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Assessing the conservation status of tree species declining in productive landscapes. The case of *Eucalyptus argophloia*

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Running title: Rare *Eucalyptus argophloia*

Summary text

Eucalyptus argophloia is a rare tree species from a sub-humid climate that occurs in three vegetation types mostly on fertile soils. Based on the decline in habitat with land-use conversion to crops and pasture it is estimated that the population has been reduced by 94.2%. Paddock trees may not be replaced as there is very little regeneration of the species including on ungrazed roadsides and further decline of the species is expected. The species can be categorised under IUCN Red Listing criteria as Critically Endangered.

Abstract

Eucalyptus argophloia is a species with a small geographic range occurring in a productive landscape with a sub-humid climate. The past distribution of the species was assessed from remnant vegetation and standing paddock trees. The species grows in three specific vegetation types within its geographic range and based on densities in remnant vegetation and reduction of habitat it is estimated that the population has been reduced by 94.2%. There is very little regeneration of the species including on ungrazed roadsides and further decline of the species is expected. The species can be categorised under IUCN Red Listing criteria as Critically Endangered. The study provides a method for using habitat association, population decline and stand structure for conservation assessment of threatened tree species in productive landscapes.

Introduction

Understanding the relationship between rarity and extinction risk is fundamental to the conservation of biodiversity. Rarity can predispose species to threats and stochastic events, particularly if a narrow geographic distribution, small local population size, and habitat specificity coincides with threatening processes (Mace and Kershaw 1997). Formal assessment of a species' conservation status integrates the concepts of rarity and endangerment by considering both inherent demographic characteristics and perceived level of threat or evidence of population decline (Mace *et al.* 2008). A recent rapid assessment of the conservation status of eucalypts used IUCN Red Listing procedures (Fensham *et al.* 2020). One of the conclusions of the study was that more detailed assessments of some *Eucalyptus* species are required, particularly in the landscapes that have been cleared and where remnants are subject to intensive livestock grazing. In these situations the assessment of decline may have been underestimated given the preferential clearing of some soil types within the geographic range of a species and the conservative estimate of deforestation that has been applied (Fensham *et al.* 1998). Furthermore there is evidence that the regeneration of eucalypts may be suppressed by grazing (Dorrough and Moxham 2005; Weinberg *et al.* 2011). Under Red Listing criteria A2, a species would be Critically Endangered if its population had undergone irreversible decline by more than 80% in three generations. This is threshold is foreseeable for a long-lived tree, such as a eucalypt, that has undergone extensive decline on productive soils that have been substantially cleared for agriculture.

The current study aims to assess the population of *Eucalyptus argophloia* to determine population density in remnant vegetation and whether the species is regenerating, both in grazed habitat and ungrazed roadsides. The habitat association of *E. argophloia* will be determined by comparing the floristics of areas with and without *E. argophloia*, and also the association of standing paddock trees with soil and vegetation patterns. This will allow mapping of the former habitat for *E. argophloia* and the history of habitat decline will be determined by mapping remnant vegetation. This information will be incorporated to perform a detailed Red List assessment and recommendations for further actions to recover *E. argophloia*.

Methods

Study species

Chinchilla white gum (*Eucalyptus argophloia*) only occurs in a restricted area north of Chinchilla in the sub-tropical climate of south-east Queensland (Fig. 1). *E. argophloia* grows to 30 m (Fig. 1), the tallest tree in the rainfall zone (mean annual rainfall 675 mm). Eucalypts in sub-humid environments exhibit fairly consistent growth rates of about 2 mm per annum (Ngugi and Botkin 2011) indicating a tree of 50 cm diameter at breast height is 250 years of age. The extent of population decline is determined over three generation lengths using IUCN criteria. Generation length is the average age of the parents of the current cohort (IUCN Standards and Petitions Committee 2019) and is assumed to be greater than 70 years for *E. argophloia* (Fensham *et al.* 2020). *E. argophloia* is lignotuberous which confers some fire tolerance (Fensham *et al.* 2020).

Eucalyptus argophloia was considered to have a promise as a timber species for sub-humid climates and 5000 ha of plantations have been established (Lee *et al.* 2011). While growth rates and tree form have not proved adequate for commercial timber production (Lee *et al.* 2011) the species is far more extensive in plantations than in the wild. The wild populations mostly occur on Freehold land and its habitat has been extensively cleared for pasture and crops. Most of this clearing occurred prior to the earliest aerial photography from 1945. A conservative assessment of deforestation suggests that the population has declined by only 44% (Fensham *et al.* 2020). This represents a VU status under criterion A2. However, the final proposed status of *E. argophloia* is EN under criterion B1 because of ongoing decline as a result of an observed lack of regeneration and a limited geographic range (Fensham *et al.* 2020).

Field methods

While many populations have been fragmented and diminished by clearing, *Eucalyptus argophloia* has been left as a shade tree and the remaining paddock trees were mapped using binoculars with all areas visible within 1.2 km of the roads. The presence of *E. argophloia* was recorded in each area of remnant vegetation using either binoculars or field inspection. The occurrence of paddock trees and remnants with *E. argophloia* were included in convex polygons circumscribing the geographic range of the species (Fig. 2). Herbarium records and discussions with local landholders provided no accurate locations that could be used to expand the historical geographic range. However, *E. argophloia* has almost certainly been cleared for cropping in areas beyond the current distribution. The species does not occur along active drainage lines and these were excluded from the polygons. Within these areas, five general vegetation types were discerned and soils were sampled from each of the vegetation types. A sample was taken from each remnant patch and also from the intersections of a 1.2 km grid where the vegetation type could be discerned by remaining paddock trees and the microtopography. A surface sample was taken from a sub-sample of three bulked samples at a sampling point. Depth to clay (light clay - heavy clay; McDonald *et al.* 1998) was determined by augering to a maximum depth of 50 cm. Soil samples were analysed for soil texture using 16 textural grades from sand – heavy clay (McDonald *et al.* 1998), pH and conductivity using a TPS Aqua W-2821 meter.

Mapping and analytical methods

The original extent of the vegetation types in the geographic range of *E. argophloia* were mapped using 1945 and 1951 historical aerial photography, ground-truthing with remnant vegetation, microtopography and regrowth trees after clearing. The final map was produced from 833 field observations with the average distance between observations 169 m, and no pair of observations more than 1156 m apart. The association of the vegetation types with the soil variables: surface soil texture, depth to clay, surface soil pH and conductivity were graphically prepared. After assessing for homozygosity, differences in the soil variables in relation to vegetation type were examined using a one-way ANOVA with Tukey's test to compare individual means. Depth to clay was skewed with many zero values and values set at 50 cm for sites where clay was not reached. Because the low and high values provided a homoscedastic distribution parametric testing was not precluded and a one-way ANOVA was also used to test for differences in soil variables with and without *Eucalyptus argophloia* within each of the three vegetation types where it occurs.

The geographic range of *Eucalyptus argophloia* was spatially associated with six identified vegetation types. For the three vegetation types where *E. argophloia* occurred, 34 quadrats were randomly located in separate remnants for floristics, stand structure and *E. argophloia* density. The sites included some sites without *E. argophloia*. All trees were identified and measured for diameter at 1.2 m H along a 50 m long quadrat. *E. argophloia* were measured in a 20 m-wide plot and all other species were measured in a 10-m wide quadrat. Individuals less than 1.2 m H were counted. For multi-stemmed plants the surface area of each stem was summed and back-transformed to a single DBH for further analysis.

An ordination of the presence-absence tree species data was conducted using non-metric multi-dimensional scaling. This was conducted to examine the discrimination between habitats with and without *Eucalyptus argophloia* which was excluded from the analysis. Stand structure was assessed to identify the presence of young trees as an indicator of regeneration. Population densities of *E. argophloia* for the three vegetation types where it occurs were determined from the individual plots where this species occurred.

In order to assess the impact of livestock grazing on *Eucalyptus argophloia*, ten roadside plots (ungrazed) were paired with ten paddock plots (grazed). Each plot was 50 m × 10 m and plots were 10 m apart with 25 m between the pairs in the ungrazed and grazed treatment. In each plot the identity of the trees was determined and the diameter of all trees measured and the height of trees less than 1.2 m H measured.

Remnant habitat was mapped on available imagery from 2019 to document habitat decline within the geographic range of *Eucalyptus argophloia*. For each vegetation type the population size of *E. argophloia* was determined by multiplying the average density of *E. argohophloia* in the transects where it occurred by the combined area of the remnants where *E. argophloia* occurred. Standing paddock trees outside the remnants were tallied separately. The historical population sizes before clearing was calculated assuming the original vegetation had the same proportion of occurrence as the current remnants and also the same density. An assessment of threat status according to IUCN Red List criteria (IUCN 2012) was conducted following guidelines in IUCN Standards and Petitions Subcommittee (2019). Decline is assessed over three generations (3 × 70 years) which includes the span of European settlement.

Results

Eucalyptus argophloia occurs in six discrete areas separated by active streams, with a combined geographic range of 201.4 km^2 although 88.2% of the total range is in one polygon (Fig. 2). The Extent of occurrence of *E. argopophloia* is 432.5 km^2 and the Area of occupancy 256.0 km^2. Within these areas the following vegetation types were mapped: 1)

Callitris glaucophylla and/or *Eucalyptus chloroclada* forest on plains; 2) *Melaleuca squamophloia* forest on plains; 3) *Acacia harpophylla* and/or *Casuarina cristata* on plains without gilgai; 4) *Acacia harpophylla* forest on plains with gilgai microtopography; 5) mixed forest (*Eucalyptus tereticornis* and/or *E. woolsiana* and/or *E. populnea* and/or *Angophora leiocarpa* and/or *A. floribunda*) on alluvium. *E. argophloia* was present in types 3, 4 and 5 and absent or extremely rare in types 1 and 2 (Table 1).

Callitris glaucophylla and/or *Eucalyptus chloroclada* forest on plains occurred on soils with a median value of 1 (sand) (Fig. 3). Mixed forest on alluvium, and *Melaleuca squamophloia* forest on plains had intermediate surface texture soils with median value of 8 (clay loam). These differences in surface texture were mostly reflected in the depth to clay although *Melaleuca squamophloia* forest on plains has shallower depth to clay than mixed forest on alluvium (Fig. 3). *Acacia harpophylla* and/or *Casuarina cristata* on plains without gilgai had surface soils with median values of 11 (sandy clay). The soils of these vegetation types varied with *Acacia harpophylla* forest on plains with gilgai microtopography having the heaviest textured surface soil with a median value of 14 (light clay). The vegetation types could not be discriminated on the basis of soil pH (mostly 6-7) or conductivity (40-70 $\mu S\ cm^{-2}$). There were no significant differences in any soil variable for sites with and without *E. argophloia* for any of the three vegetation types where it occurs ($P>0.05$).

The floristics of the vegetation types where *Eucalyptus argophloia* occurs indicate a clear distinction between *Callitris glaucophylla* and/or *Eucalyptus chloroclada* forest on plains and the two other vegetation types supporting *E. argophloia* (*Acacia harpophylla* and/or *Casuarina cristata* on plains without gilgai and *Melaleuca squamophloia* forest on plains) (Fig. 4). The floristics of the latter two vegetation types are poorly distinguished (Fig. 4). The sites with *E. argophloia* are not clearly distinguished from the sites without *E. argophloia* in any of the three vegetation types where it occurs (Fig. 4).

Only 8.2% of 280 *Eucalyptus argophloia* individuals were ≤10 cm dbh in the remnant vegetation (Fig. 5 and Fig. 6) and none were observed in the paddocks. This contrasted with the stand structure of other tree species such as *Casuarina cristata, Geijera parviflora, Melaleuca squamophloia, Acacia harpophylla* and *Eremophila mitchellii* that were well represented in the small size classes. There was no small-sized *E. argophloia* in either the roadside or the paired grazed paddock despite small-size classes in other species (Fig. 6).

Of the three vegetation types supporting *Eucalyptus argophloia, Acacia harpophylla* and/or *Casuarina cristata* on plains was the most extensive and has been most extensively cleared (Table 1). Overall it is estimated that the population has declined by 94.2% to an estimated 31,722 trees. Of these 2,178 are live paddock trees amongst dead trees without any regeneration. Only 80 ha of remaining habitat (estimated 5,340 trees) is in two tiny conservation reserves and the future of the populations in remnants is uncertain given the lack of regeneration.

The species qualifies as Critically Endangered under criterion A2 because of past irreversible decline within three generations (see Fensham *et al.* 2020). The population has declined by an estimated 94.5% as assessed as a decline in habitat quality as remnant vegetation has been converted to pasture and crops. *Eucalyptus argophloia* also qualifies as Endangered under criteria B1 because of a limited EOO (432.5 km^2), AOO (256.0 km^2) and ongoing decline with loss of paddock trees and potential ongoing decline in remnant vegetation given a lack of regeneration.

Discussion

Eucalyptus argophloia occurs in six areas in a flat landscape dissected by active streams, the largest of which is only 177.6 km^2. It does not occur on the floodplain of these active streams (Fig. 1). Within the flat landscapes between the streams, *E. argophloia* occurs in three out of the six vegetation types within its range (Table 1). It does not occur on the clay soils that support brigalow and form a gilgai landform, but does occur in the slightly lighter clay soils that also support *Acacia harpophylla* and *Casuarina cristata* without gilgai landforms. *E. argophloia* also occurs on sand sheets in association with *Callitris glaucophylla* and *Eucalyptus chloroclada.* Clearly *E. argophloia* is not associated with heavy clay surface soils, but it also does not occur in flooded areas (without stream channels) despite medium-textured (loams-clay loams) soils that are suitable outside the flooded area. It does occur in association with forest composed of dense mono-specific thickets of *Melaleuca squamophloia* with medium-textured surface soils. On the edges of the thickets the *Melaleuca* grades into brigalow and it was these marginal habitats that were preferred by *E. argophloia*. Within all the vegetation types where *E. argophloia* occurs it may also be absent (Table 1).

Eucalyptus argophloia occurs in a productive landscape that that has been extensively cleared for pasture and crops. The population has declined from approximately 540,321 individuals to 29,608 individuals (5.8%) including paddock trees and 27,444 (5.1%) including individuals in remnants only. Broadscale vegetation clearance has slowed recently in Queensland as a result of state legislation (Evans 2016) but the clearing of remnant vegetation has not ceased altogether (Maron *et al.* 2015). Only 0.8% of the original habitat is in two small conservation reserve (Fig. 2).

There is hardly any regeneration of *E. argophloia* with only 7.7% of all measured trees less than 10 cm dbh. Several mechanisms may be at play. Young trees may be excluded by browsing as has been demonstrated for other eucalypts in areas intensively grazed by livestock (Dorrough and Moxham 2005; Fischer *et al.* 2009; Weinberg *et al.* 2011). However, there is also a lack of regeneration on the roadsides, which are not grazed by domestic livestock but are grazed by high densities of swamp wallabies (*Wallabia bicolor*), red-necked wallabies (*Macropus rufogriseus*) and grey kangaroos (*Macropus giganteus*). *Eucalyptus chloroclada* and *Callitris glauchopylla* were the other species lacking small plants (Fig. 5) and the grazing sensitivity of the latter has been demonstrated previously (Spooner *et al.* 2002; Allcock and Hik 2004). Many eucalypts germinate more readily in an ashbed (Henry and Florence 1966; Burrows *et al.* 1990) and it has been suggested that a lack of fire may be an important reason why *Eucalyptus tricarpa* is not regenerating despite grazing relief in temperate regions (Orscheg *et al.* 2011). A longterm landholder verified that there has been a lack of fire throughout this district for more than 50 years (Betty Walsby pers. comm.). However, evidence for *Eucalyptus melanophloia*, a species with a geographic range overlapping with *E. argophloia*, suggests that fire is not crucial for germination and regeneration. A rare germination event for *E. melanophloia* coincided with high rainfall during the 2010/2011 summer (Fensham *et al.* 2017). For this species germination occurred with and without burning. The wet season between September 2010 and March 2011 had similar rainfall at Chinchilla (904 mm) compared to the site of the *E. melanophloia* study (931 mm) but if regeneration of *E. argophloia* occurred during this wet summer the seedlings did not survive. The reason for the lack of regeneration for *E. argophloia* could be further elucidated with monitoring and a burning trial coinciding with high rainfall. In the meantime the most likely factor inhibiting regeneration is browsing by livestock and macropods.

The assessment of *Eucalyptus argophloia* under Red Listing criteria indicates that it is Critically Endangered under criteria A2 because it has declined by more than 80% within three generations. Declines are highly likely to continue into the future without regeneration and ongoing death of old trees. *E. argophloia,* together with *E. carolaniae, E. crenulata, E. dalveenica, E. morrisbyi, E. ornans, E. purpurata* and *E. yarriambiack* have all been extensively cleared on productive soils and are the only eucalypt species identified as Critically Endangered (Fensham *et al.* 2020). Of these species *E. argophloia* has the largest geographic range. The recent conservation assessment of all eucalypts (Fensham *et al.* 2020) mostly used herbarium specimen records to estimate geographic range and estimated decline based on an intersection of geographic range and land-use with conservative decision rules to determine deforestation. This rapid assessment for *E. argophloia* indicated an EOO of 358 km^2, a AOO of 80 km^2, a geographic range of 254 km^2, and estimate of population decline as 44%. The detailed assessment of *E. argophloia* conducted here expanded the EOO to 432.5 km^2 and the AOO to 256.0 km^2, diminished the geographic range to 199 km^2 and revised the estimate of population decline to 95%. The more detailed survey of *E. argophloia* verifies that the broadscale Red Listing assessment may have underestimated decline under category A (Fensham *et al.* 2020). The underestimation of population decline for *E. argophloia* could be the result of the low threshold for deforestation (<5% cover) in land-use categories that are ambiguously deforested and preferential clearing of habitat on productive soils compared to the overall rate of deforestation in a geographic range.

The study provides guidance for the use of habitat association, population decline and stand structure for conservation assessment of threatened plant species in productive landscapes that have been extensively cleared. It verifies that detailed surveys can reveal unexpectedly high population estimates of rare plants (Fensham *et al.* 2019) and vindicates the use of criterion A as a reflection of extinction risk. *E. argophloia* is one of the most imperilled eucalypts in its natural habitat.

Acknowledgments

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Conflict of Interest Statement

The authors declare no conflicts of interest

Table 1. Information on vegetation and *Eucalyptus argophloia* populations within the geographic range of *E. argophloia*, including the three vegetation types that support substantial populations of *E. argophloia* and the two vegetation types that only rarely support the species.

Vegetation type	Original area (ha)	Remnant area (ha)	Percentage remaining	Paddock trees	Proportion of remnants with *E. argophloia*. (n)	Density of *E. argophloia* (ha^{-1})	Estimated original population	Estimated current population including paddock trees (% of original)
Callitris glaucophylla and/or *Eucalyptus chloroclada* forest on plains	1209.1	328.11	27.14	156	72.10 (29)	43.5	37947	10454 (27.55)
Acacia harpophylla and/or *Casuarina cristata* on plains	7372.4	96.57	1.31	1298	38.01 (24)	81.4	228182	4287 (1.88)
Melaleuca squamophloia forest on plains	1535.5	124.35	8.1	724	89.18 (33)	122	167063	14253 (8.53)
Total	10117	549.03	5.43	2178	71.17 (86)	75.6	544408	31722 (5.83)

Eucalyptus tereticornis and/or *E. populnea* and/or *E. woolsiana* and/or *Angophora leiocarpa* and/or *A. floribunda* forest on alluvium	2071	302.05	14.58	4	NA	NA	NA	NA
Acacia harpophylla forest on plains with gilgai microtopography	7954	49.32	0.62	16	NA	NA	NA	NA
Total	10025	351.37	3.5	20	NA	NA	NA	NA

Figure captions

Figure 1. Large (left) and small (right) *Eucalyptus argophloia* paddock trees in front of a remnant dominated by *Acacia harpophylla* with emergent *E. argophloia*.

Figure 2. Locality map with five areas marked by thick black lines showing the geographic range of *E. argophloia.* Conservation Reserves are shaded.

Figure 3. Box plots representing soil variables, a) Depth to clay (cm); b) Surface soil texture (16 textural grades from sand – heavy clay); c) soil pH, d) soil conductivity (µS cm^{-2}), for the five vegetation types in the geographic range of *E. argophloia.* E, mixed forest (*Eucalyptus tereticornis* and/or *E. woolsiana* and/or *E. populnea* and/or *Angophora leiocarpa* and/or *A. floribunda*) on alluvium; G, *Acacia harpophylla* forest on plains with gilgai microtopography; A, *Acacia harpophylla* and/or *Casuarina cristata* on plains without gilgai; M, *Melaleuca squamophloia* forest on plains; C, *Callitris glaucophylla* and/or *Eucalyptus chloroclada* forest on plains. For depth to clay all pairs are significantly different (P<0.05) except G and A; for surface soil texture all pairs are significantly different except for E and M. There are no significant differences between pairs for soil pH and soil conductivity.

Figure 4. Non-metric multi-dimensional scaling ordination of tree and shrub presence-absence excluding *Eucalyptus argophloia. Acacia harpophylla* and/or *Casuarina cristata* on plains without gilgai (squares); *Melaleuca squamophloia* forest on plains (triangles); *Callitris glaucophylla* and/or *Eucalyptus chloroclada* forest on plains (circles); sites with *E. argophloia* (closed symbols); sites without *E. argophloia* (open symbols).

Figure 5. Mean (and standard error) densities of stems according to size class of eight tree species (present in more than six sites with at least three individuals). The number of stems in the less than or equal to 1 cm class for *Acacia harpophylla* is indicated. Species are ordered from most frequent to least frequent sites (*Eucalyptus argophloia* = 16 sites, 151 individuals; *Callitris glaucophylla* = 11 sites, 294 individuals; *Casuarina cristata* = 9 sites, 100 individuals; *Geijera parviflora* = 9 sites, 67 individuals; *Melaleuca squamophloia* = 8 sites, 124 individuals; *Acacia harpophylla* = 6 sites, 314 individuals; *Eremophila mitchellii* = 6 sites, 169 individuals; *Eucalyptus chloroclada* = 6 sites, 36 individuals).

Figure 6. Stand structure in ungrazed roadside (left) and grazed paddock (right).

Figure 1

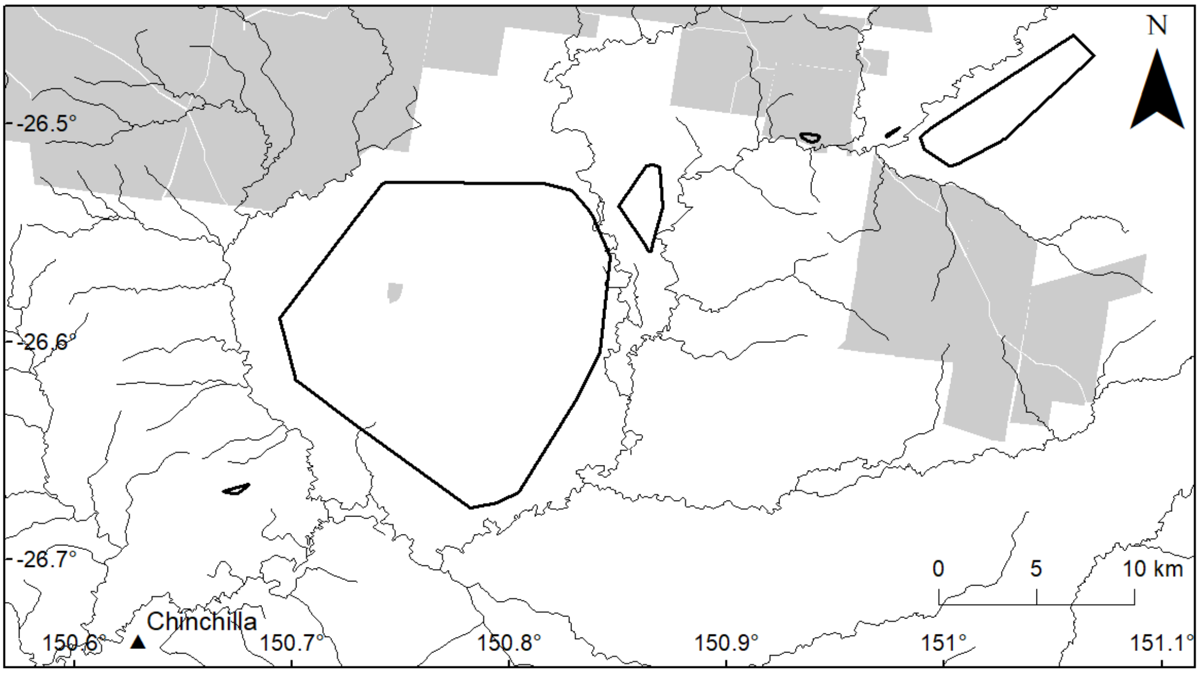

Figure 2

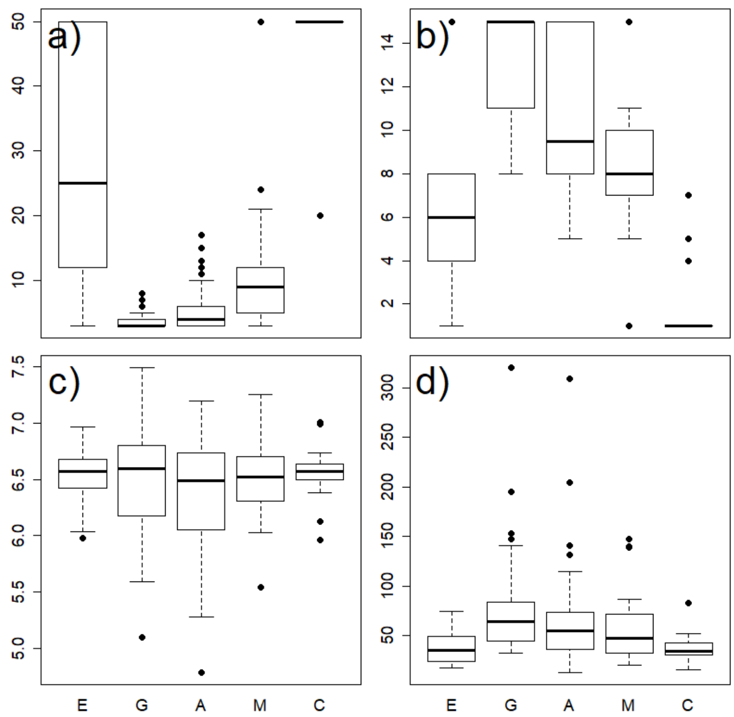
a)
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Figure 3

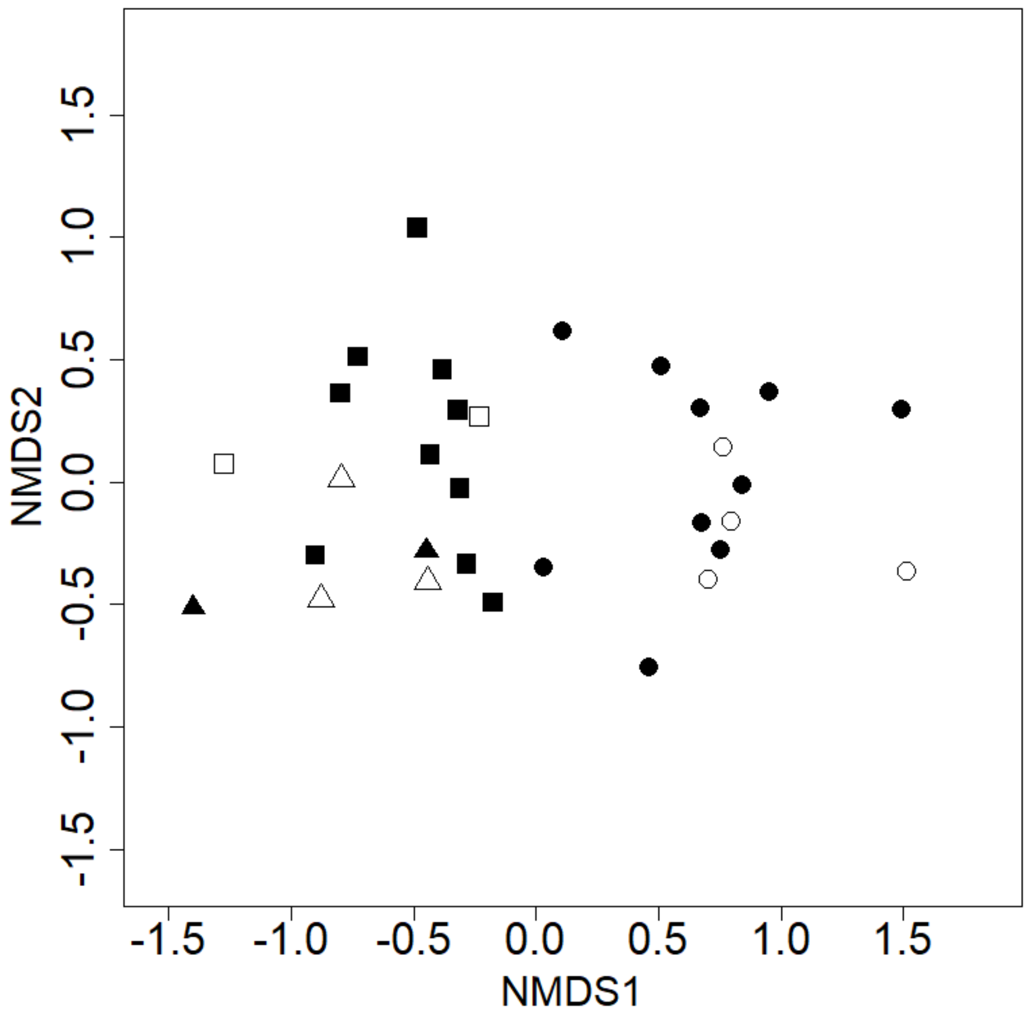

Figure 4

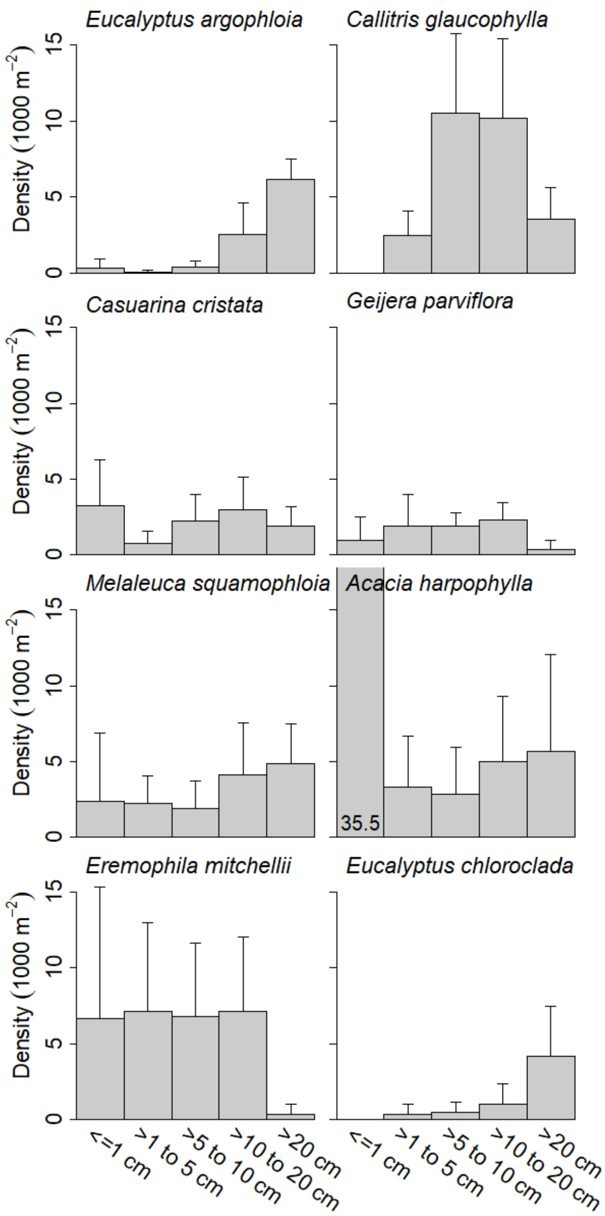
Eucalyptus argophloia
Callitris glaucophylla
Casuarina cristata
Geijera parviflora
Melaleuca squamophloia
Acacia harpophylla
Eremophila mitchellii
Eucalyptus chloroclada
Density (1000 m⁻²)
0
5
10
15
35.5
<=1 cm
>1 to 5 cm
>5 to 10 cm
>10 to 20 cm
>20 cm

Figure 5

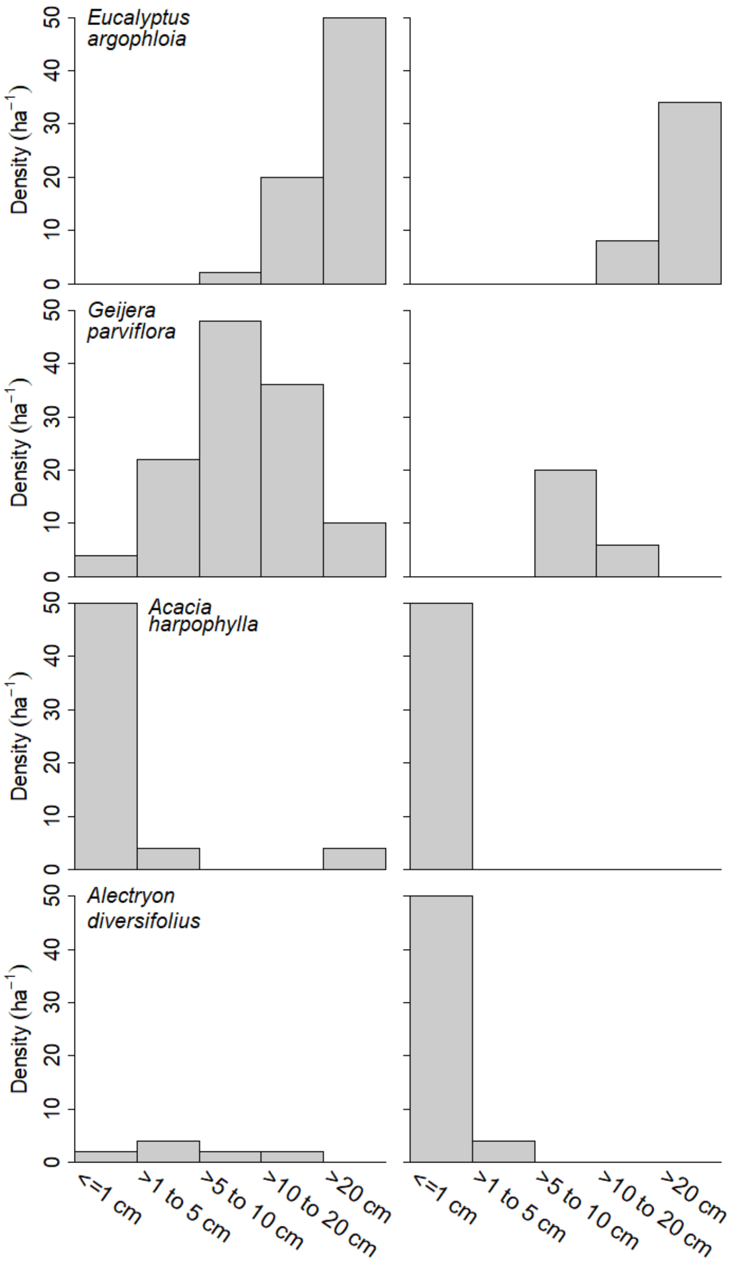

Figure 6

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