CR	EN, CR
E. elaeophloia	159.86	12	100-199			na	D	EN	NL, NL
E. erectifolia	1976.24	92	<100			na	D	EN	NL, NL
E. farinosa	180.28	12	na		Future mining	2	D2	VU	NL, NL
E. filiformis	647.53	4	3-10			na	D	CR	NL, NL
E. fracta	26.07	12	na		Future mining	2	D2	VU	NL, VU
E. georgei	1256.47	76	na		Active mining	7	B	VU	NL, NL
*E. halophila**	4798.35	180	<1000			na	D1	VU	NL, NL
E. imlayensis	2.92	4	5	249	Dieback	1	B; C; D	CR	EN, CR
E. impensa	1.74	12	114		Dieback	1	B	CR	EN, CR
E. infera	34.49	24	na		Active mining	1	B	VU	VU, VU
E. johnsoniana	469.84	112	647	5	Active mining	5	B; C	EN	VU, VU
E. jutsonii	181.44	44	250-999	100	Active mining	7	B; C; D	VU	NL, NL
E. kabiana	3.78	8	na		Lack of recruitment	2	B	EN	VU, VU
E. macarthurii	2204.41	168	4000-10000	>1000	Urbanisation	na	C	VU	EN, EN
E. magnificata	700.76	40	na		Active mining; recruitment	9	B	VU	NL, EN
E. mcquoidii	49.99	20	na		Obligate-seeder with fire	1	D2	VU	NL, NL
E. megacornuta	839.49	88	<1000			na	D1	VU	NL, NL
E. mitchelliana	91.74	40	<1000			na	D1	VU	NL, NL

E. molyneuxii	12.23	12	<100			na	D	EN	NL, T
*E. morrisbyi**	283.38	76	7-29	50-800	Lack of recruitment	1	C; D	CR	EN, EN
E. newbeyi	1071.40	8	na		Obligate-seeder with fire	2	D2	VU	NL, NL
E. nudicaulis	2295.16	36	600-1000	7-29	Active mining	na	C	EN	NL, NL
E. nutans	1503.43	12	na		Obligate-seeder with fire	1	D2	VU	NL, VU
*E. ornans**	0.04	8	10	100	Flood	1	B; C; D	CR	NL, NL
E. paludicola	4680.53	184	720-750	10	Recruitment	na	C	EN	EN, EN
E. petrensis	12888.14	116	1000	100	Urbanisation	na	C	EN	NL, NL
E. platydisca	194.49	16	na		Active mining	4	B	EN	VU, VU
E. praetermissa	27.50	8	na		Obligate-seeder with fire	1	D2	VU	NL, NL
E. pumila	50.37	24	400			na	D1	VU	NL, VU
E. purpurata	81.49	8	na		Active mining	1	B	CR	
E. recurva	527.23	32	6	250	Active mining	na	C; D	CR	CR, CR
E. relicta	225.24	8	<500			na	D1	VU	NL, NL
E. rhomboidea	95.50	24	na		Active mining	4	B	EN	NL, NL
E. rugulata	277.32	24	na		Active mining	3	B	EN	NL, NL
E. semota	6639.78	12	na		Future mining	3	D2	VU	NL, NL
*E. splendens**	47.05	28	na		Roadsides	5	B	EN	NL, NL
E. steedmanii	702.68	60	na		Active mining	6	B	VU	VU, VU
E. stoatei	878.00	28	1000-2000	6	Active mining	3	B; C	EN	NL, NL
E. suberea	727.84	76	274			na	D1	VU	VU, VU
E. synandra	18171.16	88	1060	249	Active mining	na	C	EN	VU, VU
*E. vesiculosa**	104.62	8	na		Obligate-seeder with fire	1	D2	VU	NL, NL
E. virginea	2834.96	8	<1000			na	D1	VU	NL, NL

E. walshii	28.11	12	36		na	D	CR	NL, NL
E. yarriambiack	8.72	16	na	Roadsides	1	B	CR	NL, T

Table 4. Species listed under the Environment Protection & Biodiversity Conservation (EPBC) Act, 1999, their Extent of occurrence (EOO), Area of Occupancy (AOO), other relevant parameters and listing under Australian state legislation (CR, Critically Endangered; EN, Endangered; VU, Vulnerable) that do not qualify as threatened in this assessment. Threats listed within conservation advice, listing advice or recovery plans were reviewed for each assessment. The locations were assessed in relation to accepted threats.

Species	EOO (km^2)	AOO (km^2)	Accepted threats	Locations	Mature individuals	Putative threats	EPBC listing	State listing
A. inopina	1886.4	148	Urbanisation	26	>10000	Weeds, too-frequent fire, urbanisation	VU	VU
A. robur	1811.1	108			>10000	Roads/ utilities, agriculture, timber harvesting	VU	VU
C. clandestina	232.2	48	Future mining	9	2000-5000	Mining, grazing	VU	VU
C. leptoloma	436.8	32	Historic mining; Future mining	6	>10000	Mining, agriculture, grazing	VU	VU
C. petalophylla	1893.3	100			>10000	No documentation available		VU
C. rhodops	349.2	104	Active mining	19	>10000	Mining	VU	VU
C. xanthope	8106.8	116	Active mining	13	>10000	Mining, roads/ utilities	VU	VU
E. approximans	47.21	24			2500-5000	Too-frequent fire, agriculture		VU
E. argutifolia	9832.4	84	Active mining; urbanisation	13	19704	Small population (<1000), mining, roads/ utilities, weeds, agriculture, grazing	VU	VU
E. beaniana	7995.2	68			>10000	Roads/ utilities, timber harvesting	VU	VU
E. boliviana	2.7	12			1000-2000	No documentation available		VU
E. broviniensis	36.6	16			1020	No documentation available		EN

E. burdettiana	106.3	12			3500	Restricted range, roads/ utilities, too-frequent fire	EN	EN
E. ceracea	209.4	36			>10000	Restricted range, mining, too-frequent fire	VU	VU
E. coronata	675.1	24			7510	Small population (<250), roads/ utilities, too-frequent fire, climate change, phytophthora	VU	EN
E. corticosa	421.6	52			>1000	Restricted range, roads/ utilities, too-frequent fire, agriculture		VU
E. dunnii	14127.0	164			>82000	No documentation available		VU
E. hallii	743.6	136			>10000	Urbanisation, agriculture, timber harvesting	VU	VU
E. insularis	1988.4	44			1500	Restricted range, too-frequent fire,	EN	
E. langleyi	535.4	60			>10000	Roads/utilities, weeds, too-frequent fire	VU	VU
E. largeana	3616.9	124			>2000	Weeds, agriculture, grazing	EN	EN
E. macarthurii	2204.4	168	Urbanisation	protected	4000-10000	Weeds, agriculture, grazing	EN	EN
E. mooreana	1997.8	68			1000	Small population (<1000), too-frequent fire, grazing	VU	VU
E. pachycalyx	130886.3	276			>10000	Restricted range, roads/utilities, too-frequent fire		EN
E. parvula	1219.9	168			>2000	Roads/utilities, weeds, grazing, seed collection	VU	EN

E. pulverulenta	14162.2	164			5400	Restricted range, mining, roads/utilities, weeds, grazing, seed collection	VU	VU
E. saxatilis	856.5	80			2400	Restricted range, grazing		EN
E. scoparia	177.2	72			>10000	Restricted range, too-frequent fire, agriculture, timber harvesting, grazing	VU	VU/ EN
E. sicilifolia	113.0	40			>2000	No documentation available		VU
E. sturgissiana	312.6	88			1198	Restricted range, roads/utilities, too-frequent fire		VU
E. taurina	666.9	60	Active mining	13	>10000			VU
E. tetrapleura	2329.6	168			>2000	Roads/utilities, weeds, agriculture, timber harvesting, grazing	VU	VU
E. virens	66968.4	96			1000-3000	Agriculture, timber harvesting	VU	VU

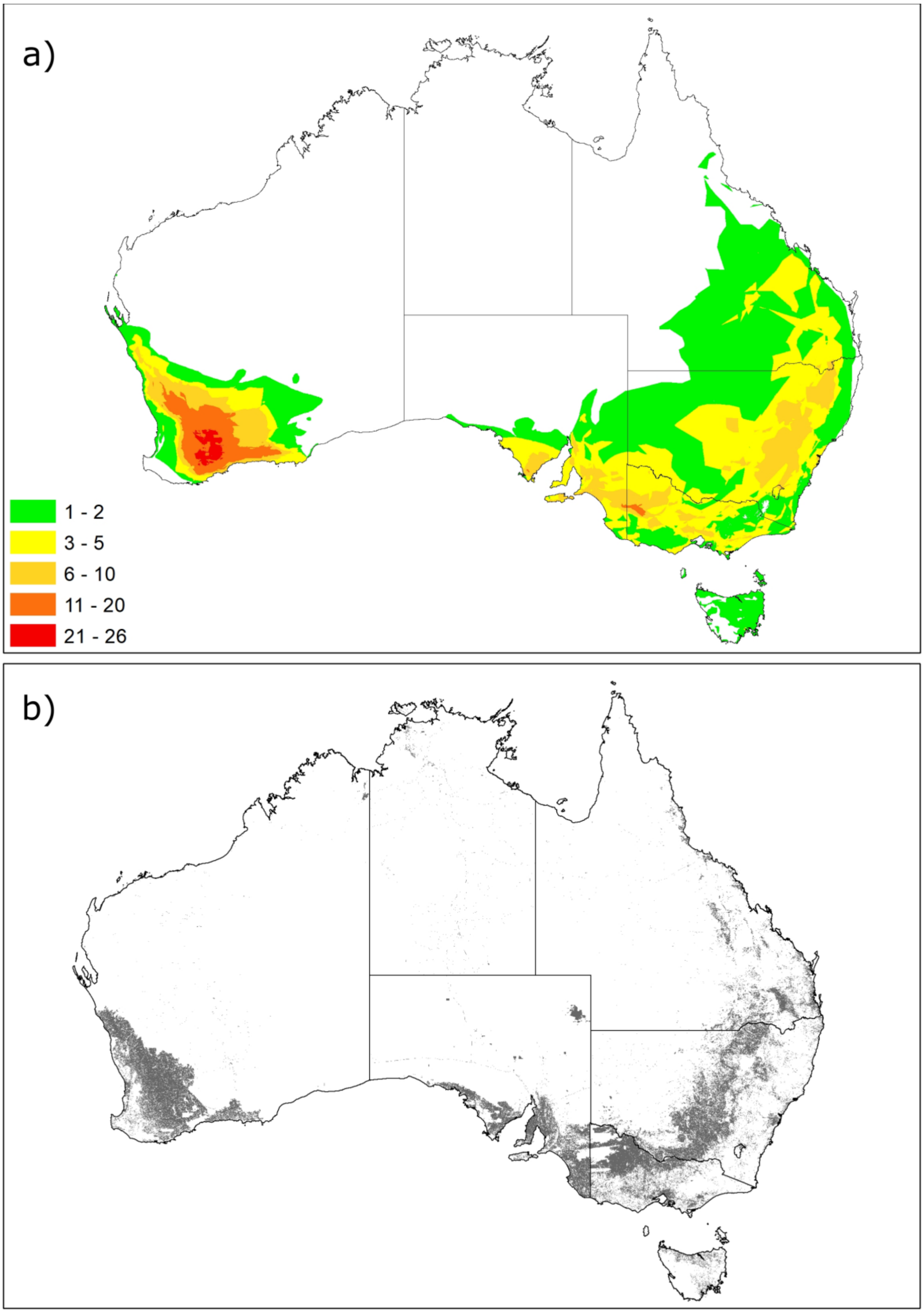

Figure 1. a) Threatened species richness for eucalypts (CR, EN, VU) listed under category A; and b) ‘unambiguous deforestation’ (dark grey) due to intensive land-use. Note there is also deforestation in other areas (see Methods).

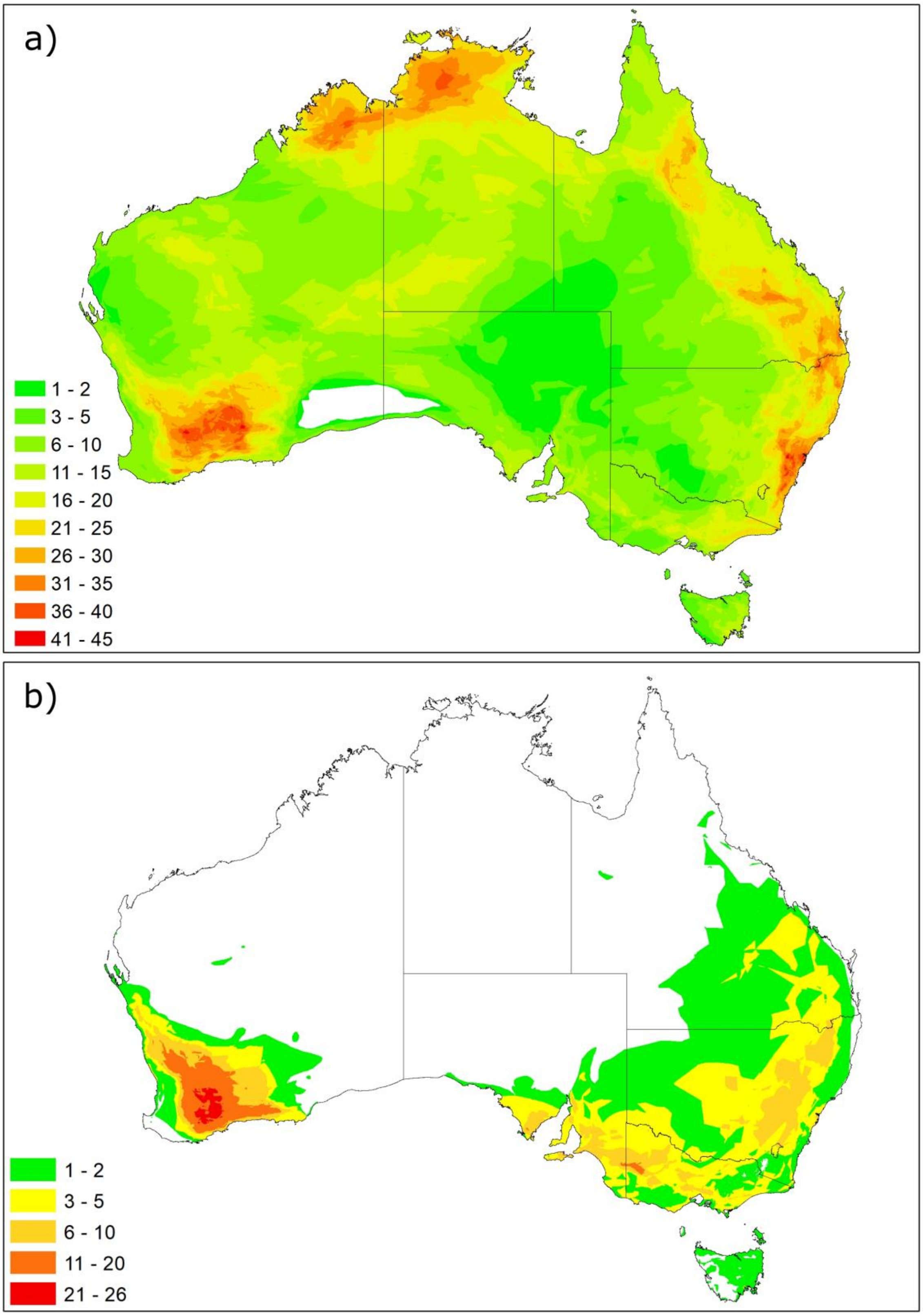

Figure 2. a) Distribution of eucalypt species richness; b) Density of threatened eucalypt species (CR, EN, VU) proposed here for listing under all Red List categories.

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