The Eucalypts of Northern Australia:

An Assessment of the Conservation Status of Taxa and Communities

A report to the Environment Centre NT, January 2014.

Donald C. Franklin[1] and Noel D. Preece[2]

[1] Ecological Communications, 24 Broadway, Herberton Qld 4887, Australia
[2] Biome5 Pty Ltd, PO Box 1200, Atherton, Qld 4883, Australia

All photographs are by Don Franklin.

Suggested citation: Franklin DC & Preece ND. 2014. *The Eucalypts of Northern Australia: An Assessment of the Conservation Status of Taxa and Communities*. A report to Kimberley to Cape and the Environment Centre NT, April 2014.

Yellowjacket (also known as Scarlet Gum) (*Eucalyptus phoenicea*): foliage and flowers (left); savanna on elevated sandstone near Timber Creek, Northern Territory (below).

EXECUTIVE SUMMARY

1. We investigated the conservation status of the eucalypt taxa and communities of northern Australia including identification of regions of high species richness and biogeographic note. We did so using records from Australia's Virtual Herbarium (almost 52,000 records) covering the entire range of taxa recorded in our study area, shapefiles of Map Units from The Vegetation of the Australian Tropical Savannas and of the National Vegetation Information System, shapefiles of land clearing and of crown and private conservation reserves, the literature and a miscellany of other sources. We defined northern Australia as the tropical savanna region plus the embedded Wet Tropics and Central Queensland Coast bioregions.

2. The eucalypt flora of northern Australia comprises 188 species and 38 subspecies (includes one variety) (Chapter 3). All three eucalypt genera are represented, with *Eucalyptus* being most speciose and *Angophora* of marginal occurrence in the study area. *Eucalyptus* is predominant in eastern Queensland and *Corymbia* in the northern Top End of the Northern Territory. Of these, 105 species and 22 subspecies are strictly endemic to the study area and a further 24 species and 3 subspecies nearly so. Seven species are shared with New Guinea or the Islands of Wallacea to Australia's north. Species richness is greatest in the central and northern Kimberley, the northern Top End and eastern Queensland, with a peak richness of 46 species in the one degree cell covering the Atherton Tableland and adjacent western slopes of north Queensland. Species richness is markedly lower in inland areas but interpretation of the magnitude of this effect is somewhat confounded by reduced collection effort.

3. Biogeographic analysis showed strong regional patterning with a strong shift in species composition between Queensland east of the Gulf of Carpentaria and areas to the west that is consistent with biogeographic patterns identified among plants and animals in general (Chapter 4). We identified 12 regional groups of taxa with many groups exhibiting high levels of regional endemicity, an analysis that adds substantially to previous biogeographic interpretations of northern Australia.

4. We developed hierarchically-ranked metrics of restrictedness based on a combination of Extent of Occurrence, the number of degree cells, and the number of records of each taxon, with thresholds derived from IUCN criteria for Extent of Occurrence (Chapter 5). Sixteen species and seven subspecies were rated as *extremely restricted* (rank 1), while 125 species and 21 subspecies were rated as *not at all restricted* (rank 5). The greatest concentrations of *extremely restricted* taxa are in the central and north Kimberley and in the White Mountains area south-west of Charters Towers in Queensland. Restricted taxa (i.e. all except rank 5) are widespread in the central and north Kimberley, the Top End centred on the Arnhem Plateau, and in and around the Einasleigh Uplands of north Queensland.

5. Applying IUCN criteria, we assessed 19 north Australian eucalypt taxa as Threatened (three as Endangered, 16 as Vulnerable), and an additional nine as Near Threatened and two as Data Deficient (Chapter 5). Seventeen of these assessments were based solely on decline due to clearing (criterion A2b), four were rated on the basis of a combination of rarity and decline due to clearing (criteria B1a,b(ii,v) and B2a,b(ii,v)), and nine taxa were rated on the basis of extreme rarity alone (criteria D1 and/or D2). Taxa we rated as Threatened are strongly concentrated in eastern Queensland. Our ratings differ markedly from official listings of Threatened taxa, with the latter seriously under-representing the level of threat but also rating a number of taxa as Threatened which clearly are not.

6. Seventy-two of 125 Map Units (communities) in northern Australia are characterised as primarily dominated by eucalypts and a further 12 feature eucalypts as secondary dominants (Chapter 6). Combined, these units cover 69% of the tropical savanna portion of the study area (i.e. Wet Tropics and Central Queensland Coast bioregions excluded).

7. In the study area, reserves are strongly concentrated in the higher rainfall regions of the north-west and along sections of the Queensland coast especially on Cape York Peninsula and in the Wet Tropics (Chapter 5). There is considerable complementarity between crown and private reserves in their coverage of taxa

and communities (Chapters 5 & 6). Eleven species and three subspecies endemic to the study area do not occur in either a crown or private nature reserve, and a further 52 endemic species and ten endemic subspecies have reservation indices of less than 30%. Twelve of 84 eucalypt Map Units are not represented in any crown or private conservation reserve, while a further 40 of these Map Units are poorly represented with less than 10% of their area (and often less than 1%) in conservation reserves.

8. Land-clearing is strongly concentrated in the south-east of the study area and also along the Queensland coast north to the Wet Tropics (Chapter 5). Targeted assessment of taxa demonstrated indices of clearing of >30% – sufficient to qualify as threatened under IUCN criteria independent of rarity – for eight taxa. A further nine taxa have indices of between 20 and 30%, sufficient to qualify as Near Threatened under IUCN criteria. Five eucalypt Map Units (communities) have been more than 50% cleared and a further three have been 30–50% cleared (Chapter 6). Map Units subjected to extensive clearing have not been adequately reserved by way of compensation.

9. Land clearing releases large volumes of greenhouse gases into the atmosphere, particularly carbon dioxide sequestered in trees (Chapter 6). The relationship between fire and greenhouse gases is complex; however reductions in the areal extent of fires and a shift to those with lower combustion efficiency (because the grass is still green) offers great potential to reduce emissions of the trace but very potent greenhouse gases methane and nitrous oxide.

10. The major threat to the persistence of eucalypts in northern Australia is land clearing (Chapter 7). Climate change may pose a substantial threat to some populations in the future. Local reduction in populations may occur because of rainforest expansion, over-harvest for didgeridu production, and frequent intense fires driven by invasive Gamba Grass.

RECOMMENDATIONS

The most important findings of the study are outlined below, with recommendations.

A. Priorities for reservation

Our analysis shows that the reserve system in northern Australia is selective and often severely inadequate in its coverage. We recommend that on-ground conservation efforts through reservation focus on the following priorities:

1. eucalypt taxa threatened by past, present and impending land-clearing (IUCN criteria A and B) or whose rarity in itself poses a threat to their persistence (IUCN criteria B and D). See Table 12 for a list of currently-threatened taxa;
2. eucalypt communities threatened by past, present and impending land-clearing. See Figs. 33B and 34B, and Worksheet *communities* in the Supplementary file, for communities already subject to extensive clearing; and
3. eucalypt taxa and communities that are poorly reserved regardless of past or impending threats. Foci for attention include:
   • the very low level of reservation in inland (mostly pastoral) districts in all states and territories (Fig. 34A), and of the species-rich Einasleigh Uplands in north Queensland.
   • those *extremely restricted* taxa located in the central and north Kimberley and in the White Mountains area south-west of Charters Towers in Queensland that are poorly reserved;
   • all restricted taxa (i.e. all except rank 5, Table 6) – see worksheet *restricted range* in the Supplementary file – that are poorly reserved;
   • the 11 species and three subspecies endemic to the study area that not represented in any conservation reserve, and the further 52 endemic species and ten endemic subspecies that have reservation indices of less than 30% (Fig. 25); and
   • the 12 of 84 eucalypt communities (Map Units) that are not represented in any conservation reserve, and the further 40 of these Map Units that that have reservation indices of less than 10% (and often less than 1%) (Fig. 33A).

Key responsibilities: conservation efforts could include protection via both crown and private reserves. State and territory governments and their agencies have prime responsibility, while the Australian Wildlife Conservancy, Bush Heritage Australia and Indigenous groups can also play a substantial role.

B. Land clearing

Land clearing is the single greatest threat to the eucalypts of northern Australia (Chapter 7). The threat is past, present and impending.

Recommendations A1 and A2 above are most pertinent. Strategically, if agricultural intensification cannot be avoided then it must be linked to land use planning in which the eucalypts and eucalypt communities proposed for clearing are strongly matched by taxon and community, and to the extent possible geographically, by substantial and secure reservation.

Recognition and pricing of the carbon emissions involved in clearing, and in particular the provision of incentives for landholders based on the costs of emissions, is a tool with huge potential to reduce rates of land clearing and, in particular, to ensure that clearing of agriculturally marginal country does not occur.

With respect to carbon emissions, the *key responsibility* is for the Commonwealth government to facilitate the pricing of emissions of greenhouse gases and to do it in a way that enhances retention of native vegetation. A well-designed scheme offers significant advantages for many landholders, and their representative organizations can play a key role in lobbying the Commonwealth government to this end.

C. Threatened taxa and communities

Up-to-date listing of threatened taxa and communities is a key element to the appraisal of threatening processes, particularly land clearing, and in particular the appraisal of development proposals. All relevant jurisdictions, including the IUCN, accept nominations from the public. It is evident that these jurisdictions have not evaluated threats and nominated taxa and communities adequately. Nevertheless, a substantial body of relevant information and skill lies with jurisdictional agencies such as state and territory herbaria.

Key responsibilities: We recommend that:

1. relevant state and territory agencies make all pertinent information available and assist in reviewing these data in more detail; and
2. funds be sought to review these data in more detail and to prepare nominations for listing and de-listing under state, territory and Commonwealth legislation and in the IUCN Red List of threatened species.

D. Research

A much better understanding of the ecology of eucalypts and eucalypt communities in northern Australia is required for proper management of threats and especially for land use planning where agricultural intensification is unavoidable. These research topics are fundamental to assessment and management of risks. We particularly recommend the following research topics:

1. the reproductive ecology of eucalypts. Key issues include identification of supra-annual patterns and drivers of flowering and how these might be influenced by climate change; and identification of pollinators capable of providing this service at the relevant spatial scales;
2. the landscape ecology of those pollinators capable of responding to infrequent mass-flowering of eucalypts, most notably the Little Red Flying-fox (*Pteropus scapulatus*) and Varied Lorikeet (*Psitteuteles versicolor*). For example, what level of connectivity is necessary for full maintenance of the ecosystem services they provide, and are there thresholds of habitat fragmentation beyond which pollination declines;
3. aspects of the demography of eucalypts that remain poorly understood, including seedling establishment, the longevity of the seedling bank and of mature trees and how this varies with species, environments and disturbance across northern Australia;
4. the evolutionary relationships among species in order to better understand the historical factors which have shaped the current distribution of species;
5. field surveys of potentially threatened taxa to determine their distribution and abundance;
6. field surveys of remote areas, particularly in the Kimberley and any others with a poor collection record (e.g. many inland areas), to locate new taxa and fill in our knowledge of the distribution of known taxa;
7. more accurate (i.e. locally applicable) estimates of the emission of greenhouse gases resulting from land-clearing to properly cost the consequences of that clearing;
8. the consequences of climate change for eucalypts; and
9. identification of Evolutionary Significant Units for the conservation of north Australian eucalypts with both general application and particular relevance to the ability of species to cope with and respond evolutionarily to climate change. ESUs may be identified on the basis of geographic isolation, genetic distinctness or locally-adaptive features.

Key responsibilities: re-prioritisation of research to address key elements of basic ecology is required by universities and research-funding agencies. Further funding is required particularly from state, territory and Commonwealth governments.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

The vast sweep of tropical savanna and open forest across northern Australia is one of the greatest structurally-intact natural areas of the world. It shares a key feature with the eucalypt forests and woodlands of southern and eastern Australia – the dominant trees over most of it are eucalypts. Beyond that quintessentially Australian trait, key differences are apparent in the vegetation compared to other parts of Australia. Among them, rainfall is strongly summer-dominated and temperatures are high throughout the year, the understory is mostly grassy, and fires are frequent and of relatively low intensity (*cf.* infrequent fires of extreme intensity in southern Australian forests) (Woinarski *et al.* 2007a; Bowman *et al.* 2010a). The eucalypts themselves differ too compared to those of other parts of Australia, notably in the relative prominence of the genus *Corymbia* (Gill *et al.* 1985), and of species that are seasonally deciduous (Franklin in prep.) (Fig. 1), have discolourous leaves held horizontally, are pollinated by birds and bats (Franklin & Noske 2000), have lower levels of volatile oils in the foliage (Steinbauer 2010), and perhaps also have larger seeds.

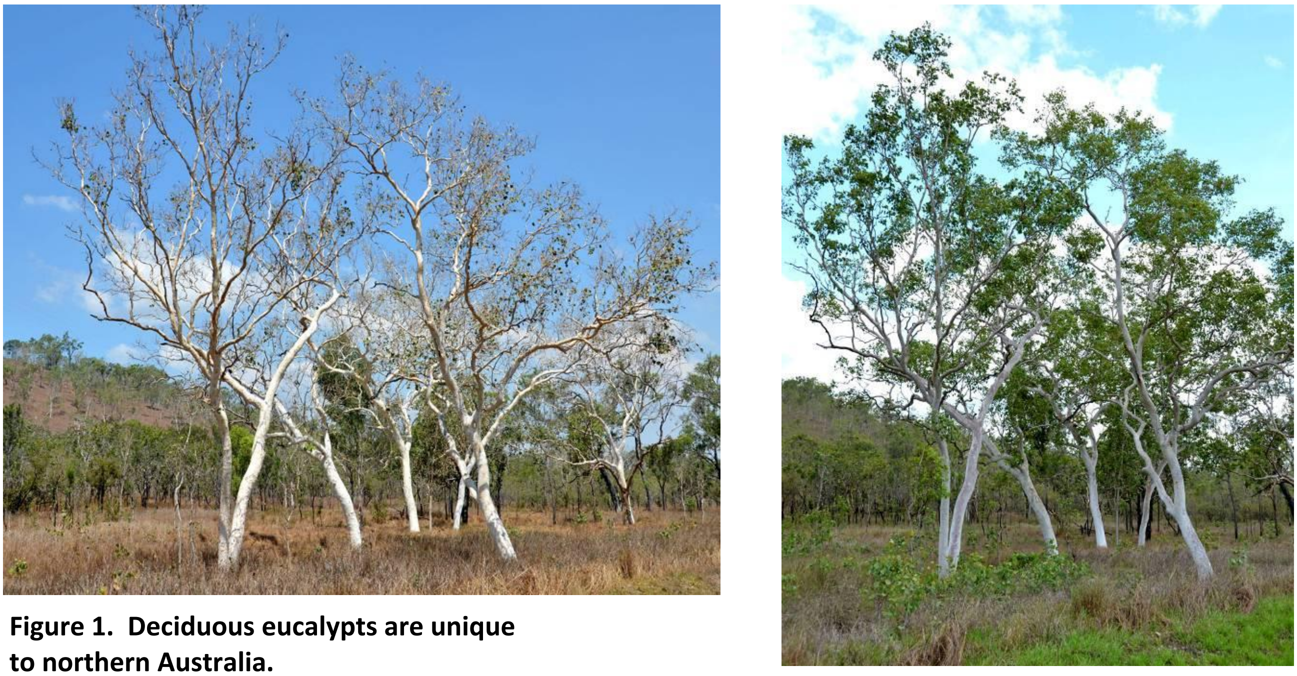


Figure 1. Deciduous eucalypts are unique to northern Australia.
These images are of a stand of Poplar Gum (*Eucalyptus platyphylla*) north of Mareeba in north Queensland, photographed late in the dry season (left) and three months later early in the wet season (right).

The term "eucalypt" refers to members of three closely-related genera: *Angophora, Eucalyptus* and *Corymbia.* The distinctness of *Angophora* has long been recognised, these being the only eucalypts with obvious petals. In both *Eucalyptus* and *Corymbia*, the primordial petals fuse (along with the sepals in some species) to form a bud cap that is not obviously petaloid, the showy colour of flowers being provided by the stamens. Prior to 1995, all non-angophoroid eucalypts were placed in *Eucalyptus*, a situation that became untenable when independent genetic studies using different techniques (Sale *et al.* 1993; Udovicic *et al.* 1995) demonstrated that bloodwoods and the ghost gum group (paper-fruited bloodwoods) were more closely related to *Angophora* than they were to other *Eucalyptus* species. This problem was resolved with the re-assignation of the several hundred species of bloodwoods and ghost gums to form the genus *Corymbia* (Hill & Johnson 1995). Such a major change was not universally welcomed, particularly as the morphological evidence for inclusion of the ghost gum group in *Corymbia* was considered by some to be thin and questionable (notwithstanding genetic evidence). However, the three genera are now more or less universally accepted and are recognised by all state herbaria in northern Australia and in the 2011 revision of the eucalypts by the Australian Plant Census that is employed in this study (see Study Area and Methods for details).

The formal diagnostic morphological characters that distinguish *Corymbia* from *Eucalyptus* (Hill & Johnson 1995) are obscure. All *Corymbia* species have urn-shaped or globular fruits with deeply-recessed valves (Fig. 2), though this feature is not diagnostic. Many *Corymbia* bear their flowers in branched terminal inflorescences (*cf.* often unbranched and usually axillary in most *Eucalyptus*) and have tessellated (tiled) bark, and the red bloodwood group in particular feature strongly penniveined foliage (the veins are feather-like *cf.* arched lateral veins and well-developed reticulation in most *Eucalyptus*).

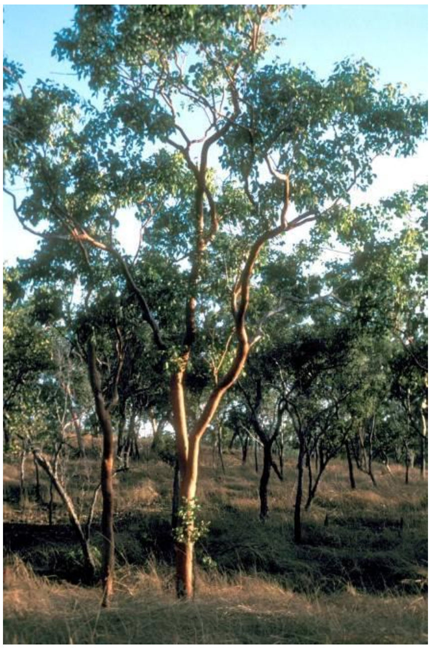
Figure 2. Urn-shaped (or globular) fruits with an open throat and deeply embedded valves are characteristic of *Corymbia* but do not absolutely distinguish it from *Eucalyptus*. Photo: Twin-leaved Bloodwood (*Corymbia cadophora* subsp. *cadophora*), Mornington Wildlife Sanctuary, Kimberley region, Western Australia.

The eucalypt-dominated vegetation of northern Australia comprises vast tracts of tropical savanna, substantial areas of woodland and open forest particularly in the wetter north and east, and small but significant stands of tall moist and wet sclerophyll forest mostly in the vicinity of rainforest in the wet tropic regions of Queensland (Fox *et al.* 2001) (Fig. 3). One species, River Red Gum (*E. camaldulensis*) is largely confined to watercourses whilst a number of others such as Ghost Gum (*C. bella*), Long-fruited Bloodwood (*C. polycarpa*) and Coolabah (*E. microtheca*) are strongly associated with seasonally-dry floodplains or ephemerally flooded alluvial plains adjacent to watercourses. Eucalypts may also be found in small rainforest patches and the edges of larger rainforest stands both in the monsoon rainforests of north-western Australia and Cape York Peninsula (e.g. Bowman & Dunlop 1986) and the evergreen tropical rainforests of north-east Queensland (Tng *et al.* 2012a). These occurrences are usually interpreted as evidence of recent expansion of rainforest into eucalypt stands (Harrington & Sanderson 1994; Bowman *et al.* 2010b; Tng *et al.* 2012b); indeed, the expansion of rainforest into eucalypt forest is considered (somewhat controversially) as a threatening process to several regional ecosystems in eastern Queensland (Goosem *et al.* 1999). There is one exception: Cadaghi (*Corymbia torelliana*) is often regarded as a true rainforest eucalypt; it is endemic to the Wet Tropics of north-east Queensland where it is found only on the margins of evergreen rainforest or close by (e.g. Turton & Duff 1992) (Fig. 4).

Figure 3. Some eucalypt ecosystems of northern Australia.

Grass and trees: the tropical savanna. Right: Variable-barked Bloodwood (*Corymbia dichromophloia*) in the wet season, near Daly Waters, Northern Territory.

Below: in the dry season, Hills Salmon Gum (*Eucalyptus tintinnans*), Yinberrie Hills between Katherine and Pine Creek, Northern Territory.



Right: open forest of Darwin Woollybutt (*Eucalyptus miniata*) and Melville Island Bloodwood (*Corymbia nesophila*), Cobourg Peninsula, Northern Territory.

Below left: dry sclerophyll forest with Lemon-scented Gum (*Corymbia citriodora*), Atherton Tablelands, north Queensland. Below centre: tall moist sclerophyll forest of Red Mahogany (*Eucalypts resinifera*), Tumoulin Forest Reserve, north Queensland. Below right: River Red Gum (*E. camaldulensis*), 100 Mile Swamp, Undara, north Queensland.

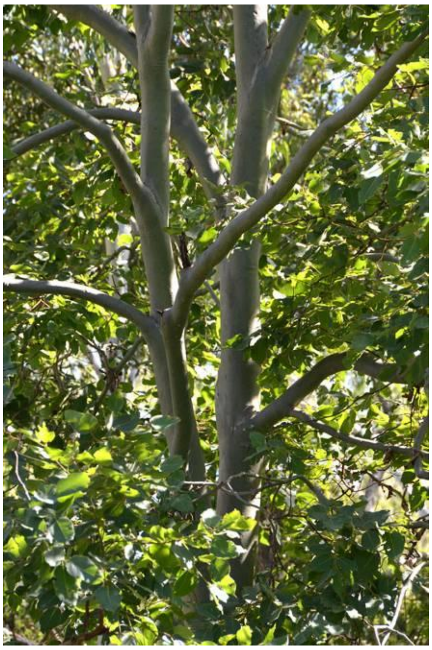


Figure 4. Almost a rainforest tree: Cadaghi (*Corymbia torelliana*). Photographed in habitat near Kuranda, north Queensland.

The savannas of northern Australia occur across a wide range of substrates and landscape settings: on lateritic lowlands, basalt plains, sandstone ranges and plateaus, rolling rocky hills, limestone outcrops and more (Fox *et al.* 2001) (Fig. 5). Typically, the foliage cover of trees is less than 30%, but these grade into open forest with higher cover. In most settings eucalypts are the dominant tree, but in some settings and especially more arid savannas, non-eucalypts may be the main species and eucalypts a minority or even absent. By definition the ground layer of savanna features grasses. However, a shrubby understory may develop particularly where fire is infrequent due to the protection provided by boulders.

Figure 5. Contrasting settings for tropical eucalypt savannas in northern Australia.

Right: Eucalypt savanna (foreground) grading into eucalypt open forest (background) near Mt Carbine, north Queensland.

Below: Savanna of Variable-barked Bloodwood (*Corymbia dichromophloia*) in foreground against a background of sandstone outcrops, Keep River National Park, Northern Territory.

In savanna environments, fire is both a natural (lightning-induced) and anthropogenic phenomenon that includes a long history of Aboriginal burning (e.g. Kershaw 1985). The consequences of Aboriginal burning are controversial (e.g. Notaro *et al.* 2011; Preece 2013) but the northern savannas and their eucalypts have an evolutionary history that strongly pre-dates arrival of the Aborigines (Bowman 1998, 2002, 2003). Though documentation is limited (Burrows *et al.* 2008; Werner & Franklin 2010; Lawes *et al.* 2011), the eucalypts of northern Australia appear almost universally to resprout from epicormic stem shoots and lignotubers after loss of canopy during fire (Nicolle 2006; Burrows 2013). A notable exception is Rose Gum (*E. grandis*) of north-eastern Australia, a tall tree of wet sclerophyll forest that lacks a lignotuber (Burgess & Bell 1983) and is probably an obligate seeder (Tng *et al.* 2012a; Franklin 2013).

Our knowledge of the taxonomy and distribution of north Australian eucalypts has advanced greatly in recent decades (e.g. Hill & Johnson 1995, 2000) but much remains to be learned. A number of species complexes remain to be adequately resolved (e.g. the *E. alba* group of species and *C. arafurica*/*bella*, Ian Cowie personal communication; see also discussion of many taxa in CPBR 2006). New forms and possibly species have recently been discovered (e.g. a bloodwood near Longreach; Rod Fensham personal communication). The 2011 checklist adopted as the standard for this report includes five undescribed taxa, and State herbaria recognise a number of described and undescribed species not (yet?) incorporated into the checklist.

Our knowledge of the ecology of the eucalypts of northern Australia is patchy and even less well-developed. Relevant aspects will be reviewed in this report. Major works on eucalypt ecology (most recently Williams & Woinarski 1997) have relied heavily on generalisations from the temperate and subtropical forests and woodlands and semi-arid mallee scrubs of eastern, southern and south-western Australia. Knowledge of the response of savanna eucalypts to fire is largely incidental to studies of savanna ecology (but see references to resprouting above). Notwithstanding long-held concerns for the future of wet sclerophyll forest in north Queensland due to rainforest invasion (Ash 1988; Unwin 1989; Harrington & Sanderson 1994; Goosem *et al.* 1999; Stanton *et al.* 2014), just slightly greater than nothing is known about the ecology of these forests or their constituent species (reviewed by Franklin 2013). Beyond studies of the impact of fire on flowering and recruitment in three eucalypt species in Kakadu National Park (Setterfield & Williams 1996; Setterfield 1997; Williams 1997), and the knowledge that two species are unusual in producing root sprouts (Lacey & Whelan 1976), there have been no detailed studies of the reproductive biology of north Australian eucalypts. The longevity of north Australian eucalypts is unknown but for a few hints (Fensham & Bowman 1992; Werner *et al.* 2008).

This study, therefore, is a pioneering effort based on unavoidably incomplete data. We present analyses for northern Australia based on a heavily-vetted download of records from Australia's Virtual Herbarium, on data underlying the vegetation mapping of Fox *et al.* (2001), and a miscellany of other sources. Our primary aims are, for northern Australia, to:

- to provide an overview of the eucalypt flora including levels of endemicity and species richness (Chapter 3)
- identify biogeographic patterns including "hot-spots" of endemicity (Chapter 4);
- assess the status of taxa including restricted occurrence and conservation status relative to IUCN criteria (Chapter 5); and
- provide an assessment of the conservation status of eucalypt ecosystems along with a exploration of the implications of greenhouse gas emissions, sequestration and abatement for their management (Chapter 6).

The methods we employed are summarised, and a description of the study area provided, in Chapter 2; methods are elaborated where necessary in appendices. Shapefiles are provided to facilitate conservation assessments of threatened taxa and the reservation and clearing status of eucalypt communities. We also provide a supplementary Excel file containing a checklist of taxa and a variety of project outputs including data to supplement the shapefiles. Metadata for this supplementary file is provided in Appendix 4.

<u>CHAPTER 2: STUDY AREA AND METHODS</u>

Study area

Northern Australia (Fig. 6A) was defined by combining the 22 bioregions of the “Tropical Savanna” region as determined by the now-defunct Tropical Savannas Cooperative Research Centre (Anon. 1996; TSCRC 2001), with the two embedded rainforest bioregions (Queensland’s Wet Tropics and Central Queensland Coast) (Fig. 6B). The bioregions are the IBRAs of Thackway & Creswell (1995) with minor updates since (IBRA v7).

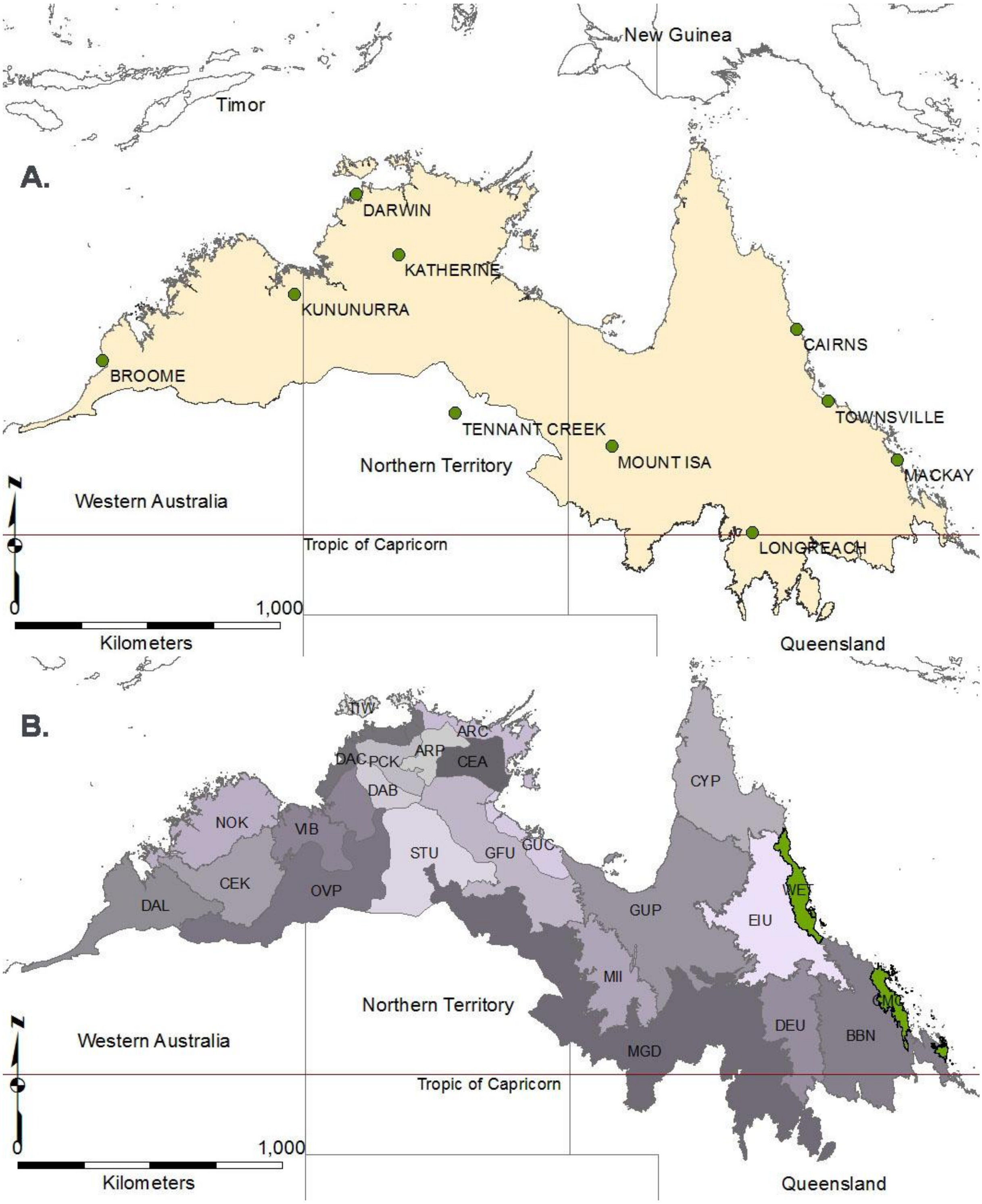


Figure 6. The north Australia study area: A. yellow-shading with major towns; B. showing the 21 savanna bioregions (various shades of grey) and two rainforest bioregions (green).

The rationale for including the rainforest bioregions is that these exclusions from the formally-defined savanna region include extensive eucalypt forests, that quite a number of eucalypts endemic to northern Australia occur across the boundaries into the rainforest bioregions, and that rainforest largely self-excludes by the absence of eucalypts. We note further that the formally-defined savanna region includes extensive areas of non-savanna and non-eucalypt habitat including the Iron-McIlwraith Ranges rainforests of Cape York Peninsula (Heinsohn & Cermak 2008) and the extensive Lancewood (*Acacia shirleyi*) thickets and woodlands of the Northern Territory and Queensland (Woinarski & Fisher 1995; Fox *et al.* 2001).

The southern limit of the study area is set broadly by aridity in the west and centre as shown by its "failure" to extend south to the Tropic of Capricorn in those areas (Fig. 6), and by winter temperatures (=latitude) in Queensland where the boundary approximates the Tropic of Capricorn and thus the sub-tropics south of c. 23° South. The arid limit of the tropical savannas corresponds to a mean annual rainfall (MAR) of c. 400 – 500 mm. In the far north – the Tiwi Islands and the tip of Cape York Peninsula, MAR approaches 2,000 mm. Rainfall in the tropical rainforest bioregions varies from c. 1,100 mm to more than 4,000 mm, with rainforest replacing eucalypt forest generally where MAR exceeds c. 1,400 to 2,500 mm depending on altitude, soils and fire history. Rainfall is strongly seasonal, mostly falling between November and May inclusive with some local variations, but seasonality is much reduced in the rainforest bioregions.

Northern Australia is not all flat and low-lying. The central Kimberley highlands approach 1,000 m above sea level (ASL) in a number of places, whilst extensive areas in central-north and north-east Queensland exceed 500 m ASL, the Evelyn Tableland and a number of other parts of Queensland's Wet Tropics bioregion exceed 1,000 m ASL. Isolated peaks elsewhere in Queensland also exceed 1,000 m including the mountains inland from Mackay. Elevation has some relevance to the occurrence of eucalypts but is no bar to them; Tindal's Stringybark (*E. tindaliae*) occurs in extensive stands almost to 1,300 m ASL on the western Atherton Tablelands (Fig. 7), though Tablelands peaks with higher rainfall are vegetated by rainforest rather than eucalypt forest. A number of eucalypts are associated with higher peaks in the Kimberley and Arnhem Plateau, notably the King Leopold Range Mallee (*E. mooreana*) which is largely confined to peaks above 650 m (Gardner 1960). However, it is possible that the occurrence of this species is related to altitude purely because they occur on residual landforms that have otherwise been highly eroded. However, in north-east Queensland, altitudinal effects on temperature and rainfall are strong and there appears to be one straightforward species-replacement across altitude, Large-fruited Red Mahogany (*E. pellita*) occurring mostly below 400 m ASL and being "replaced" by Red Mahogany (*E. resinifera*) at higher altitudes.

Figure 7. Tindal's Stringybark (*Eucalyptus tindaliae*) 1,250 m above sea level, Mt Wallum, north Queensland.

Northern Australia has a hot climate; all but a few highland areas have an average maximum temperature in the coolest month (July) of at least 23°C and an average annual pan evaporation of from 1,600 to 4,000 mm (BOM 1988). Average minimum temperatures in the coolest month are below 9°C in some inland areas but more than 20°C along parts of the north coast. Occasional frosts – which may limit the occurrence or regeneration of some species – occur in some inland and upland areas.

Infertile lateritic, sandstone and granitic soils are a feature of substantial areas of northern Australia, though lateritic soils are mainly a feature of higher rainfall areas. More fertile limestone and basalt soils are widely scattered, whilst localised alluvial deposits are widespread particularly along watercourses including coastal floodplains. A number of eucalypts are strongly associated with alluvial deposits, for example the Ghost Gum *Corymbia bella* and the northern Australian subspecies of White Gum (*E. alba* var. *australasica*). Many others have strong associations with infertile rocky sites.

For a detailed physiographic description of northern Australia we recommend Woinarski *et al.* (2007a).

Methods

Checklist of taxa

The species, subspecies and varieties of eucalypt that occur in the study area were identified from state and territory checklists, EUCLID (CPBR 2006), Australia's Virtual Herbarium (AVH; http://avh.chah.org.au/) and recent taxonomic papers. As nomenclatural standards vary between sources, these were standardised by extensive cross-matching to the Australian Plant Census (APC; http://www.anbg.gov.au/chah/apc/; eucalypts updated in 2011). More detail of the identification and standardisation of relevant taxa is provided in Appendix 1, and a finalised checklist of 188 species, 37 subspecies and one variety (forming 205 ultrataxa), including authority names, state/territory occurrence within northern Australia and matching names in EUCLID, is provided in a supplementary Excel file (worksheet *checklist*).

Location records

Georeferenced records of each north Australian eucalypt taxon were downloaded from Australia's Virtual Herbarium (AVH; http://avh.chah.org.au/). Duplicate records (same collector, date and location) were reduced to a single record using the Remove Duplicate Records function in AVH. Intensive vetting focussed on outliers compared to benchmark distribution maps (often EUCLID [CPBR 2006] but other sources where appropriate). Further detail of the vetting process is given in Appendix 2. The term *record* hereafter means "unique herbarium record" and is at times qualified as such.

Georeferenced point records of each taxon were imported from Excel files to ArcGIS (10.2), displayed as maps of taxa and converted to shapefiles (.shp). Shape files used the coordinate reference system of the Project layer, GDA94. From these data sources, a variety of metrics were calculated, including, for taxa:

- the number of records;
- the number of records in the north Australian study area;
- the number of degree cells (i.e. 1° of latitude by 1° of longitude) in which they occurred; and
- Extent of Occurrence (EOO) – area of the convex polygon that embraces all records (including marine areas, consistent with Gaston & Fuller (2009)

For degree cells, we calculated:

- the number of species (subspecies); and
- the number of records

Most taxon-specific and biogeographic analyses are derived from these records and metrics.

Biogeography

We numerically classified a matrix of species by the degree cells in which they were recorded in two ways: *a*. species by degree cells in which they were recorded (see results for exclusions and *post hoc inclusions*); and *b*. select* north Australian degree cells by the species recorded in them. To do so, the similarity between species (a.), and cells (b.) was calculated using the Bray-Curtis similarity coefficient and group-average linking. Simulation profile tests (SIMPROF) were used to evaluate whether cluster nodes were the product of non-random processes (i.e. *real* pattern). These analyses were undertaken in the software Primer 6 (Clarke & Gorley 2006).

* North Australian cells with acceptable data for this analysis were defined through the following steps:

1. if more than 50% of the cell was in the study area, it is was provisionally classified as part of northern Australia (n = 168 cells)
2. the median no. of records for cells classified at step 1 was 90; cells with some land in the study area (less than 50%) (the remainder being marine and which had more than 90 records) were added to the provisional list (9 cells; residual n = 177 cells)
3. after consideration of patterns of collection effort and species richness (see results) and because biogeographic analyses are particularly sensitive to low species counts, cells with fewer than 10 species were deleted (35 cells deleted; residual n = 142 cells)
4. after preliminary analysis indicated that one cell (25/146 with 11 species) was generating considerable tension in the analysis, it too was deleted (final n = 141 cells)

Conservation assessment of species and subspecies

For species, we examined the relationship between three metrics of "restrictedness", EOO, the number of records and the number of degree cells, using 4th root values of the metrics and least squares regression. 4th root values retain the linear relationship but are more informative than raw values and avoid undue influence of outliers on regressions. A prioritised four-tier evaluation of restrictedness using all three metrics was developed as explained in our results.

High resolution shapefiles were obtained for vegetation clearing (Qld to 2010; NT to 2007; NVIS for WA, 2004/5), and for each of crown and private reserves. Crown reserves are defined as those declared under conservation-related acts of parliament, for e.g. national parks and nature reserves and are believed to all be current at the time of analysis (Nov. 2013). Private reserves are defined as Indigenous Protected Areas and those owned and/or managed by the Australian Wildlife Conservancy and Bush Heritage Australia; these too are believed to be current at the time of analysis (Nov. 2013). Using GIS software, we calculated the number of records that were in each of crown and private reserves for all study-area endemic eucalypt taxa; combined, these are our *reservation index*. For selected taxa (see results), we calculated the number of records that were in cleared land – our *index of clearing*.

State, territory and national and IUCN lists of the eucalypt taxa of northern Australia that are listed as Threatened or related categories such as Near Threatened or Data Deficient were checked as follows:

- Western Australia: downloaded from FloraBase, http://florabase.dec.wa.gov.au/, 2 July 2013;
- Northern Territory: checklist provided by NT Herbarium (Ian Cowie, pers. comm., 28 June 2013);
- Queensland: Bostock & Holland (2010) and Peter Bostock (pers. comm., 10 July 2013);
- National: downloaded from http://www.environment.gov.au/cgi-bin/sprat/public/publicthreatenedlist.pl?wanted=flora, 2 July 2013 & 8 July 2013;
- IUCN: downloaded from http://www.iucnredlist.org/, 8 July 2013; and
- ROTAP (Briggs & Leigh 1996).

Using the taxon metrics and other information available to us, we assessed taxa that:

a. were potentially exposed to substantial land-clearing by nature of their distribution;
b. have a very restricted occurrence; or
c. are already listed as threatened, near threatened or data deficient

against IUCN criteria for threatened species (IUCN 2001; IUCN S&PS 2011).

Eucalypt communities

Formal analyses are based on the Map Units of Fox *et al.* (2001). These were intercepted with GIS coverages for reserves and clearing. For a consideration of greenhouse gas issues, information is not available at the level of Map Units, so available data are summarised and reviewed mostly at the level of broad structural formations.

CHAPTER 3: SPECIES AND SPECIES RICHNESS

Genera, species and infraspecific taxa

The eucalypt flora of northern Australia comprises 188 species (including 20 species which have subspecies), 37 subspecies and one variety (hereafter counted as a subspecies) (Table 1). A little over half of species are in the genus *Eucalyptus* and most of the remainder are in the genus *Corymbia*, the genus *Angophora* being represented in the study area by only three species (two of these only as outliers) and only in eastern Queensland (Figs. 8, 9A). In contrast, *Corymbia* and *Eucalyptus* are both widespread and mostly each constitute c. 25–75% of local species richness, with *Corymbia* relatively more predominant in the north and west including the Gulf of Carpentaria lowlands and most of Cape York Peninsula, and *Eucalyptus* more predominant along the Great Dividing Range in Queensland (Fig. 9B,C).

Table 1. Eucalypt richness in the north Australia study area by taxon level, state/territory and genus.

	Total	Qld	NT	WA	*Angophora*	*Corymbia*	*Eucalyptus*
Number of species	188	130	69	65	3	78	107
Number of subspecies	38	22	14	17	1	18	19
Number of ultrataxa*	206	136	74	73	3	88	117

* an *ultrataxon* is the lowest available taxonomic unit. Thus, for example, a species with no described subspecies is an ultrataxon but a species with subspecies is not – the subspecies are.

Figure 8. Highly disjunct occurrence of Rough-barked Apple (*Angophora floribunda*) at Tumoulin on the Atherton Tablelands, north Queensland. This occurrence, comprising stands over at least several square kilometres of rural land, is c. 700 km north of the main range of the species which is to the south of the north Australian study area. Other north Australian populations have recently been discovered near Townsville (CPBR 2006).

Eucalypt species richness is greatest in Queensland (Table 1). This may reflect the greater area of Qld than NT or WA in the study area – patterns of species richness are evaluated in the next section.

After vetting, 51,853 unique herbarium records were obtained, a mean of 276 records per species (range 1 – 4,580). As a sub-set of the above, 5,662 records were obtained for subspecies present in the study area, a mean of 149 per subspecies (range 1 – 1,002 per subspecies), but many records of species that have subspecies could not be attributed to subspecies (see Appendix 2).

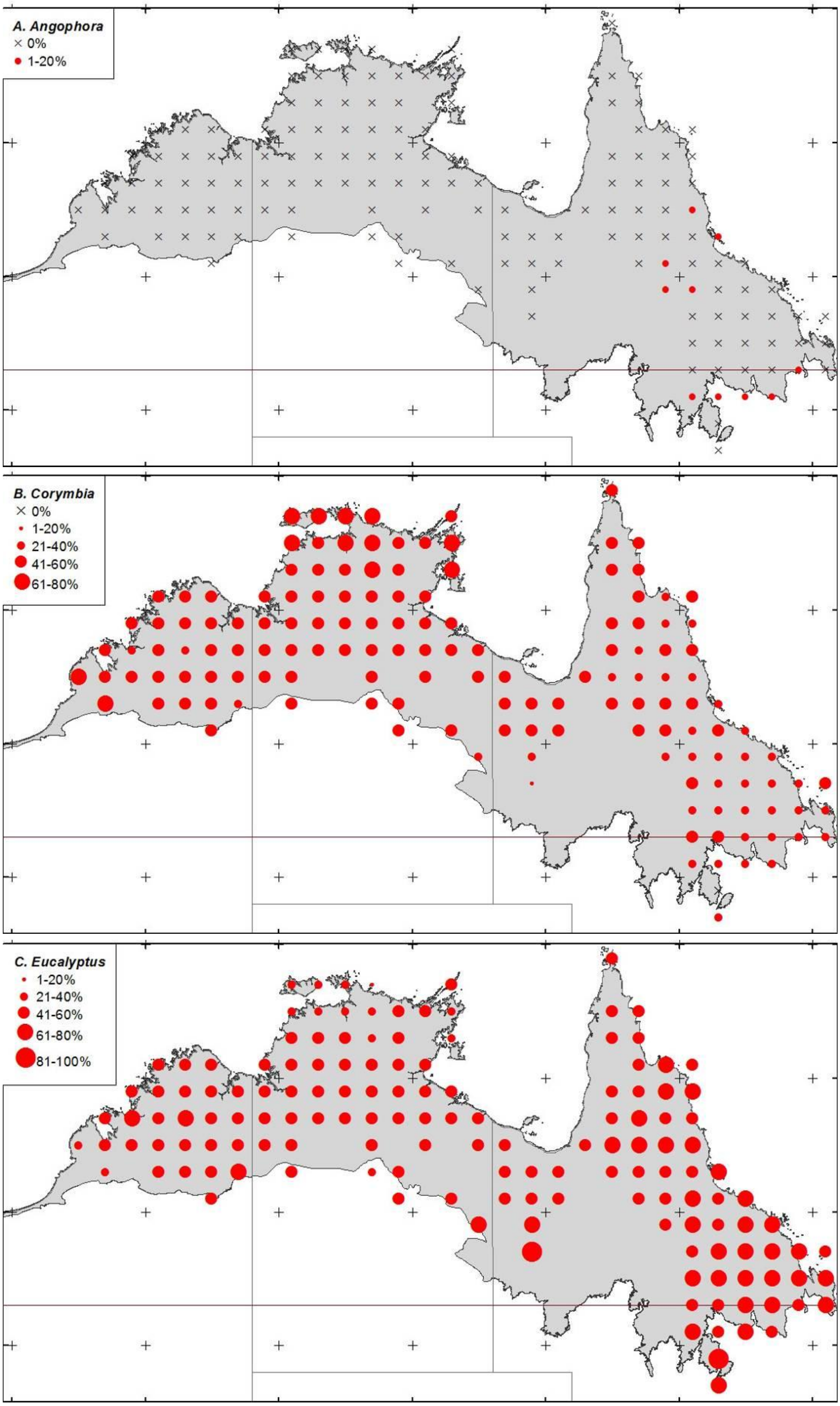


Figure 9. Proportional species richness of eucalypt genera in degree cells in northern Australia. Only cells with more than 10 recorded northern Australian species have been included. Cells that include land outside the study area may have additional species not included the analysis.

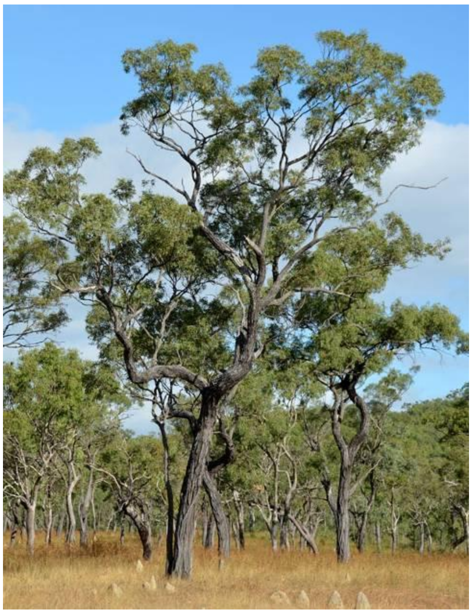
Endemicity and extra-Australian eucalypts

Approximately 56% of north Australian eucalypt species are endemic to the study area (e.g. Fig. 10), whilst a further 13% are close to endemic, being found either only to the north in New Guinea and/or the islands of Wallacea, or marginally to the south of the study area (Table 2). Percentages are remarkably similar for subspecies.

Table 2. Endemicity (no. and % of taxa) of northern Australian eucalypts.
NA = the north Australian study area. “Records” means unique herbarium collection. Categories are hierarchical and exclusive, so that taxa included in *Endemic to NA & islands to north* do not re-appear in categories below such as *Near endemic*. A

Endemicity group	No. of species	No. of subspecies	% species	% subspecies
A. Endemic to NA & islands to north	7	0	3.7	0.0
B. Endemic to NA	105	22	55.9	57.9
C. Near endemic to NA (80–<100% of records)	17	3	9.0	7.9
D. Predominantly north Australian (50–<80% of records)	11	3	5.9	7.9
E. Predominantly not north Australian (20–<50% of records)	21	4	11.2	10.5
F. Marginal to NA (>0–<20% of records)	27	6	14.4	15.8
Total	**188**	**38**	**100**	**100**

Figure 10. Two of 105 eucalypt species endemic to northern Australia.
Left: Whitebark (*Eucalyptus apodophylla*), south of Darwin, Northern Territory.
Right: Lemon-scented Ironbark (*E. staigeriana*), Palmer River, north Queensland.



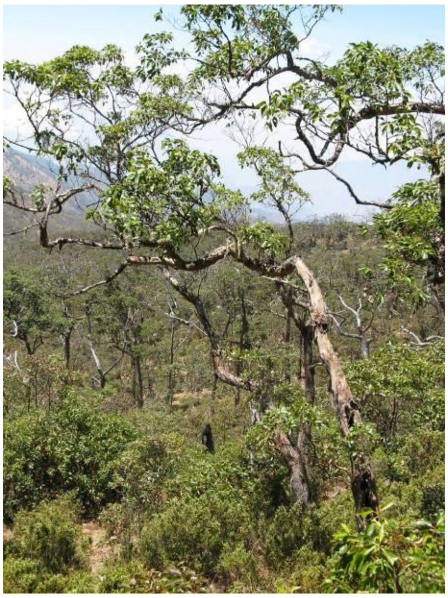
Thirteen eucalypt species occur to Australia’s north (Table 3). Of these, 9 species also occur in northern Australia and two of these also further south, whereas four species occur only outside Australia (Tables 2, 3). One species, *E. alba*, has varieties restricted to Australia and extra-Australia locations respectively though these varieties are so distinct it is almost inconceivable that they are actually the same species (DCF personal observation, Ian Cowie personal communication). Some of the extra-Australian occurrences (Fig. 11) are in savanna environments remarkably similar to those of northern Australia whereas *E. urophylla* is a montane open forest species, *E. orophila* occupies a unique sub-alpine environment on Timor and *E. deglupta* is a very-tall rainforest species (Tng *et al.* 2012a).

Table 3. Extant extra-Australian eucalypts.

Taxon	Extra-Australian occurrence	Occurs in northern Australia?	Occurs south of NA?	Key references	Notes
Corymbia disjuncta	Papua New Guinea & West Papua	yes	no	Carr (1972) as *E. confertiflora*; Hill & Johnson (1995)	
Corymbia latifolia	Papua New Guinea	yes	no	Hill & Johnson (1995)	
Corymbia novoguinensis	Papua New Guinea & West Papua	yes	no	Carr (1972) as *E. polycarpa*; Hill & Johnson (1995)	
Corymbia papuana	Papua New Guinea & West Papua	yes	no	Carr (1972) as *E. papuana*; Hill & Johnson (1995)	circumscription of *C. papuana* in both references differs substantially from that employed by the Australian Plant Census.
Corymbia tessellaris	Papua New Guinea	yes	yes	Hill & Johnson (1995)	
Eucalyptus alba var. *alba*	Papua New Guinea and Lesser Sunda Islands (Timor, Flores, Solor, Adonara, Lembata, Panta, Alor, Atauro, Wetar, Damar, Romang)	no (but *E. alba* var. *australasica* does)	no	Martin & Cossalter (1977); Monk *et al.* (1997); Trainor (2011)	The Australian and extra-Australian varieties differ in a wide range of traits and are unlikely to be truly conspecific.
Eucalyptus brassiana	Papua New Guinea	yes	no		
Eucalyptus deglupta	Sulawesi, Philippines (Mindanao), West Papua, New Britain, Ceram	no	no	Ladiges *et al* (2003)	a rainforest tree
Eucalyptus orophila	Timor-Leste, where confined to the top c. 300 m of Mt Ramelau	no	no	Pryor *et al.* (1995)	closely related to *E. urophila*
Eucalyptus pellita	Papua New Guinea & West Papua	yes	no	Hill & Johnson (2000) as *E. biterranea*	
Eucalyptus tereticornis subsp. *tereticornis*	Papua New Guinea	yes	yes		most *E. tereticornis* in Australia is same subspecies as in PNG
Eucalyptus urophila	Lesser Sunda Islands including Timor, Flores, Alor & Wetar	no	no	Hill & Johnson (2000)	
Eucalyptus wetarensis	Wetar (one of the Lesser Sunda Islands)	no	no	Pryor *et al.* (1995)	closely related to *E. urophila*

Figure 11. Some extra-Australian eucalypt environments.

Above: if this savanna of *Eucalyptus alba* var. *alba* was not perched on a 1,400 m mountain (Mt Curi, Timor-Leste (East Timor)) overlooking the ocean, one could envisage it being on rocky hills in northern Australia.



Left: montane woodland of *Eucalyptus alba* var. *alba*, c. 600 m above sea level, Atauro Island, Timor-Leste.

Centre: montane open forest of *Eucalyptus urophylla*, c. 1,200 m above sea level, Mundo Perdido, Timor-Leste.

Right: sub-alpine woodland of *Eucalyptus orophila*, c. 2,800 m above sea level on Mt Ramelau (Tata Mailou), Timor-Leste.

Species richness

The recorded richness of species in degree cells ranges from one to 46, with peak richness in the degree cell covering the Atherton Tableland and adjacent western slopes in Qld (cell centred at 17°30'S by 145°30'E). Other cells with more than 40 recorded species are: Mt Surprise – The Lynd in north Queensland (cell centred at 18°30'S by 144°30'E, 41 species) and the White Mountains – Pentland Hills area south-west of Charters Towers in north-central Queensland (cell centred at 20°30'S by 145°30'E, 41 species). Areas with more than 30 recorded species were in the central Kimberley (WA), Wyndham – Kununurra (WA), a band in the Top End (NT) extending from the Arnhem Plateau west to Litchfield National Park and to the south-west of Katherine but notably excluding the north coast, and in areas of Queensland adjacent to the peak cells mentioned above (Fig. 12A). In general, recorded species richness was low and often fewer than 10 species in cells along the inland boundary of the study area and especially in the plains of the Barkly Tableland (NT and Qld).

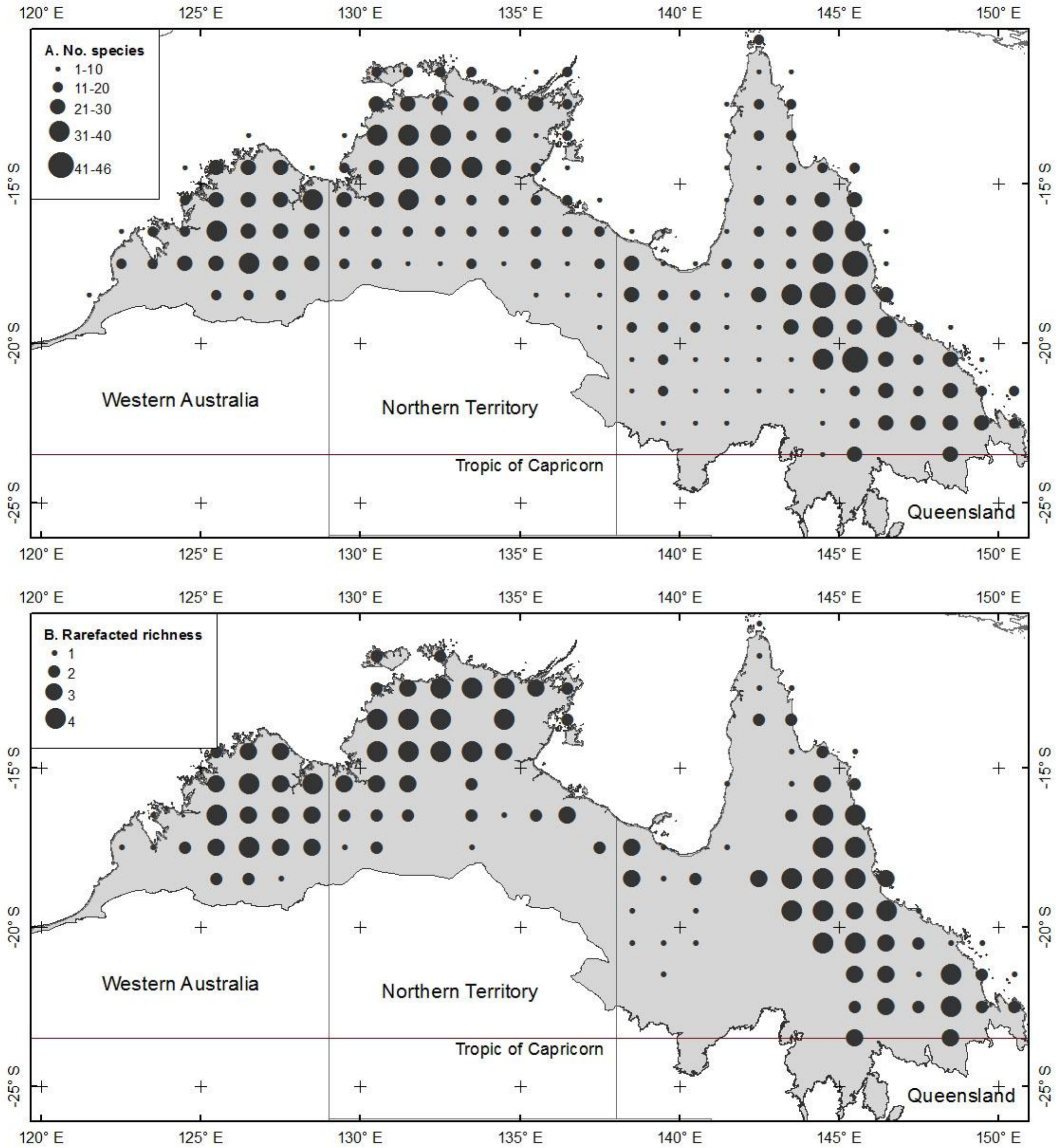


Figure 12. Species richness of eucalypts in northern Australia: A. recorded; B. rarefacted.
Cells with land area outside the study area have been excluded because they may contain additional species. Rarefacted richness is the mean richness of samples of 50 records and is thus constrained to those cells with 50 or more records. For rarefacted richness, the first quartile corresponds to 7.0 – 13.7 species, the second quartile to 14.2 – 16.6 species, the third quartile to 16.6 – 19.9 species and the top quartile to 19.9 – 25.5 species.

It is to be expected that true species richness would reflect the heterogeneity of landscapes – more diverse landscapes such as where mountains and plains are juxtaposed having more species – along with an imprint of past climates and speciation processes. Observed species richness might not reflect true patterns where collection/survey effort has been limited. Further, with the use of degree cells as the geographic units in which richness is assessed, coastal cells may be much smaller than inland cells. Most unsurprisingly, species richness is positively and approximately logarithmically related to the number of unique herbarium records (Fig. 13). The regression in this figure is indicative only as it is subject to extreme leverage by the outlying cell, but attempts to linearise the relationship with log-log plots were not very successful. This noisy relationship probably reflects both that true species richness varies greatly between cells and that the assumption that herbarium records represent a random sample of the eucalypts present is often likely to be incorrect. The assumption of randomness holds reasonably well when eucalypts are sampled as part of general plant surveys but collapses when surveys target eucalypts in particular, as has undoubtedly happened at times. Further, areas recognised as species rich may be targetted more heavily than those thought to be species poor. Thus, the regression does not constitute a prediction that further survey effort will necessarily increase the number of species detected.

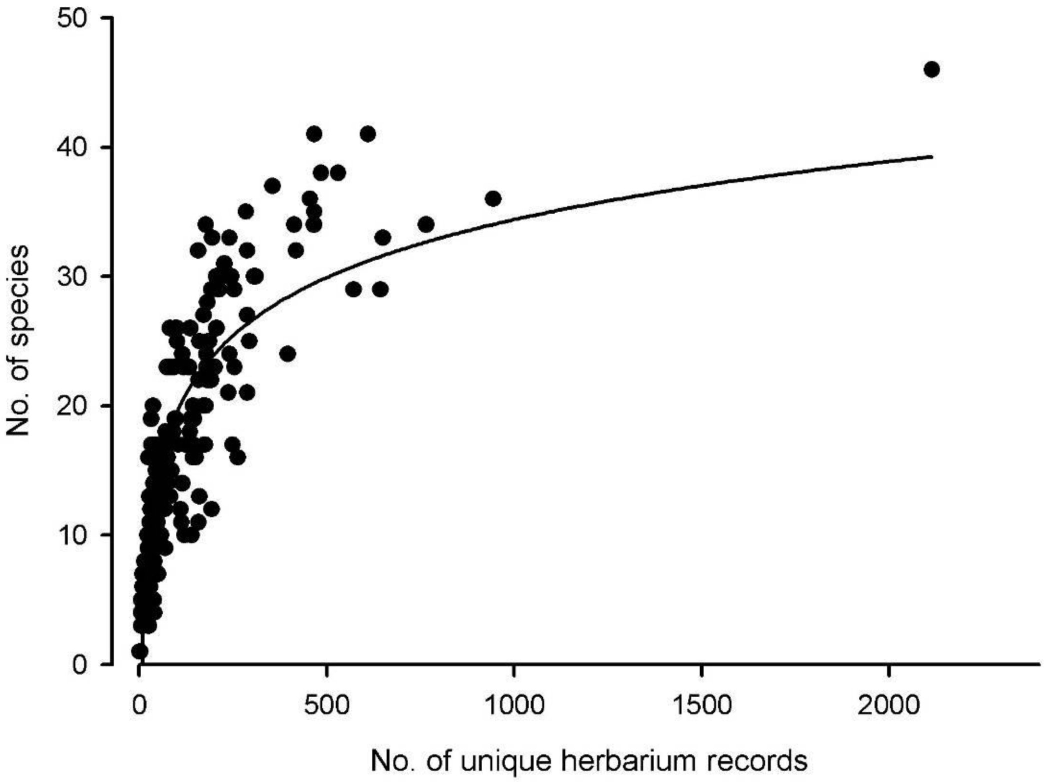


Figure 13. Number of eucalypt species recorded in north Australian degree cells as a function of the number of unique herbarium records of eucalypts.
The logarithmic fitted line is: No. of species = 14.9 $\log_{10}$(no. of records) – 10.3; r^2 = 0.76.

The number of unique herbarium records varied from 1 to 2,114 per degree cell with a mean of 147.1 and a median of 82. The marked difference between the mean and median reflects the strongly skewed frequency of sampling, with most cells having fewer than 500 unique herbarium records and many having fewer than 50 (Fig. 14).

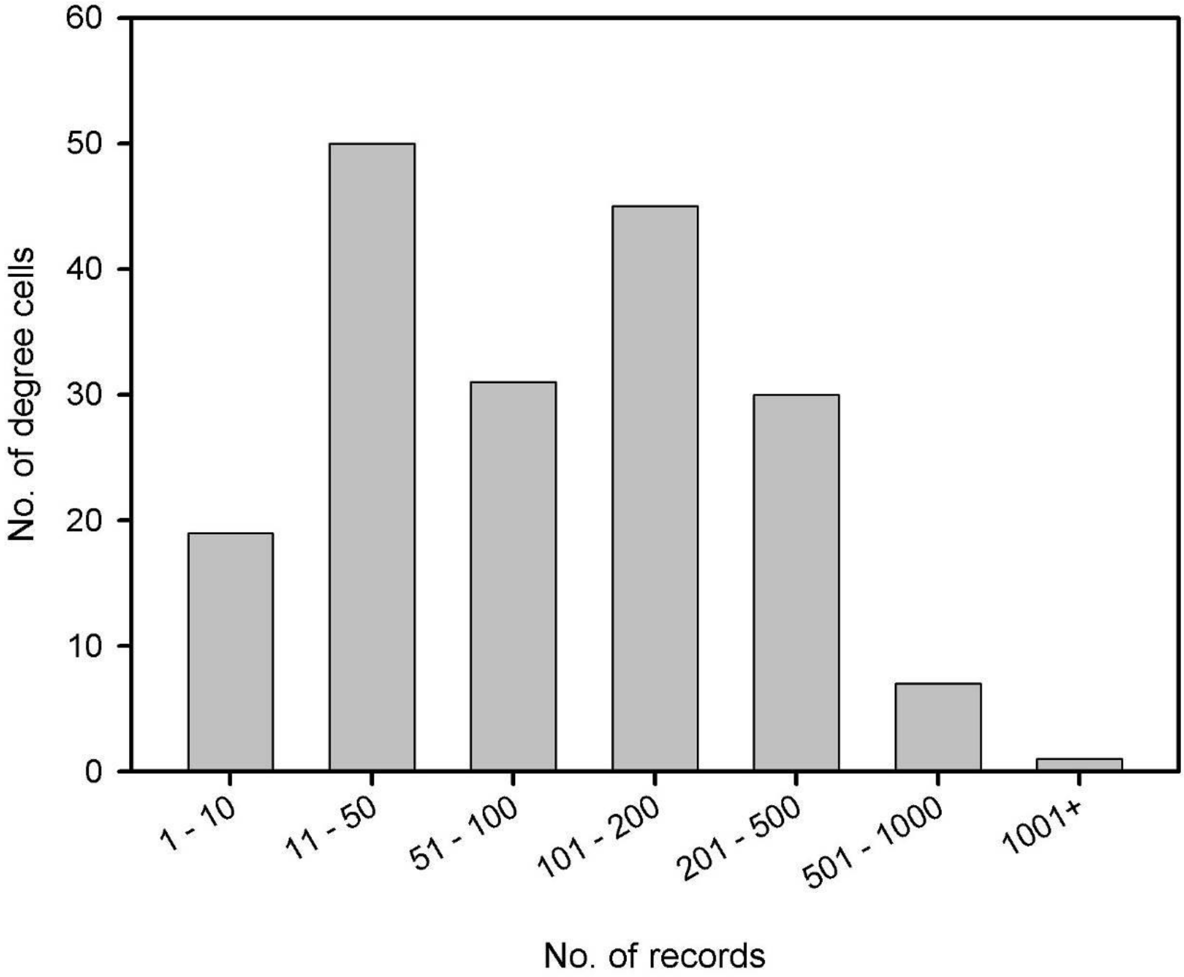


Figure 14. Number of degree cells in northern Australia by abundance of unique herbarium records of eucalypts.

A partial solution to improve representation of true geographic patterns of species richness is to randomly sub-sample equal-sized subsets of the collection record for each cell, a process known as rarefaction. The subset sample size is a trade-off between maximising the sample size and maximising the number of cells available for analysis. After some exploration of possibilities, we have adopted a sub-set sample size of 50 records, yielding 116 cells available for analysis. Rarefaction triggered only minor re-arrangement in the rank-order of cells by richness (unpublished data) and suggests similar geographic patterns with richness peaking in the Kimberley (WA), the central and western Top End (NT) and in north-east and eastern Queensland (Fig. 12B). It provides the suggestion that only a few remote degree cells adjacent to documented hot-spots may also be hot-spots for eucalypt species richness which are not adequately represented in the record. It also suggests an additional hot-spot for species richness just inland and south-west of Mackay in Queensland. Rarefacted species richness is relatively low in inland areas that have been adequately sampled for inclusion in the analysis (min. 7 species per cell), but many cells have been inadequately sampled for this analysis. Notably, species richness is relatively fairly low on Cape York Peninsula by either measure.

The identified hot-spots for eucalypt richness are indeed all areas of landscape including topographic heterogeneity (i.e. there are rocky ranges with considerable variation in elevation and doubtless also landforms and soils).

CHAPTER 4: BIOGEOGRAPHY

A classification of species according to their occurrence suggested that most eucalypts fall into 11 semi-discrete geographical groups (Fig. 15), a twelfth, small group (L) being identified qualitatively from excluded and unclassified species (Table 4). Thirteen species were excluded from the analysis due to very small ranges, and seven were not classified, but *post hoc* examination (*Notes* field in Table 4) reduced this tally to one and four respectively. Within groups, % similarities were quite low, yet groups in general showed remarkable geographic cohesion and often high levels of regional endemism (Table 4, Fig. 16), a tension we attribute to considerable dissimilarities (patchiness) at local (degree cell) scales.

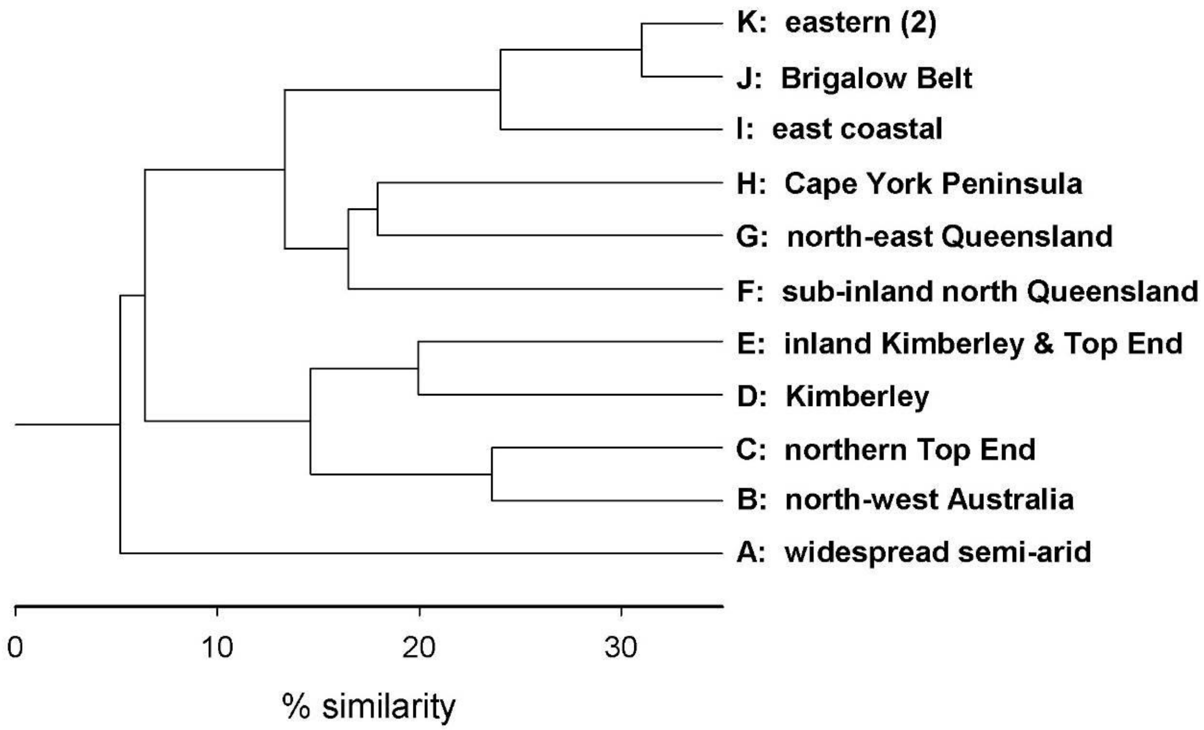


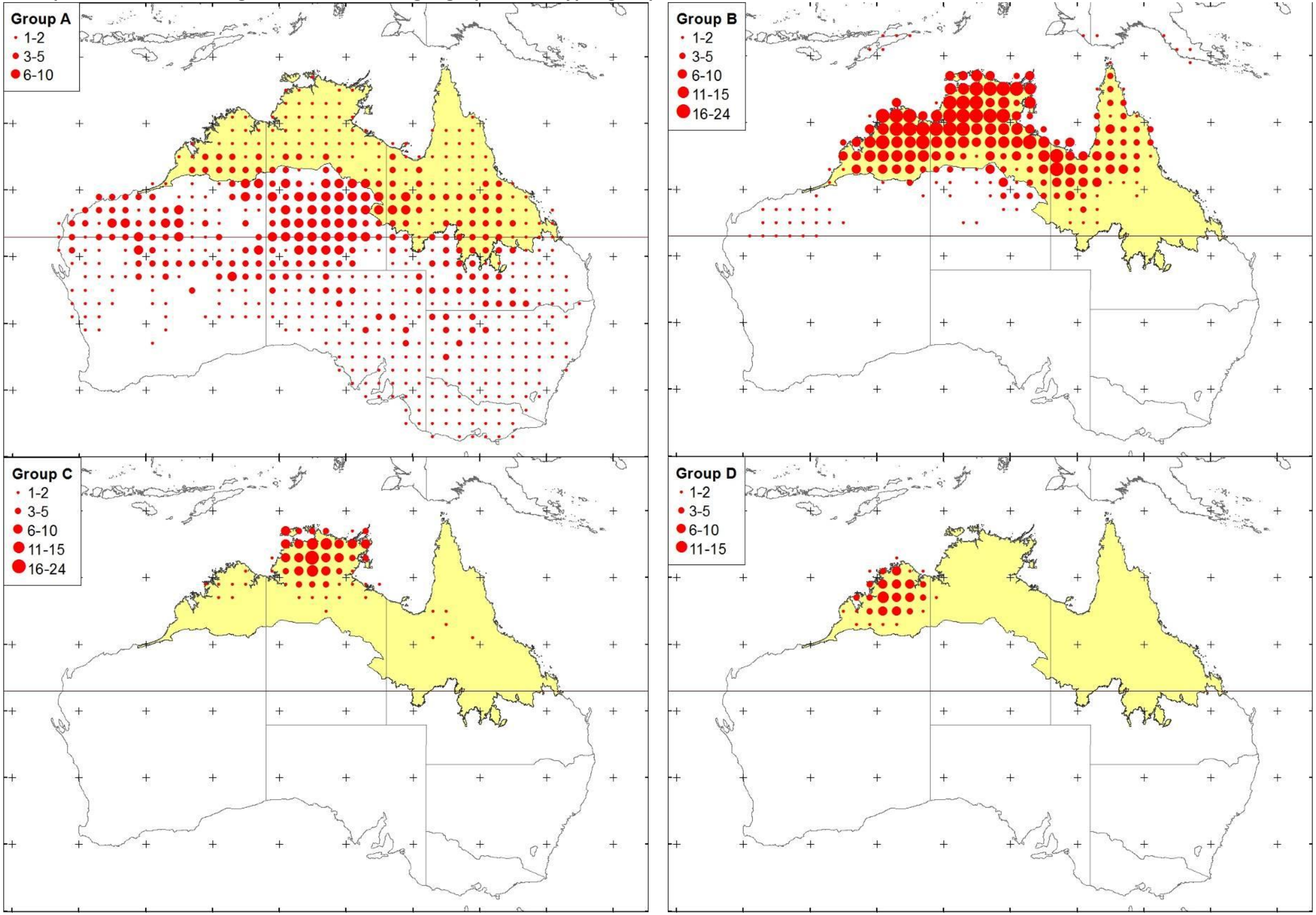
Figure 15. Dendrogram of north Australian eucalypt species based on their presence in degree cells and collapsed *post-hoc* into biogeographic groups.
Cells are of 1° of latitude by 1° of longitude anywhere in the species range. Data were presence/absence only. Species occurring in only one or two cells were excluded. Resemblances were calculated using the Bray-Curtis similarity coefficient and clustered using group averaging. Groups were defined by visual examination of the raw dendrogram independent of biogeographic features, with seven species not classified as they formed isolated one- or two-species groups. All nodes (and many more lower nodes) are the product of significantly non-random structure (simulation profile tests [SIMPROF], $P < 0.001$).

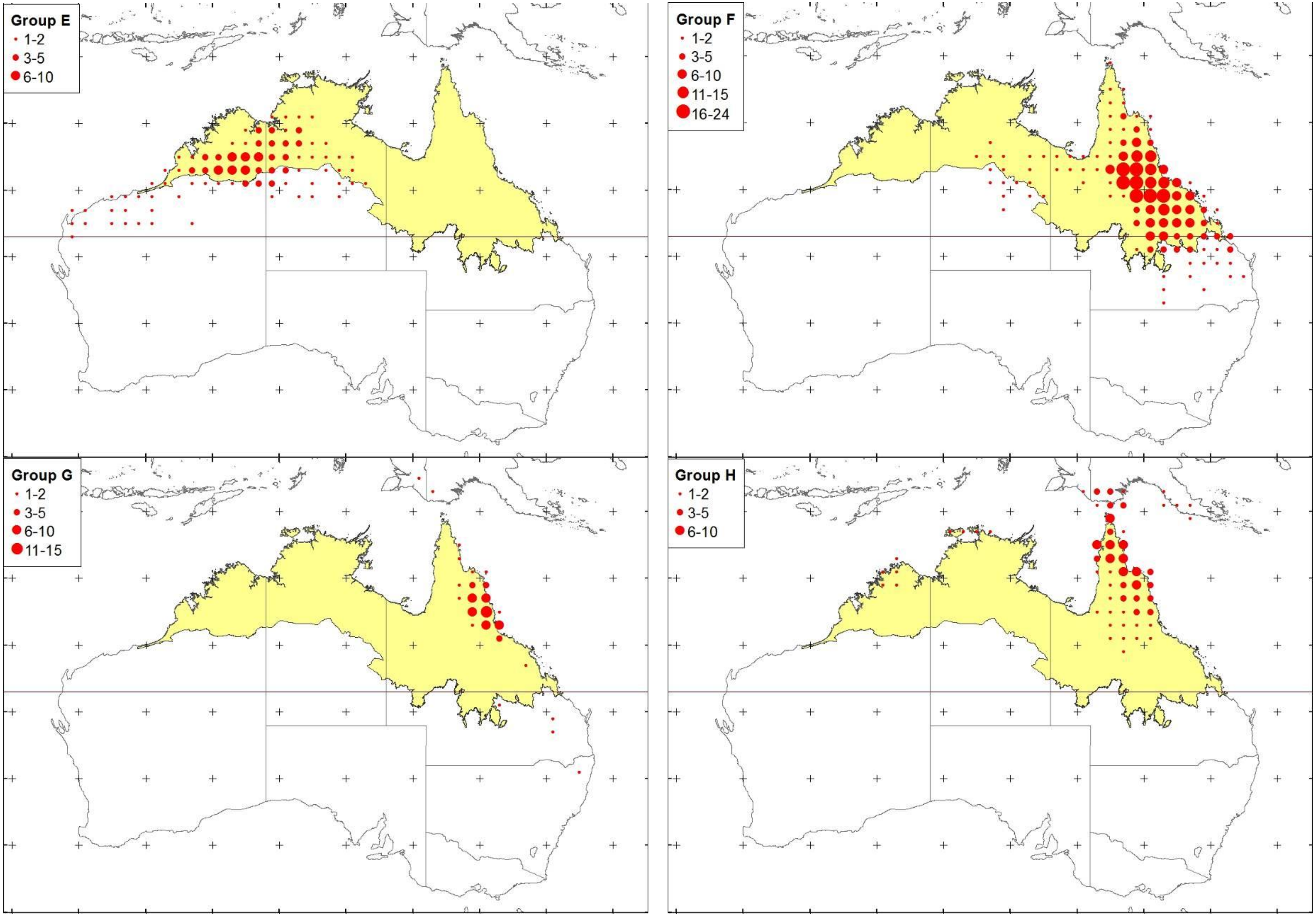
The groups form three broad clusters comprising: a. species that are widespread mainly in inland northern Australia and further inland (Group A); b. northern Australian species that occur mostly around and west of the Gulf of Carpentaria (Groups B – E) and those that mostly occur east of the Gulf of Carpentaria and in some cases south into coastal south-eastern Australia (Groups F – K) (Fig 15).

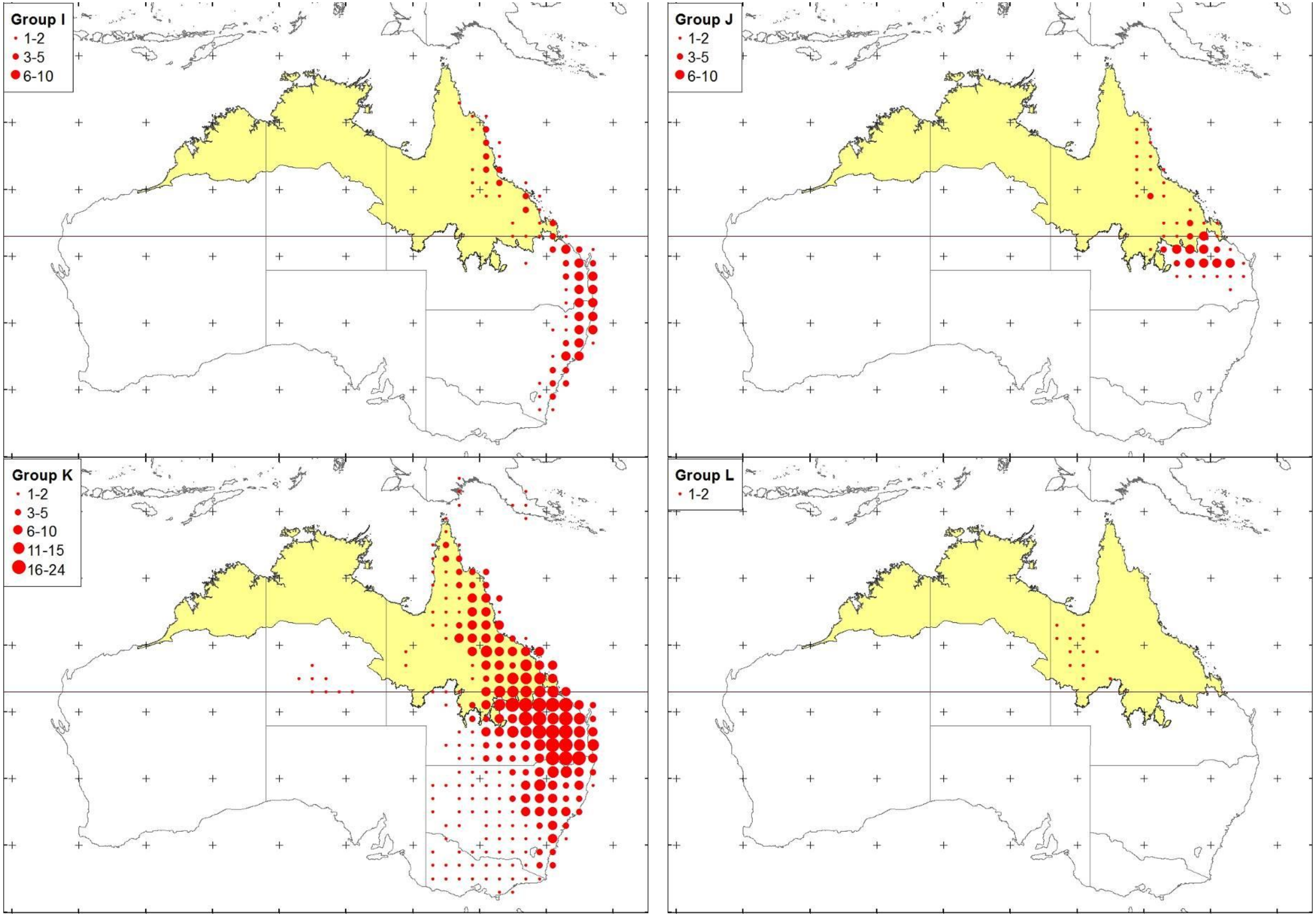
Table 4. Geographic group characteristics of north Australian eucalypt species.
"excluded" species are those excluded from the classification (Fig. 15) because recorded from fewer than three degree cells. "unclassified" species didn't fit groups, which could arise because of an unusual distribution pattern or as a result of few records. Excluded and unclassified species added to totals by *post hoc* examination are shown as "+" in the No. of species field and listed in the Notes field. A full list of group codes for species is provided in the supplementary Excel file, worksheet *Biogeography*.

Group	Characterisation	Explanation	No. of species	Example species	Notes
A	widespread semi-arid	across all northern states but few to north and east coast; extending well into central Australia	11	*C. aparrerinja* *C. terminalis* *E. camaldulensis* *E. coolabah*	
B	north-west Australia	Kimberley & Top End ± Gulf hinterland, Cape York Peninsula, Timor and New Guinea; not in central Oz	26	*C. dichromophloia* *C. grandifolia* *E. alba* *E. miniata*	
C	Top End of the Northern Territory	mostly endemic to northern Top End centred on Arnhem Plateau; 3 spp. also in north Kimberley, 1 in Qld	20 + 1	*C. arnhemensis* *C. kombolgiensis* *E. gigantangion* *E. tintinnans*	excluded *E. koolpinensis* is also endemic; total 18 Top-End-endemic species
D	Kimberley	all endemic to the Kimberley (1 extending east to Keep River, NT, which is biogeographically part of the East Kimberley)	17 + 3	*C. cadophora* *C. torta* *E. argillacea* *E. mooreana* *E. ordiana*	excluded *C. paractia*, *E. ceracea* & *E. kenneallyi* also endemic; 20 endemics in total
E	inland Kimberley & Top End	inland of B, typically in narrow arc from VRD to south Kimberley ± Barkly Tableland, W to Broome & coastal Pilbara; not in Qld	9 + 1	*C. abbreviata* *C. flavescens* *C. pachycarpa* *C. zygophylla* *E. brevifolia*	hot country specialists; excluded *E. gregoriensis* is endemic to VRD
F	sub-inland north Queensland	centred on Desert Uplands and drier parts of Einasleigh Uplands; mostly endemic to Qld, none in NSW	27 + 3	*C. dallachiana* *C. leichhardtii* *C. serendipita* *E. microneura* *E. shirleyi*	excluded species *C.* sp. Pentland Hills, *E. farinosa* & *E. quadricostata* are also endemic
G	north-east Queensland	strongly centred from SE Cape York Peninsula to Wet Tropics and inland to wetter parts of Einasleigh Uplands	13	*C. rhodops* *C. torelliana* *E. lockyeri* *E. staigeriana*	major centre of endemism near Great Divide (e.g. W of Herberton)
H	Cape York Peninsula	Cape York Peninsula ± New Guinea; *C. nesophila* also in N Kimberley and N Top End	8 + 1	*C. papuana* *E. brassiana* *E. megasepala*	excluded *E. acroleuca* is also endemic – Lakefield
I	east coastal	moist tropical coast and uplands extending S to NE NSW & occasionally further	8 + 1	*C. intermedia* *E. acmenoides* *E. grandis* *E. resinifera*	unclassified *E. latisinensis* is endemic to Qld coast south of Shoalwater Bay
J	Brigalow Belt	distributions centred on or endemic to the brigalow regions of inland south-eastern Queensland, a few extending N; all endemic to Qld	8 + 3	*C. bunites* *C. hendersonii* *C. watsoniana* *E. cloeziana* *E. suffulgens*	unclassified *C. aureola* and excluded *C.* sp. Springsure & *E. sicilifolia* are also endemic
K	eastern (2)	*cf.* I, extends to drier areas further inland and/or further N & S; often centred in SE Qld	21	*A. leiocarpa* *C. citriodora* *E. tereticornis*	
L	Mt Isa uplands	endemic to NW Qld	+ 2	*E. leucophylla* *E. nudicaulis*	identified qualitatively (see text)

Figure 16. Species richness in degree cells of the biogeographic eucalypts groups in Table 4.




Group E
1-2
3-5
6-10
Group F
1-2
3-5
6-10
11-15
16-24
Group G
1-2
3-5
6-10
11-15
Group H
1-2
3-5
6-10


Group I
1-2
3-5
6-10
Group J
1-2
3-5
6-10
Group K
1-2
3-5
6-10
11-15
16-24
Group L
1-2

Species that are endemic to northern Australia are concentrated in the north-west Australian Biogeographic Groups B–E and in the four north Queensland groups (F–H, L), and are especially a feature of the northern Top End, Kimberley and north-east Queensland groups (C, D & G) (Table 5). The remaining groups (A, I–K) consist mostly of species that are marginal to or predominantly not north Australian.

Table 5. Relationship between biogeographic group (from Table 4) and endemicity group (from Table 2) characterised by the number of eucalypt species.
NA = not allocated to a biogeographic group.

	Biogeographic group													
Endemicity group	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**NA**	**Total**
A. Endemic to NA & islands to north		3					1	3						7
B. Endemic to NA		14	21	20	4	21	11	6	3			2	3	105
C. Near endemic to NA		8			2	7								17
D. Predominantly north Australian					3	2	1			2	3			11
E. Predominantly not north Australian	5	1			1				5		8		1	21
F. Marginal to NA	6								4	6	10		1	27
Total	**11**	**26**	**21**	**20**	**10**	**30**	**13**	**9**	**12**	**8**	**21**	**2**	**5**	**188**

In most cases it is appropriate to view subspecies as belonging to the same group as their parent species notwithstanding their generally more restricted distributions. Exceptions are:

- *C. ptychocarpa* subsp. *aptycha* is restricted to the Top End and thus belongs to Group C (parent is in Group B)
- *C. stockeri* subsp. *stockeri* is perhaps endemic to a small area just west of the Atherton Tableland and thus may belong to Group G (parent is in Group H)
- the subspecies of *E. camaldulensis* partition the species' wide range somewhat idiosyncratically with regard to biogeographic groups; subsp. *arida* retains the parental primary association with the inland semi-arid zone (Group A); subsp. *acuta* most nearly aligns with Group F though there is one record in NSW; subsp. *obtusa* most nearly aligns with Group B; subsp. *simulata* occurs mainly in NE Qld but does not conform to Group G
- *E. melanophloia* subsp. *nana* occurs in isolated patches near Mt Isa and in central Australia and thus most nearly fits Group A (parent is in Group K because it is widespread in eastern Australia from central NSW northwards)
- *E. oligantha* was classified in Group C (Top End) but occurs in the Kimberley and thus could have been classified in Group B. The subspecies are reported to partition the range geographically, subsp. *oligantha* occurring in the Top End (Group C) and subsp. *modica* in the Kimberley (Group D) (Hill & Johnson 2000), but this interpretation is controversial (CPBR 2006)

An alternative perspective on the biogeography of north Australian eucalypts is provided by a classification of degree cells by the species recorded within them (Fig. 17). This is not merely an inversion of the previous analysis as in this case all records from cells outside the study area have been excluded. Poorly represented cells have also been excluded (see Methods).

In this classification, the primary division is between Queensland [eastern + northern] and north-west Australia including the Gulf lowlands of Queensland. However, the precise definition of the boundary is not well-defined especially inland (Fig. 18) due to poor documentation of the eucalypts of cells in that region and perhaps also particularly low species richness in that area.

Further subdivision into five sub-groups is strongly supported statistically (Fig. 18; P all < 0.001) but the level of subdivision is arbitrary. Cells on the semi-arid inland fringe of the study area north of the Tropic of Capricorn form a discrete sub-group within north-west Australia rather than a primary discrete group of their own (*cf.* Fig. 16), the emphasis with commonalities to the north arising because distributions inland of the study area have been excluded from the current analysis.

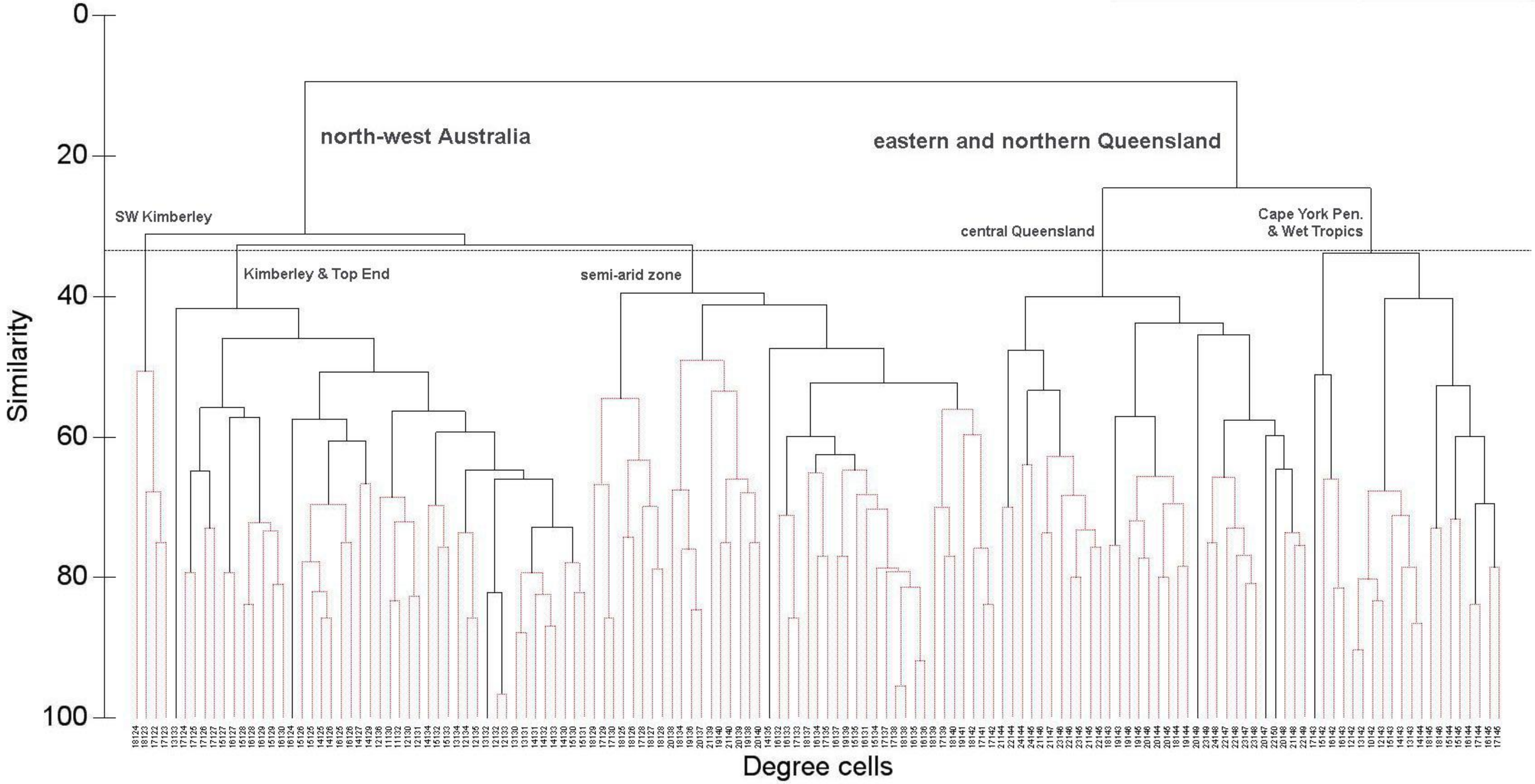


Figure 17. Dendrogram of north Australian degree cells classified by the eucalypt species recorded within them.
Black solid lines show groups that are the product of significantly non-random structure (simulation profile tests [SIMPROF], P < 0.05). The dotted line marks the division into the five nominated biogeographic groups. Degree cells are coded by latitude on their northern edge and longitude on their western edge; thus, 18124 indicates the degree cell whose centroid is 18°30'S by 124°30'E.

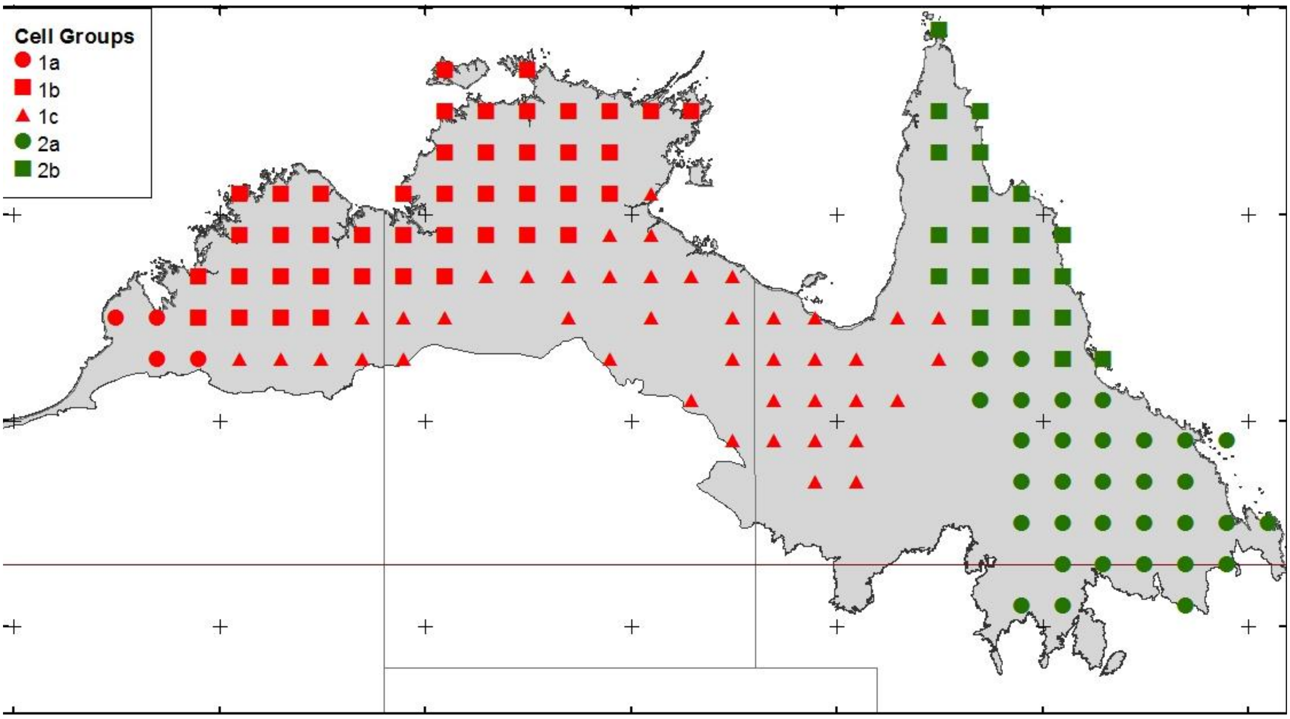


Figure 18. Degree cells classified according to the eucalypt species present in them.
Groups and sub-groups are derived from the classification in Fig. 17; i.e.:

1 = north-west Australia; 2 = eastern and northern Queensland

1a = SW Kimberley; 1b = Kimberley & Top End; 1c = semi-arid zone; 2a = central [eastern] Queensland; 2b = Cape York Peninsula & Wet Tropics.

CHAPTER 5: CONSERVATION ASSESSMENT OF SPECIES AND SUBSPECIES

Restricted range and occurrence

Extent of Occurrence (EOO) and the number of degree cells in which a taxon has been recorded (a coarse proxy for Area of occupancy (AOO)) are alternate metrics of range size and understandably, therefore, the two are very strongly correlated (Fig. 19). Nevertheless, they measure contrasting conservation attributes (Gaston & Fuller 2009). Residual values from that correlation provide an indication of the nature of each taxon's distribution, species that have been recorded in fewer cells than predicted by their EOO having a patchy distribution (or feasibly, a patchy record of that distribution).

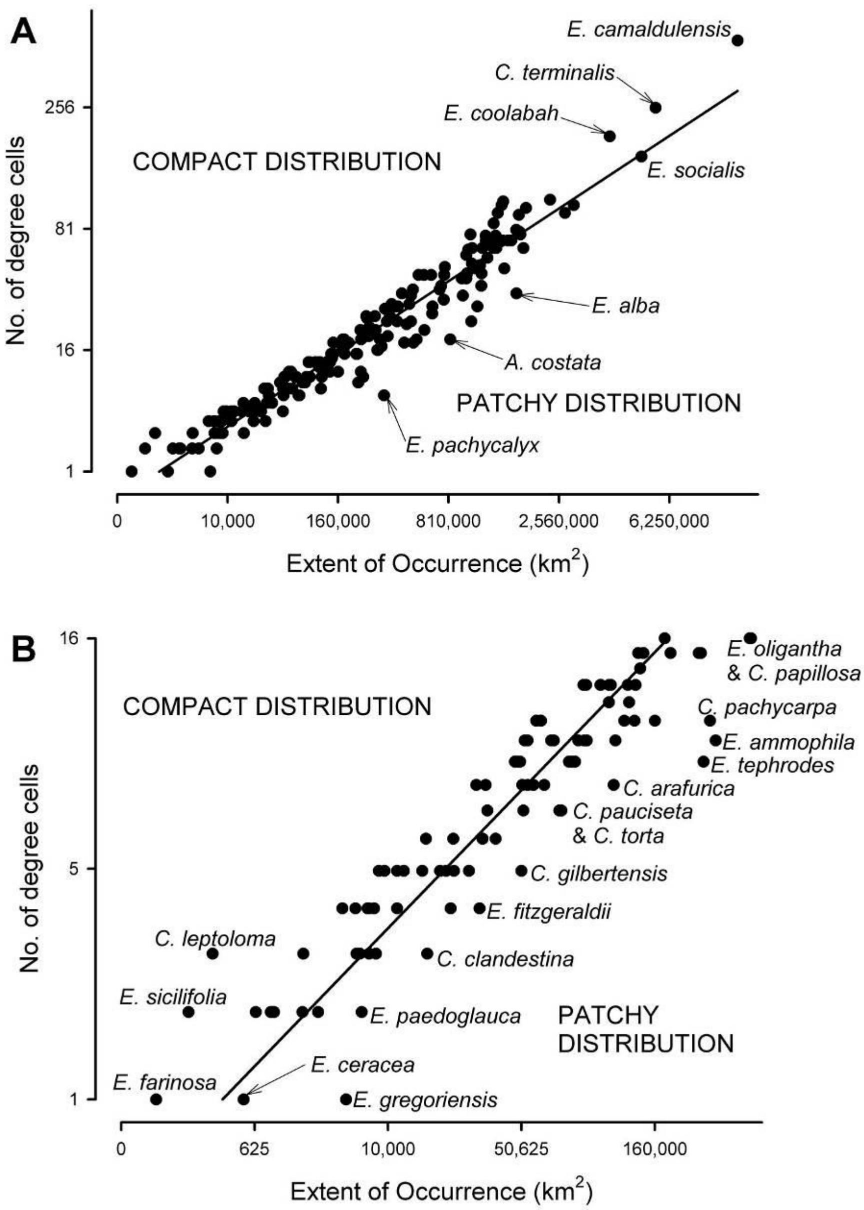


Figure 19. Two range metrics (4th-root scale) for north Australian eucalypt species: A. 185 species; B. as in A but zoomed in to those with the smallest ranges.

Three north Australian species (*C.* sp. Pentland Hills, *C.* sp. Springsure, *E. kenneallyi*) have been excluded on the basis of having no measurable Extent of Occurrence (EOO) – only 1 or 2 point locations) from the data available to us. Unsurprisingly, the regression is a positive, strong and linear fit: (No. of cells)$^{0.25}$ = 0.0599 * EOO$^{0.25}$ + 0.772; r^2 = 0.94, $F_{1,183}$ = 2770.9, P << 0.001).

Any range/occurrence metric available to us will be somewhat to very sensitive to collection effort, which is like to vary between jurisdictions and in particular with remoteness and accessibility, and perhaps also with taxonomic and conservation interest. This issue is explored further in the next chapter. Species that are rarely recorded may indeed be very rare but might also be abundant in a restricted and largely inaccessible range. We anticipate that the number of unique herbarium records (Fig. 20) would provide a useful third perspective on rarity but be more sensitive to collection effort than either EOO or the number of cells.

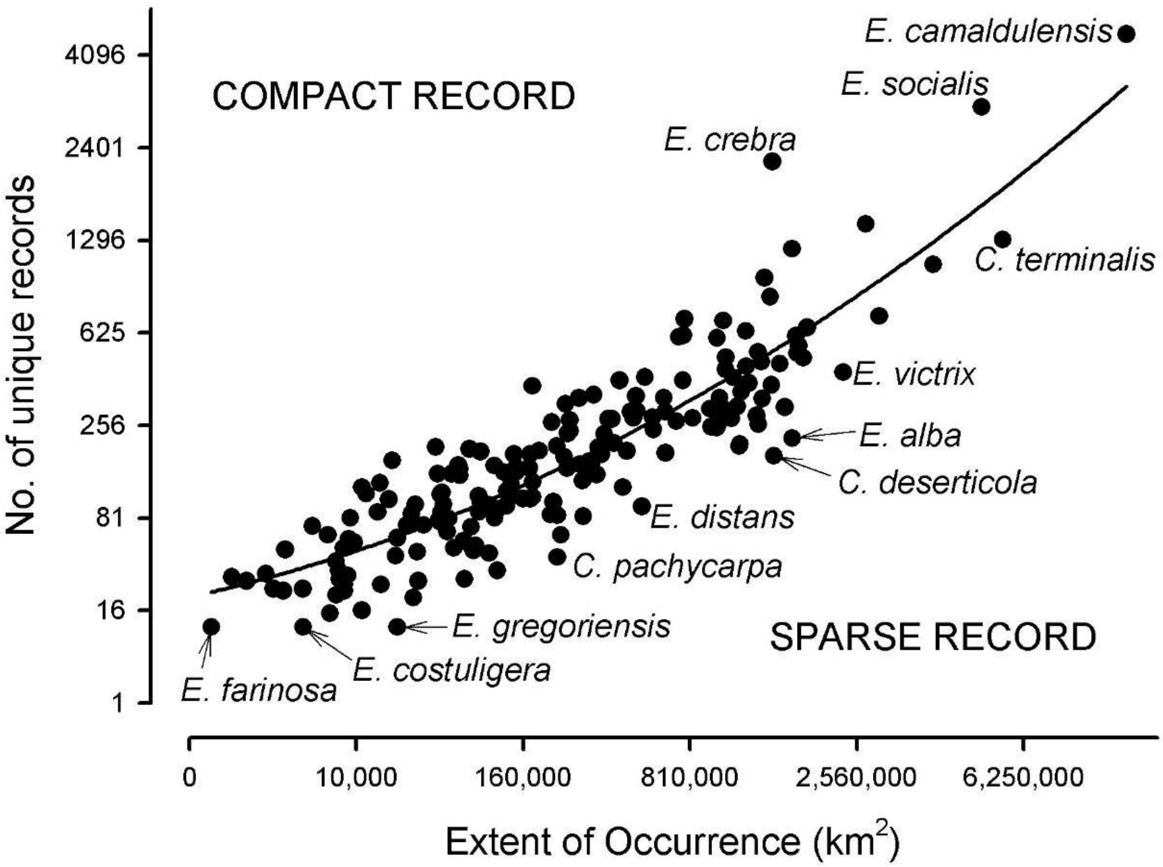


Figure 20. Relationship between Extent of Occurrence and the number of unique herbarium records for 185 north Australian eucalypt species.

Three north Australian species (*C.* sp. Pentland Hills, *C.* sp. Springsure, *E. kenneallyi*) have been excluded on the basis of having no measurable Extent of Occurrence (EOO) – only 1 or 2 point locations) from the data available to us. A second-order polynomial regression – (No. of records)$^{0.25}$ = 0.0393 * EOO$^{0.25}$ + 0.0010 * EOO$^{0.5}$ + 2.146; r^2 = 0.79, $F_{2,182}$ = 346.1, $P << 0.001$) – provided a much better visual fit than a linear regression although the improvement in r^2 was only 0.02; this contrast probably arises because the curvilinear fit better reflects the leverage effect of the few taxa with very large EOOs.

Recognising that any definition of “restricted” is necessarily arbitrary, we have developed a five-tier rank system which incorporates information from three occurrence metrics, EOO, the no. of degree cells and the no. of records based on IUCN thresholds for EOO (Table 6). The three have been matched via the correlations in Figs. 19 and 20. Taxa are ranked into one of five tiers for each of the occurrence metrics, and the most restricted of the three adopted as the taxon’s “aggregate” rank.

Table 6. Thresholds adopted in this study for 4 tiers of occurrence restriction.
Thresholds for Extent of Occurrence (EOO) correspond to the maximum EOOs under IUCN Criterion B1 for Critically Endangered, Endangered and Vulnerable respectively, though taxa must meet additional sub-criteria before so qualifying (IUCN 2001). Tier 4 has been added as representing a precautionary approach to the conservation of taxa. Thresholds for the number of degree cells and number of records have been calculated from the regressions in Figs. 19 & 20 respectively – bracketed numbers are the regressed thresholds and unbracketed numbers are the rounded thresholds adopted.

TIER	EOO (km^2)	n degree cells	n records
1. extremely restricted	100	1 (0.85)	25 (27.0)
2. very restricted	5,000	3 (2.65)	40 (42.1)
3. restricted	20,000	5 (4.85)	55 (57.6)
4. somewhat restricted	50,000	8 (7.74)	75 (76.5)
5. not restricted	>50,000	>8	>75

Between 25.0 and 28.7% of species, and between 28.9 and 42.1% of subspecies were rated as being of restricted (Tiers 1–4, Table 6) occurrence according to source metrics, and 33.5% of species and 44.7% of subspecies by the aggregated metric (Fig. 21). With just three exceptions, the parent species of restricted subspecies were not also restricted, the exceptions being:

- *C. torta*: species – Tier 4; all 3 subspecies – Tier 1
- *E. lockyeri*: species – Tier 3; subsp. *exuta* – Tier 3, subsp. *lockyeri* – Tier 1
- *E. pachycalyx*: species – Tier 4, NA subsp. *pachycalyx* – Tier 2.

Subspecies totals have been inflated by limited identification of species to their associated subspecies particularly via the no. of records, and should in consequence be treated with some caution. Rankings for each source metric, along with the aggregated metric, are presented for all taxa individually in the supplementary Excel file.

For the considerable majority of taxa, the three occurrence metrics yielded identical scores (Fig. 22). However, this was largely attributable to the majority of taxa being rated as not restricted for any of the source metrics. Among those for which at least one source metric suggested restricted occurrence, discordance of the range of 1 to 2 ranks (species) and 1 to 3 ranks (subspecies) was most frequent. This suggests both that the source metrics provide complementary perspectives on restricted occurrence but also the need to further evaluate the application of metrics to individual cases.

Issues surrounding the 16 species and 7 subspecies with an aggregated metric of *extremely restricted* are explored in Table 7. Without exception, taxa rated as *extremely restricted* overall had restricted rankings for all metrics. Taxa, and especially subspecies, were more likely to qualify as *extremely restricted* because of a small number of unique herbarium records than because of restricted EOO or no. of degree cells, and some such taxa are clearly associated with remote areas where access is difficult and opportunities to collect specimens infrequent. Some opportunities to enhance the record of restricted-occurrence species and especially subspecies exist by further examination of existing collections. The course scale of degree cells introduces an element of chance in that some species with a moderate EOO are confined to a single cell (e.g. *E. gregoriensis*, EOO 5,047 km^2) whereas others with a very small EOO are spread across two cells (e.g. *E. sicilifolia*, EOO 41 km^2). However, analysis with a finer scale grid to overcome this is constrained by the sparseness of collections in most of the study area. Nevertheless, a number of taxa are very convincingly *extremely restricted* regardless, for instance being known from just a single location (*C. cadophora* subsp. *polychroma*, *C.* sp. Pentland Hills and *C.* sp. Springsure) or very few locations. IUCN S&PS (2011) advocates that threat assessments proceed on the available evidence regardless of limitations (there are always limitations). The metrics and rankings for each taxon are provided in the supplementary Excel file at the worksheet *taxon assessments*.

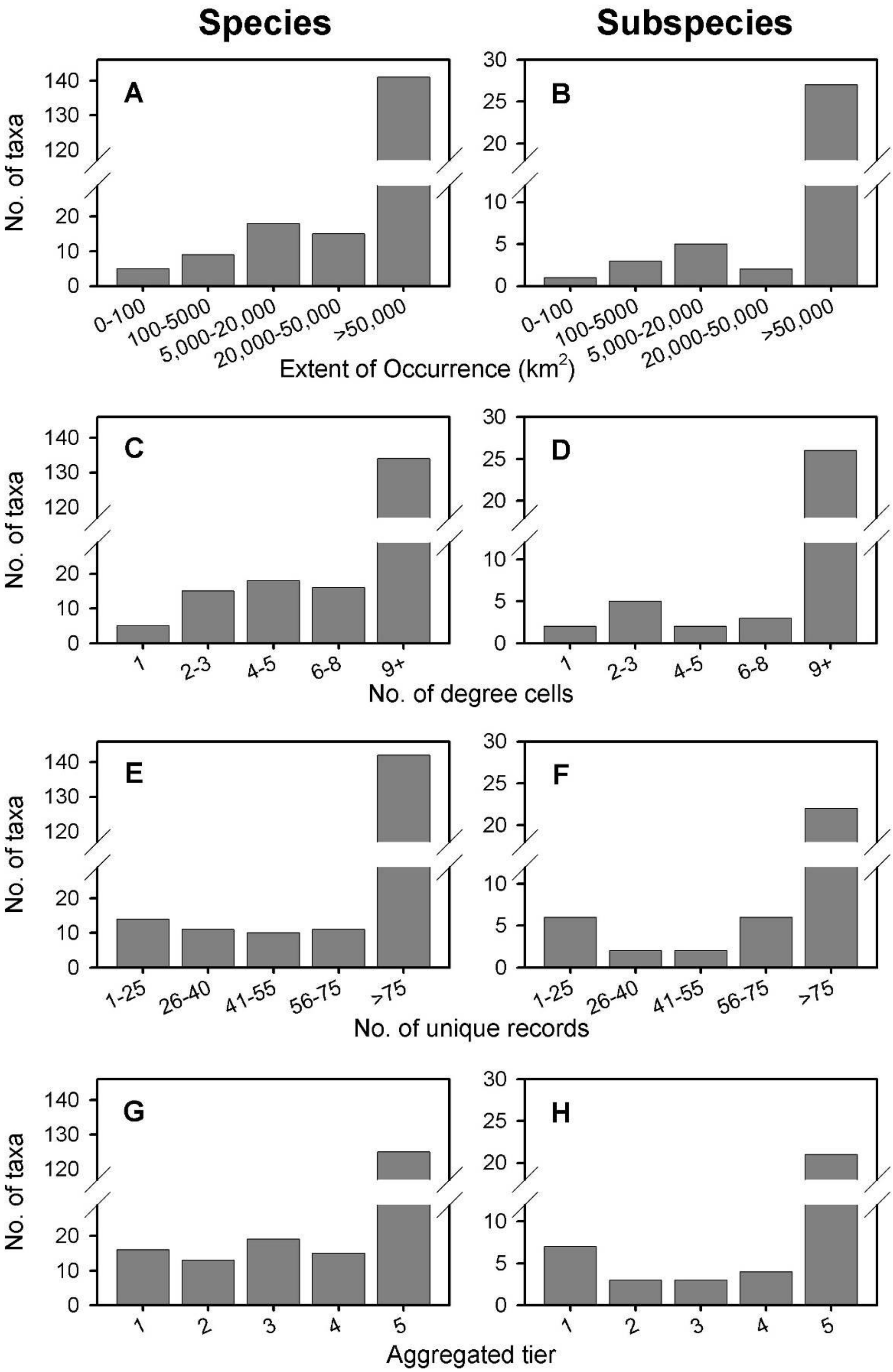


Figure 21. Relative frequency of three range/occurrence metrics among north Australian eucalypt species (A, C, E) and subspecies (B, D, F), and an aggregated metric of restricted occurrence (G, H). Classes correspond to the thresholds in Table 6. For the aggregated metric, taxa have been placed in the most restricted of the three source metrics; i.e. if a taxon rates as Tier 3 for EOO, Tier 2 for no. of cells and Tier 4 for no. of records, it is rated as Tier 2 overall.

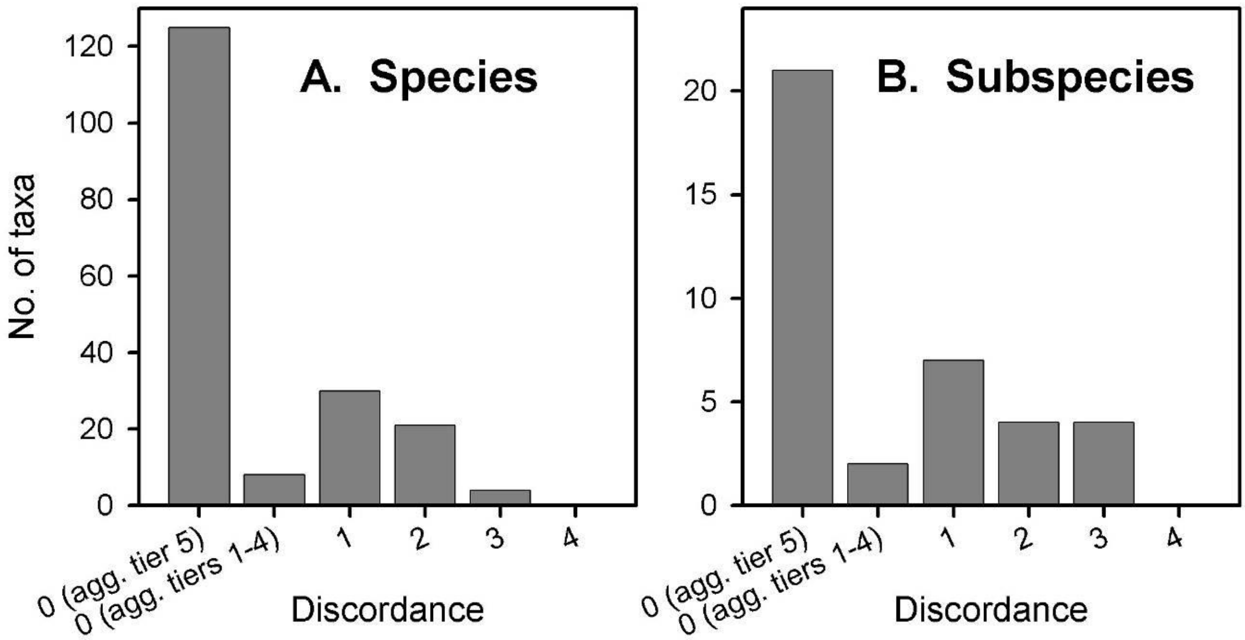


Figure 22. Discordance (max. – min.) among three source metrics of occurrence restriction for north Australian eucalypts.
By definition, aggregate tier 5 taxa (not restricted) have no discordance.

Priority 1 restricted range taxa (species and subspecies) are strongly concentrated in the central and north Kimberley (WA), with secondary peaks in the Arnhem Plateau (NT), the White Mountains / Pentland Hills area to the south-west of Charters Towers (Qld), the area from Emerald and Blackwater to Springsure (Qld) including the Blackdown Tableland (just outside the study area), and around Mt Isa (Qld) (Fig. 23). Some geographic shift in emphasis occurs with the additional consideration of lower priority restricted range taxa, including strong reinforcement of the importance of the Arnhem Plateau and adjacent areas in the northern Top End (NT) and extension of the White Mountains / Pentland Hills hotspot north to embrace the entire fringe of Queensland's Wet Tropics and inland to Georgetown and the Gregory Range (Fig. 23).

Table 7. North Australian eucalypt taxa rated as being of extremely restricted occurrence for one or more of three source occurrence metrics. Tier 1 (extremely restricted) rankings are highlighted. AVH = Australia's Virtual Herbarium (http://avh.chah.org.au/).

Taxa	Tier (EOO)	Tier (cells)	Tier (records)	EOO (km^2)	No. 1° cells	No. of records	Discordance (Fig. 22)	Notes
Species								
Corymbia aureola	3	3	1	7426	4	24	2	Only just qualified as *extremely restricted* based on the paucity of records. Scattered occurrence inland from Mackay & Rockhampton. The scarcity of records suggest it is highly localised, but notes with some records (AVH) indicate that it is locally common.
Corymbia clavigera	3	3	1	11418	5	16	2	Included on the basis of few records. Known only from within a few kilometres of the coast, including islands, in the far north-western Kimberley. Records are spread over a distance of c. 230 km and the coast is convoluted. Severe inaccessibility is likely to have constrained collection opportunities. On the other hand, much of the EOO is marine.
Corymbia paractia	2	2	1	647	2	25	1	Only just qualifies as *extremely restricted* based on the paucity of records, though its occurrence in two degree cells is marginal. Known only from c. 70 km of coast around and north of Broome, WA, with an outlier SW of Derby (CANB 474646) assumed to be incorrect.
Corymbia sp. Pentland Hills	1	1	1	0	1	1	0	All metrics suggest *extremely restricted* because based on a single specimen collected c. 80 km WSW of Charters Towers, Qld. Notes with the specimen state "very common in area".
Corymbia sp. Springsure	1	1	1	0	1	1	0	All metrics suggest *extremely restricted* because based on a single specimen collected c. 75 km S of Emerald, Qld.
Eucalyptus ceracea	2	1	2	445	1	33	1	Known from an area c. 40 x 15 km in a single degree cell from the north Kimberley – an outlier from Broome is assumed to be an error. The area is very remote so feasibly the species could be more widespread. Restricted to "skeletal sandy soils over sandstones" (Hill & Johnson 1998) on "the tops and sides of sandstone escarpments" (CPBR 2006).

Table 7 continued

Taxa	Tier (EOO)	Tier (cells)	Tier (records)	EOO (km^2)	No. 1° cells	No. of records	Discordance (Fig. 22)	Notes
Eucalyptus costuligera	2	2	1	2176	3	11	1	Included on the basis of few herbarium records. Known from an area c. 100 x 40 km WSW of Kununurra, WA. An AVH record extending the range c. 100 km to the S is a coordinate error. “locally abundant but apparently restricted on dry, elevated skeletal soils over sedimentary rocks ” (Hill & Johnson 2000).
Eucalyptus farinosa	1	1	1	3	1	11	0	Known only from two sites 15 km apart c. 90 WSW of Charters Towers, Qld, and thus rated as *extremely restricted* based on all three metrics. In describing the species, Hill (1997) noted a population of >1,000 individuals and that it is “locally frequent but restricted to shallow gritty soils on the slopes of a steep granite range. This species is the dominant tree on steep dry slopes”.
Eucalyptus fitzgeraldii	4	3	1	32523	4	21	3	Large discrepancy between few records and larger range metrics might be explained by the remote portion of the NW Kimberley, WA, in which it occurs. Large EOO is the product of three known “populations” c. 100 and 230 km apart, one from a single site and the others with EOOs of c. 65 & 6000 km^2.
Eucalyptus gigantangion	3	2	1	6034	3	22	2	Only just qualifies as *extremely restricted* based on few records. The species has a moderate distribution along the western edge of the Arnhem Land plateau in the NT and a recent record from Goomadeer in Arnhem Land that substantially increases the EOO is apparently acceptable. Could feasibly be more widely distributed around the Plateau, much of which is inaccessible, but note that quite a few records in AVH have coordinate errors (excluded from our analysis) that overstate the range of the species. Hill & Johnson (1998) regarded it as “highly localised” but “locally abundant” “on residual to skeletal sand over sandstone”

Table 7 continued

Taxa	Tier (EOO)	Tier (cells)	Tier (records)	EOO (km^2)	No. 1° cells	No. of records	Discordance (Fig. 22)	Notes
Eucalyptus gregoriensis	3	1	1	5047	1	15	2	Known only from limited herbarium collections from six locations scattered over a moderate EOO which is nevertheless confined to a single degree cell. Much of the potential habitat is difficult to access so the species may be more abundant than collections indicate (Walsh & Albrecht 1998), but these may infill the EOO rather than expand it. Restricted to “shallow soils over sandstones, immediately adjacent to seasonal watercourses, or on cliffs and subtending slopes fringing watercourses” (Walsh & Albrecht 1998).
Eucalyptus kenneallyi	1	2	1	0	2	2	1	Known only from two remote islands 85 km apart just off the Kimberley coast, WA. EOO not calculable because there are only two records, but regardless is likely to be small (Tier 1 or 2) and predominantly marine unless found on the mainland or other islands.
Eucalyptus koolpinensis	2	2	1	992	2	24	1	Only just qualifies as *extremely restricted* based on few records from Koolpin Gorge and 2 other locations on the Arnhem Land Plateau in the NT; it is *very restricted* based on the other metrics. Much of the Plateau is very difficult to access. The EOO has recently been expanded substantially by a collection far to the ENE of the main range. Sightings from the air (Kym Brennan per Ian Cowie pers. comm.) suggest additional locations with potential to expand the number of locations, EOO and collection base but little or no potential to expand the number of degree cells.
Eucalyptus nudicaulis	2	2	1	2131	2	25	1	Only just qualifies as *extremely restricted* based on few records from 7 locations around Mt Isa and Cloncurry, Qld; it is *very restricted* based on the other metrics. Relatively good access to the area does not encourage the thought that the EOO or no. of cells could be much increased by further survey. Confined to rocky gullies and steep quartzite hillsides between 400 & 520 m ASL (Bean 1991).

Table 7 continued

Taxa	Tier (EOO)	Tier (cells)	Tier (records)	EOO (km^2)	No. 1° cells	No. of records	Discordance (Fig. 22)	Notes
Eucalyptus sicilifolia	1	2	2	41	2	31	1	Very limited EOO c. 50 m S of Emerald, Qld which, however, straddles two degree cells and is well-collected. The EOO is almost linear, consisting of 4 "populations" spread over c. 22 km on the tops of volcanic plugs and adjacent upper scree slopes (Hill & Johnson 1991).
Eucalyptus sp. Mt Hope Homestead	4	3	1	24168	5	11	3	Sparingly recorded in specimens but with a moderate distribution in a reasonably accessible and surveyed area to the N, W & S of Charters Towers, Qld.
Subspecies								
Corymbia cadophora subsp. *pliantha*	2	2	1	1410	3	9	1	Qualifies as *extremely restricted* on paucity of records; otherwise as *very restricted*. Occurs only in the east and north-east Kimberley, WA. It is likely that a number of herbarium records of *C. cadophora* not attributed to subspecies are of this subspecies, but range overlap with subsp. *cadophora* precludes confident attribution of them without examination of specimens.
Corymbia cadophora subsp. *polychroma*	1	1	1	0	1	1	0	Rated as *extremely restricted* on all metrics, reflecting that it is "Known only from the type locality over a distance of about 2 km, in the Ragged Range, East Kimberley … where it grows on gentle sandstone slopes" (Barrett 2007).
Corymbia torta subsp. *allanii*	3	2	1	8898	2	15	2	All three subspecies qualify as *extremely restricted* based on the paucity of records, and as *restricted* or *very restricted* on other metrics. All three are endemic to the Kimberley, WA. 27 records not attributed to subspecies offer potential to increase the count for all subspecies. All subspecies occur in remote areas, though subsp. *torta* less so, so all may be relatively under-represented in the record. Thus it is possible that a rating of *extremely restricted* is not really appropriate except perhaps for subsp. *mixtifolia*.
Corymbia torta subsp. *mixtifolia*	2	2	1	164	2	6	1	
Corymbia torta subsp. *torta*	3	3	1	10240	4	9	2	

Table 7 continued

Taxa	Tier (EOO)	Tier (cells)	Tier (records)	EOO (km^2)	No. 1° cells	No. of records	Discordance (Fig. 22)	Notes
Eucalyptus lockyeri subsp. *lockyeri*	2	1	4	1207	1	68	1	Well-recorded (*somewhat restricted*) over a moderate EOO (*very restricted*) but in just a single degree cell (*extremely restricted*) on the western edge of the Atherton Tableland, north Qld. Its circumscription to a single degree cell (*cf.* 2 or 3 cells) is thus somewhat fortuitous.
Eucalyptus oligantha subsp. *modica*	3	2	1	12827	3	8	2	Hill & Johnson (2000) suggest that this subspecies is the only one of this species to occur in the Kimberley, WA, to which it is endemic. If this is so, then 44 records may be attributed to it and its cell count increased to 4, reducing its qualification from Tier 1 to 3 (*extremely restricted* to *restricted*). However, we hesitate to do so on the basis that most records have not been attributed to subspecies, one WA record has been attributed to subsp. *oligantha*, and also there is considerable uncertainty about the status of subspecies (CPBR 2006).

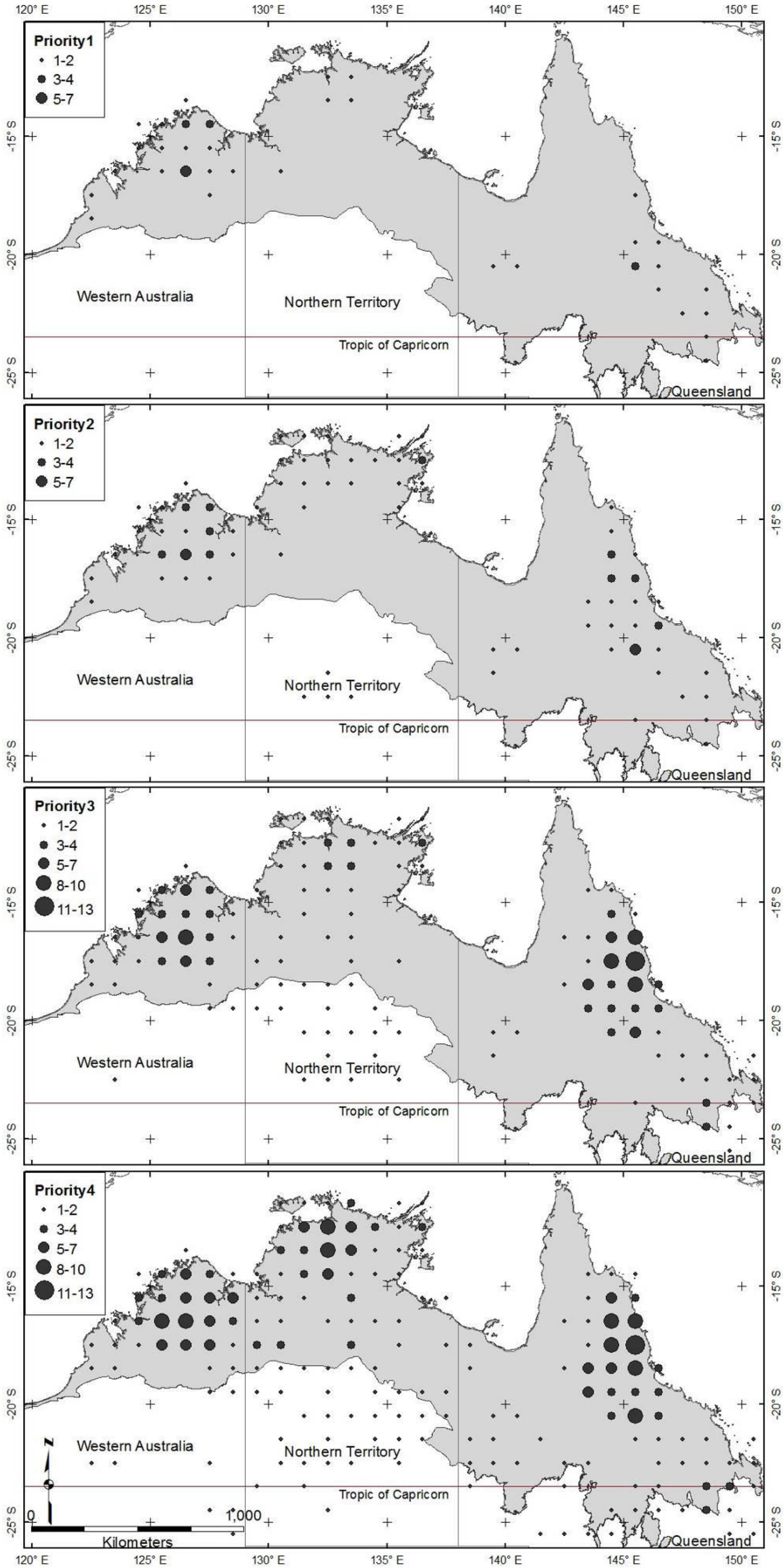


Figure 23. Richness of restricted range north Australian eucalypt taxa in degree cells in four cumulative ranked priorities. Following Table 6, Priority 1 cells contain *extremely restricted* taxa, priority 2 cells contain *extremely restricted* and *very restricted* taxa, priority 3 cells contain *extremely restricted*, *very restricted* and *restricted* taxa, and priority 4 cells contain *extremely restricted*, *very restricted*, *restricted* and *somewhat restricted* taxa.

Reservation and land clearing

Intersection of shapefiles for reservation and land clearing with those for key taxa provides indices of reservation and clearing for them. While these indices come with caveats, they are a useful approximation that should, at the very least, prompt further consideration and investigation. The accuracy of the coordinates of some herbarium records, particularly older ones, is questionable and may generate error but not bias – either an over- or under-estimation of reservation and clearing is possible in consequence. Further, the interpretation of a record as representative of a population that has been reserved or not, or cleared or not, may contain biases in the direction of either over- or under-estimation. Records may have been selectively collected along roadsides in cleared land because the uncleared land is not readily accessible or there are sensitivities about collecting in reserves, or conversely collections may be biased towards uncleared land and reserves because of restrictions on access to private property or simply that there are few or no individuals remaining in cleared land.

For the purpose of these analyses, crown reserves are national parks and other reserves declared under conservation legislation, whilst private reserves are Indigenous Protected Areas and reserves owned or managed by the Australian Wildlife Conservancy and Bush Heritage Australia.

Both crown and private reserves are concentrated in the higher-rainfall regions of the north and north-east, with exceptionally poor representation in the inland pastoral districts (Fig. 24). Private reserves provide strong coverage additional to crown reserves in the central and north Kimberley and, to a lesser extent, in the Top End of the Northern Territory, the north of Cape York Peninsula, and the inland fringe of the Wet Tropics region of north Queensland. Land clearing in the study area is strongly concentrated in the south-east and along the Queensland coast, with relatively small areas elsewhere in Queensland and in the north-west of the Northern Territory (Fig. 24).

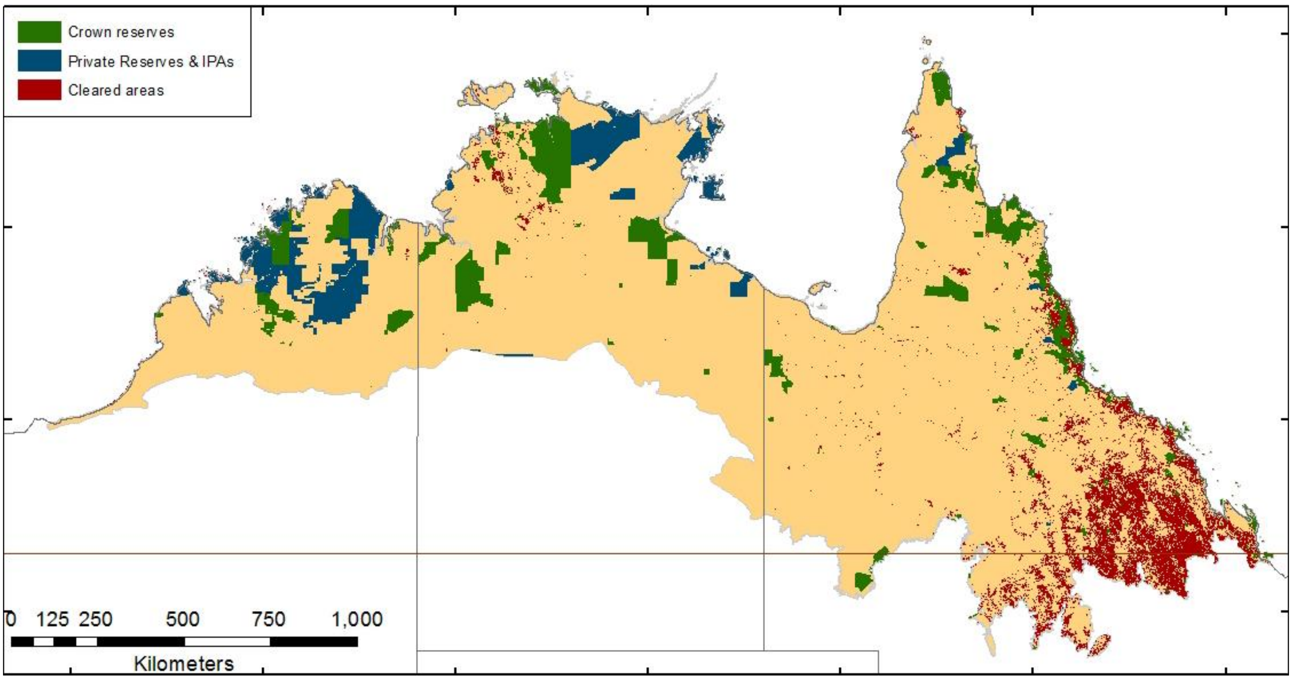


Figure 24. Distribution of reserves and land clearing in the study area.
Shapefiles of reserves appear to be all up-to-date; land clearing data are current to 2007 (NT), 2010 (Qld), and around 2004/5 (WA, based on NVIS data).

Eleven species and three subspecies endemic to the study area do not occur in either a crown or private nature reserve, and a further 52 endemic species and 10 endemic subspecies have reservation indices of less than 30% (Fig. 25). In total, 60.0% of species and 59.1% of subspecies have reservation indices of less than 30%.

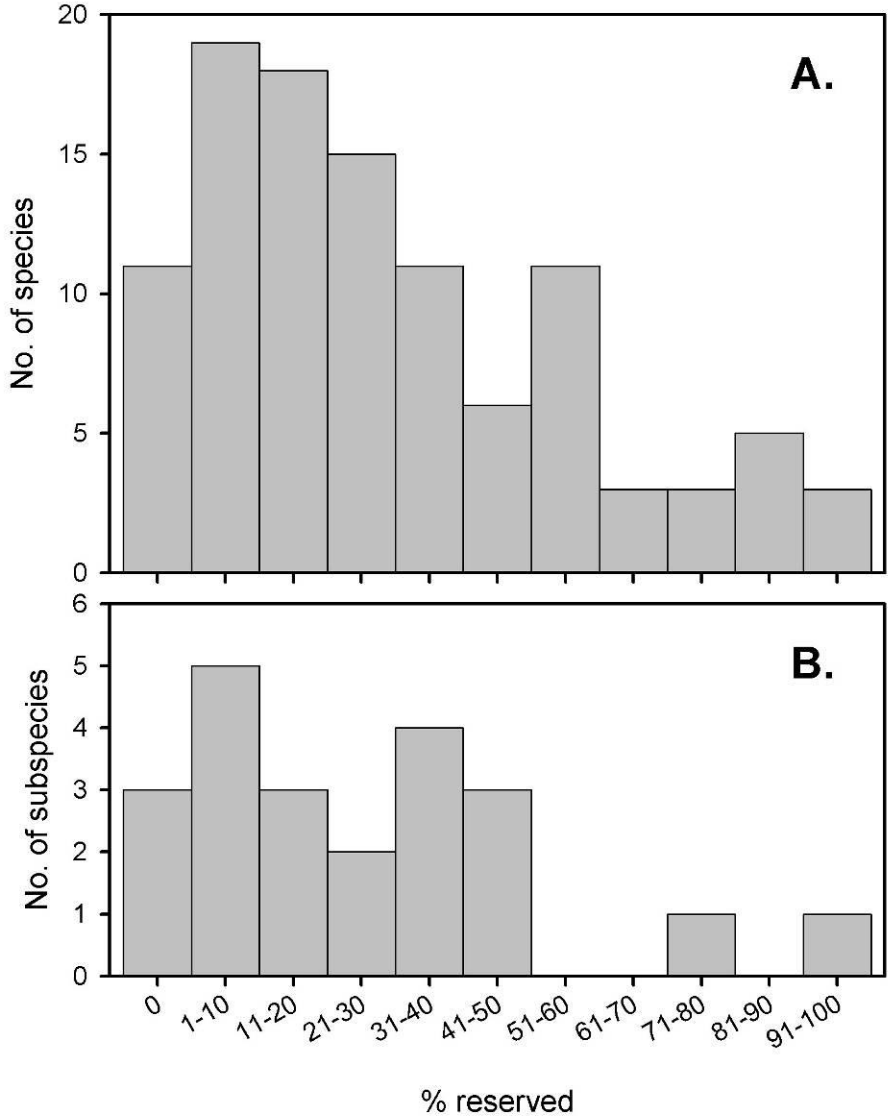


Figure 25. Frequency distribution of the reservation index for eucalypt species (A, n = 105) and subspecies (B, n = 22) endemic to the north Australia study area.

Crown and private reserves provide useful complementarity in the contribution to the reservation status of eucalypt taxa endemic to the study area, with most well-reserved taxa occurring with considerable predominance in either one or the other reserve system (Fig. 26). In the case of crown reserves, this contribution often comes from one or two large reserves incorporating a taxon of limited distribution. For example, the high crown reservation indices for *E. koolpinensis*, *E. gigantangion* reflect occurrence in Kakadu National Park, *E. gregoriensis* occurrence in Judburra (Gregory) National Park, *C. oocarpa* in Kakadu and Nitmiluk National Parks and *E. mooreana* in the King Leopold Range Conservation Park, though *E. alba* var. *australasica* occurs in nine crown reserves. In contrast, *E. fitzgeraldii* occurs in four private reserves (the AWC's Artesian Range reserve and the Uunguu, Wilinggin, and Dambinmangari IPAs), *E. pantoleuca* in three (Wilinggin IPA and the AWC's Tableland and Mornington Stations) and *C. leptoloma* in two (Mt Zero Taravale Sanctuary and Girringun IPA).

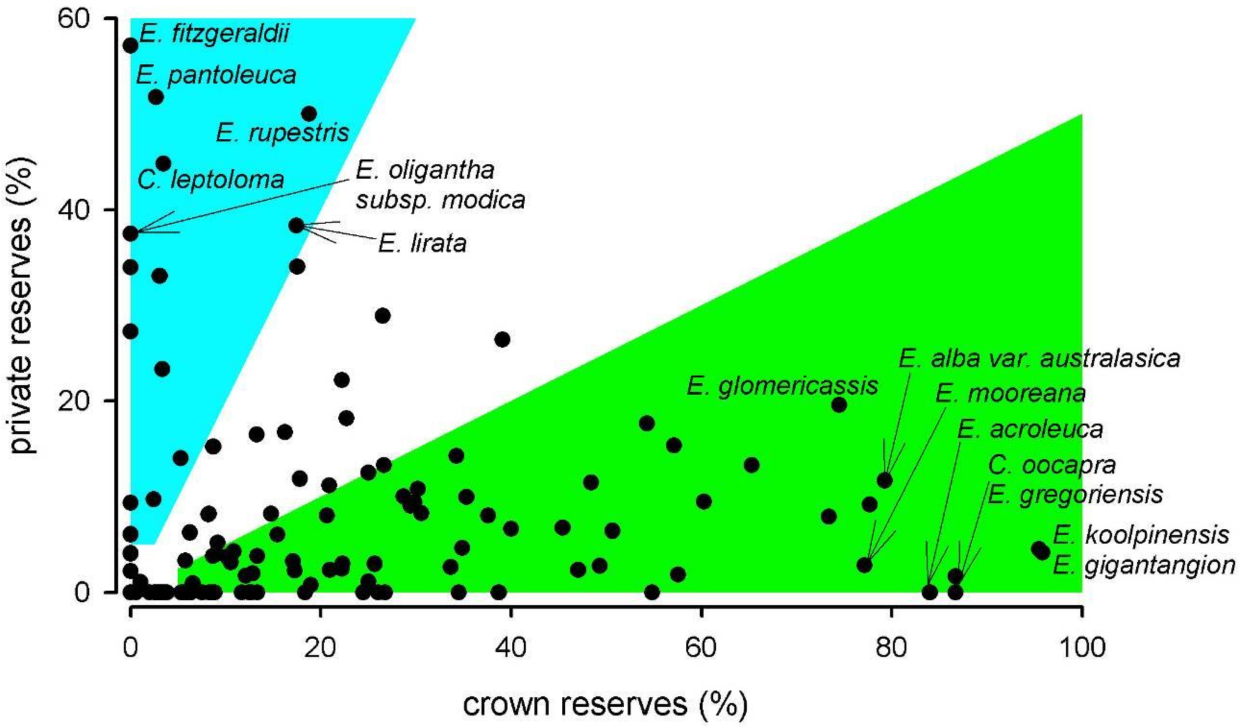


Figure 26. Relationship between the crown and private reservation indices for 127 eucalypt taxa endemic to the north Australian study area, with select taxa marked.
The coloured areas are those parts of the graph in which the index is at least double for one class of reserve compared to the other and greater than 5% for either; i.e. taxa in the blue area are particularly well-represented in the private reserve system whereas those in the green area are particularly well-represented in crown reserves.

The distribution of taxa were screened against known areas of clearing, and the clearing index calculated for 47 taxa for which clearing was considered to be of concern (potentially >30% [see assessment of threatened taxa hereafter], also if already rated as threatened). Many assessed taxa were endemic to Qld (n = 40), a few to the Northern Territory (n = 5) and a few nearly endemic to Queensland (n = 2). Two species (*E. cambageana*, *E. raveretiana*) had clearing indices of greater than 50%, 6 of between 30 and 50%, 10 of between 20 and 30%, 23 of between 0 and 20% and six of 0%. Taxa with a clearing index of more than 20% were confined to Queensland, with a strong concentration in the south-east of the study area (notably in the Brigalow Belt region) and along the east coast. Additionally, one is endemic to the Wet Tropics (*C. torelliana*) and four widespread in eastern Queensland (*C. dallachiana*, *C. erythrophloia* , *E. cloeziana*, *E. platyphylla*). The highest clearing index for a taxon outside of Queensland was *C. foelscheana*, endemic to the north of the Northern Territory, with an index of 17.7%. The significance and geographical spread of these taxa is explored further in the assessment of threatened taxa hereafter.

Taxa listed as threatened

Nine north Australian eucalypt taxa are currently listed as threatened (includes Vulnerable, Endangered and Critically Endangered) under State or Commonwealth legislation (Table 8). Nineteen taxa have some other officially-recognised status of conservation concern and a further ten taxa were listed as of concern by ROTAP (Briggs & Leigh 1996). No north Australian eucalypt taxa are listed by the International Union for the Conservation of Nature (IUCN 2013). The eight taxa listed as threatened under Commonwealth legislation are all rated as Vulnerable and with the official assessment that a recovery plan is not required. Six of these eight are endemic to Queensland, two to Western Australia and none occurs in the Northern Territory. Of taxa listed in Table 8, eight taxa listed as of concern are recognised by their respective State herbarium (3 in WA, 5 in the NT) but not in the Australian Plant Census as employed in this study. The distribution of taxa listed as either threatened or of conservation concern and recognised in the Australian Plant Census are mapped in the next chapter.

Of the three state and one national jurisdiction of relevance, only the Northern Territory appears to adhere strictly to IUCN criteria (e.g. Woinarski *et al.* 2007b). Commonwealth listings are all carried over from earlier listings, the basis for which is unclear, and only one species has been re-assessed recently – *E. raveretiana* was re-assessed in December 2010 and the status of Vulnerable maintained as "a precautionary approach" even though it failed to meet any of the EPBC Act criteria (http://www.environment.gov.au/biodiversity/threatened/species/pubs/16344-listing-advice.pdf; downloaded 26 Aug. 2013).

Figure 27. *Eucalyptus pachycalyx* subsp. *pachycalyx* (Pumpkin Gum).
Listed by Briggs & Leigh (1995) as "rare in Australia but with no known threat".
Photographed near Irvinebank, north Queensland.

Explanation and footnotes for Table 8 on next page

APC = Australian Plant Census 2011 update as adopted in this report (see *Study area and methods*).
WA status: T = threatened; P1 = Priority One: Poorly known taxa with few populations on threatened lands; P2 = Priority Two: Poorly known taxa with few populations including some on conservation lands.
NT, Qld and national status: V = vulnerable, NT = near threatened; DD = data deficient.
ROTAP = Rare or Threatened Australian Plants (Briggs & Leigh 1996). This list was the precursor to listing under the Commonwealth's *Environment Protection & Biodiversity Conservation Act.*

2 = Geographic range in Australia < 100 km
3 = Geographic range in Australia > 100 km
C = Reserved (at least one pop'n in a reserve)
K = poorly known; suspected but not confirmed to be in another category
R = rare in Australia but with no known threat
V = vulnerable; not presently endangered but might become so in 20-50 years
dash = reserved population is not accurately known

* *E. acroleuca*: we have assumed that *E.* sp.11 (Lakefield) is *E. acroleuca* (the Lakefield Box).

Table 8. North Australian eucalypt taxa listed as threatened (yellow highlight) or of conservation concern.
See previous page for footnotes and explanations.

Taxon	Official status				ROTAP	Notes
	WA	NT	Qld	National		
Taxa recognised in Australian Plant Census (2011 update)						
Corymbia aspera					3RC-	occurs in WA, NT & Qld
Corymbia cadophora subsp. *polychroma*	P1					WA endemic
Corymbia clandestina			VU	VU	2V	Qld endemic
Corymbia gilbertensis					3R	Qld endemic
Corymbia leptoloma			VU	VU	2V	Qld endemic
Corymbia paractia	P1					WA endemic
Corymbia rhodops			VU	VU	2V	Qld endemic
Corymbia xanthope			VU	VU	3VC-	Qld endemic
Eucalyptus acroleuca					2RC-	listed as *E.* sp.11 (Lakefield)*; Qld endemic
Eucalyptus ammophila					3K	Qld endemic
Eucalyptus argillacea					2K	WA endemic
Eucalyptus ceracea	T			VU	2V	WA endemic
Eucalyptus costuligera	P1					WA endemic
Eucalyptus cupularis		NT				occurs in WA & NT
Eucalyptus distans	P1				2K	occurs in WA, NT & Qld
Eucalyptus exilipes					2RC-	Qld endemic
Eucalyptus fitzgeraldii	P2				2K	WA endemic
Eucalyptus gregoriensis		DD				NT endemic
Eucalyptus howittiana					3RC-	Qld endemic
Eucalyptus kenneallyi	P1					WA endemic
Eucalyptus koolpinensis		NT			2RC-	NT endemic
Eucalyptus limitaris		DD				occurs in WA & NT
Eucalyptus lockyeri					3R	Qld endemic
Eucalyptus mooreana	T			VU	3V	WA endemic
Eucalyptus ordiana	P2				2K	WA endemic
Eucalyptus pachycalyx subsp. *pachycalyx*					3R	Qld endemic (Fig. 27)
Eucalyptus paedoglauca			VU	VU	2V	Qld endemic
Eucalyptus quadricostata					2R	Qld endemic
Eucalyptus raveretiana			VU	VU	3VC-	Qld endemic
Eucalyptus sicilifolia			VU		2RC-	Qld endemic
Taxa not recognised in the Australian Plant Census (2011 update)						
Corymbia pedimontana	P1					WA endemic
Corymbia sp. Yampi Peninsula	P1					WA endemic
Eucalyptus helenae		DD				??
Eucalyptus pachycarpa subsp. *pachycarpa*		DD				??
Eucalyptus sp. Kalkarindji		DD				NT endemic
Eucalyptus sp. Killarney		DD				occurs in WA & NT
Eucalyptus sp. Montejinni Station		DD				occurs in WA & NT
Eucalyptus sp. Pitta Creek	P1					WA endemic

Taxa that may be threatened

Background: IUCN criteria for assessment of threats

The International Union for the Conservation of Nature provides a widely accepted set of criteria for the listing of species and infraspecific taxa as threatened (IUCN 2001) and which is the basis for their internationally recognised Red List of Threatened Species (IUCN 2013). The Commonwealth and each state also assess threat status for taxa within their jurisdiction, though criteria and categories vary (sources in Table 9). The Northern Territory is the only jurisdiction in the study area to employ IUCN criteria exactly (Woinarski *et al.* 2007). Commonwealth criteria under the EPBC Act are similar but not identical to those of the IUCN, while those of Queensland and Western Australia are more idiosyncratic. Further, whereas IUCN Red List assessments are global, i.e. they apply to the entire taxon or population, regional assessments apply only to regional occurrence, so may differ on that basis between jurisdictions. For example, a species might be threatened in Western Australia but abundant in the Northern Territory and thus not threatened overall. In contrast, if a taxon is endemic to a state or territory, then in theory its threatened status should be identical at the state, national and global (Red List) levels. In practice, this is often not the case, not only because criteria vary, but also because perspectives and interpretations may vary and assessments are likely to have been undertaken at different times. The latter is important because a number of key criteria have a strong temporal component such as decline that has occurred, or is projected to occur, over three generations.

Table 9. Source for categories of threat and criteria for its assessment for Australian jurisdictions relevant to the north Australian study area.

Jurisdiction	Source of criteria and categories
Commonwealth of Australia	http://www.environment.gov.au/system/files/pages/d72dfd1a-f0d8-4699-8d43-5d95bbb02428/files/guidelines-species.pdf; downloaded 4 Dec. 2013
Queensland	http://www.ehp.qld.gov.au/wildlife/threatened-species/; downloaded 4 Dec. 2013
Northern Territory	Woinarski *et al.* (2007b)
Western Australia	http://www.dec.wa.gov.au/publications/cat_view/460-threatened-species-and-ecological-communities.html; downloaded 4 Dec. 2013

Under IUCN criteria, a taxon may qualify as Critically Endangered, Endangered or Vulnerable under any one of five broad criteria, summarised in general terms in Table 10. In each case, there are specific thresholds for reduction, size of population or range, and/or severity of threat. A taxon may be classified as Near Threatened if it falls just outside the thresholds for these criteria. Declines or threats may apply in the past, be on-going and/or be projected for the future but are in all cases constrained to be within 10 years or three generations, whichever is the longer, and in the case of projections into the future, up to a maximum of 100 years. The minimum level of decline (actual or potential) to qualify as Vulnerable (the least threatened category) is 30% over the allowed interval. A tabulation of the full criteria with thresholds is available in Woinarski *et al.* (2007b, Table II) as well as in IUCN (2001).

Table 10. Generalised criteria for listing a taxon as threatened (IUCN 2001).

Criteria
A. reduction in population size
B. restricted geographic range combined with threats
C. small population size combined with severe threats
D. very small population size, AOO or no. of locations in the absence of threats
E. population viability analysis shows high probability of future decline

Background: application of IUCN criteria to north Australian eucalypts

In this study, we apply IUCN criteria strictly and follow the additional, detailed guidelines provided by the IUCN (IUCN S&PS 2011). Further, our assessments are global in that the taxa assessed either occur naturally only in the study area or, if they occur elsewhere, we have assessed the taxon based on its entire range.

The main data available to us for these assessments are the location records downloaded from Australia's Virtual Herbarium for use throughout this report, and high-resolution shapefiles of land clearing since European settlement for Queensland (to 2010), Western Australia (to 2004/5) and the Northern Territory (to 2007). Data derived from these records and shapefiles of direct application to these assessments are: Extent of Occurrence (EOO); the number of locations (very rare taxa only); and the proportion of records that are in or from cleared land. We consider the latter to be a useful "index of abundance appropriate to the taxon" (IUCN 2001). It comes with a number of caveats most notably including that the positional accuracy of the records varies and that biases undoubtedly exist in the collection of specimens from cleared land or native vegetation. We offer it, not as a definitive measure of decline but as a first approximation; taxa flagged as having a high proportion of records in cleared areas warrant concern and further investigation.

Given these data and the possibility of further land clearing, we consider the detailed criteria and thresholds outlined in Table 11 to be applicable to our analysis. Criterion D1 is included in this table because population data are available for one very restricted subspecies. Our application of Criterion D2, which involves Area of occupancy (AOO), is based on the logic that AOO is necessarily less than EOO so that EOO provides a conservative measure of AOO. We have not included projected decline sub-criteria because the location of land-clearing in the future is uncertain, but note that B1a,b(ii,v) (Table 11) may be invoked to assess clearing proposals for restricted-range taxa and that sub-criteria A2-4 may be invoked for clearing of widespread species. Sub-criterion A3 relates to future declines alone, and A4 to a combination of past and future declines, whereas A2 relates to past declines alone. No north Australian eucalypt is likely to meet the IUCN sub-criterion of experiencing extreme fluctuations in population or other relevant metrics. No north Australian eucalypt has been the subject of a population viability analysis (criterion E, Table 10).

Table 11. IUCN sub-criteria and thresholds potentially applicable to our assessment of the eucalypts of northern Australia.
Thresholds separated by slashes apply to Critically Endangered/Endangered/Vulnerable respectively.

Sub-criteria and thresholds
A2b: Decline of 80/50/30% in the last three generations due to land clearing which may not have ceased or may not be reversible based on an index appropriate to the taxon
B1a,b(ii,v): Extent of Occurrence is less than 100/5,000/20,000 km^2 AND
a. severely fragmented or known to exist at only 1/5/10 locations AND
b. continuing decline in the number of mature individuals due to clearing
B2a,b(ii,v): Area of Occupancy is less than 10/500/2,000 km^2 AND conditions a & b as in B1a,b(ii,v)
D1: Population fewer than 50/250/1000 adults
D2: Area of occupancy is less than 20 km^2 (Vulnerable only)

A key issue arising out of Table 11 is that sub-criterion A2b requires definition of "three generations". The IUCN interval is actually *10 years or three generations, whichever is greater*, but as eucalypts are long-lived, the latter clearly applies. Most land clearing in northern Australia has occurred in the last 100 years, though some clearing occurred a little earlier, mainly in coastal areas of the Wet Tropics and Central Queensland Coast bioregions (Holmes 1966; ASLIG 1990). Clearing of the brigalow belt in the south-east of the study area commenced in the 1920s and became much more widespread in the 1950s and 1960s (Gasteen *et al.* 1985). In coastal areas where at least some of vegetation cleared was rainforest rather than eucalypt forest or woodland, widespread settlement was mostly associated with soldier settlement within the last 100 years (e.g. Atherton Tableland). Based on the information reviewed below, we have assumed that all land-clearing in northern Australia has occurred within the last three generations of all eucalypt species.

Conceptually, generation time in a plant is the interval between germination and the median age of the parent at germination of its offspring. This may be approximated by a number of measures depending on the nature of the demographic data available (IUCN S&PS 2011). For example, it might be calculated as the sum of the time from germination to first reproduction (the juvenile stage) plus half the reproductive life of the adult, though in practice this will likely be an underestimate because trees continue to grow and thus increase their reproductive output after reaching reproductive age.

The juvenile stage in the life of a eucalypt will commonly be very much longer in nature than is possible in cultivation because most north Australian eucalypts are exposed to frequent fire which may maintain young plants in a "dormant seedling bank" for many years, as also may competition from adults even in the absence of fire (reviewed by Williams 2009). The process has been illustrated in detail for eucalypts in Kakadu National Park (NT) by Werner (2012), Werner & Franklin (2010), Werner & Prior (2013) and Werner *et al.* (2006) and also on Melville Island by Fensham & Bowman (1992). However, many north Australian eucalypts may not be particularly long-lived as adults because of proneness to hollowing by termites (Werner & Prior 2007).

There appear to be no estimates of generation time for any eucalypt, and few estimates of lifespan, the latter summarised by Williams & Brooker (1997). The two estimates of lifespan available from northern Australia are for somewhat less than and somewhat more than 100 years (reviewed in Fensham & Bowman 1992). A generation time of 50 years may be deduced with the following assumptions, all of which we believe to be conservative: 20 years as juvenile in seedling bank; lifespan 80 years; and median age at germination of offspring is half-way through adult life. These assumptions yield the following calculation:

$$((80 - 20) / 2) + 20 = 50 \text{ [years]}$$

and thus that three generations is 150 years – covering all land-clearing in the north Australian study area.

The only other causes of decline among north Australian eucalypts that we could envisage might possibly approach 30% is that triggered by the expansion of rainforest into wet sclerophyll forest in north Queensland. The main eucalypt affected is Rose Gum (*E. grandis*). The process of rainforest expansion is concentrated in tropical areas whereas Rose Gum also occurs extensively in moist sub-tropical areas south of our study area. Tng *et al.* (2012b) estimated that the rate of decline in "tall open forest" in north Queensland to be about 4% per 100 years, though *E. grandis* is likely to be disproportionately affected compared to other eucalypts in this ecosystem (Harrington & Sanderson 1994) as it occurs at its wettest and thus most invasion-prone fringe. We have not considered this cause of decline further in evaluating threatened status.

Thresholds of population size for Vulnerability are 10,000 if associated with severe threat of decline or 1,000 in the absence of decline. Populations are defined as the number of mature individuals with some further qualifications that are not relevant to eucalypts (IUCN S&PS 2011). To our knowledge, the only population estimate for a north Australian eucalypt is of 500+ for *C. cadophora* subsp. *polychroma*, a subspecies which is known from just a single hillside (Barrett 2007). In speculating about population sizes, the density of eucalypts should be borne in mind. The density of trees greater than 10 cm diameter (>10 cm DBH) in savanna plots in Kakadu, Litchfield and Nitmiluk National Parks (NT) averaged 185/ha (all trees) and 116/ha for eucalypts, and from 38 to 68/ha for five common species, the latter only in plots in which they were present (Russell-Smith *et al.* 2010; Brett Murphy pers. comm.). Lehmann *et al.* (2009) reported densities of two abundant eucalypts (individuals > 10 cm DBH) in Kakadu National Park (NT) as 40.5 and 55 per hectare. The density of trees >10 cm DBH in tropical savannas declines as one moves inland in the

Northern Territory, 5 sites ranging from c. 140/ha in the north to fewer than 20/ha at a site close to the inland fringe of our study area (Hutley *et al.* 2011). (In all of the above studies, the term “savanna” includes open forests such as occur on well-drained soils around Darwin and in the north of Kakadu.) Thus, hypothetically, a savanna eucalypt species that comprises 50% of the trees in a stand might achieve a population of 1,000 mature individuals in from 14 to 100 hectares, so that only the most extraordinarily-restricted taxon is likely to number fewer than 1,000 mature individuals.

“Severely fragmented” is defined relative to generic processes that may cause local extinction with little prospect of recolonisation from other populations. Considerable detail of the issue is provided by IUCN S&PS (2011).

“Location” must be associated with a defined threat and be of geographic extent that is relevant to a single event from that threat (IUCN S&PS 2011). The major threat associated with eucalypts in northern Australia is land clearing, which typically occurs at scales of up to several thousand hectares at a time. Thus, for instance, two eucalypt populations of 1 ha each 500 m apart should be regarded as one location rather than two for the purposes of sub-criterion B1a. Available protocols (IUCN S&PS 2011) include dealing with the situation where some populations may be vulnerable to clearing but others are in a reserve.

A further consideration is uncertainty and application of the category Data Deficient. “Liberal use of Data Deficient is discouraged” (IUCN S&PS 2011). If information is sufficient to classify a species as being one of Near Threatened, Vulnerable, Endangered or Critically Endangered, then guidance is provided to select the most appropriate category. However, if Least Concern is also a prospective classification, and especially if the uncertainties range from Least Concern through to Critically Endangered, then a classification of Data Deficient is appropriate. In evaluating uncertain situations, a strict evidentiary approach (“there is not enough evidence to show that it meets a criterion for Vulnerable”) should be replaced with a “precautionary but realistic attitude” which might involve use of “plausible lower bounds” but not “‘worst case scenario’ reasoning”.

Assessment of north Australian taxa

We assessed 19 north Australian eucalypt taxa as threatened (three as Endangered, 16 as Vulnerable), and an additional nine as Near Threatened and two as Data Deficient (Table 12). A further nine were appraised because of an official rating and rated by us as being of Least Concern. All but two ratings are for full species, and in the case of the two subspecies, we did not find reason to rate the parent species. Seventeen of our assessments (Least Concern excluded) were based solely on decline due to clearing (criterion A2b), which is correctly but rarely applied to long-lived trees. Four taxa were rated on the basis of a combination of rarity and decline due to clearing (criteria B1a,b(ii,v) and B2a,b(ii,v)), and nine taxa were rated on the basis of extreme rarity alone (criteria D1 and/or D2).

Our ratings bear only moderate resemblance to official ratings. Eleven of the taxa that we rated as threatened (EN, VU), along with eight we rated as Near Threatened, have not received any conservation rating of concern by the Commonwealth, NT or states. Of nine taxa rated as Vulnerable by the Commonwealth, NT or States, we rated two as Endangered, two as Vulnerable, one as Near Threatened, two as Data Deficient and two as Least Concern. In a few cases only is the discrepancy likely to have arisen because we have access to less information than that available to official assessors, most notably in the two species we rated as Data Deficient. In particular, additional information about Area of Occupancy may be available which may trigger some variation in our assessments. Two of our ratings as Least Concern (*E. distans*, *E. limitaris*) arise because our assessment is global but the official assessments are for a state which comprises only part of the range of the species.

Table 12. Assessed threatened status of north Australian eucalypt taxa.
Taxa are arranged alphabetically within ranked level of threat (our assessment). Official status is for the Commonwealth if available and otherwise the named state, as detailed in Table 8. EN = Endangered; VU = Vulnerable; NT = Near threatened; DD = Data deficient; LC = Least Concern. IUCN Criteria are as in Table 11.

Taxon	Official status	Our assessment	IUCN Criterion	Supporting information
Eucalyptus cambageana	-	EN	A2b	Index of clearing = 63.8%
Eucalyptus raveretiana	VU	EN	A2b	Index of clearing = 54.7% (reservation index 0.8%)
Eucalyptus sicilifolia	VU	EN	B1a,b(ii,v) B2a,b(ii,v)	EOO = 41 km^2; known from 5 locations; Index of clearing = 25.8%; on-going threat of clearing (reservation index 38.7%)
Corymbia cadophora subsp. *polychroma*	P1 (WA)	VU	D1, D2	known population 500+ (Barrett 2007), EOO <<20 km^2 (known from a single hillside); evidence is sufficient to suggest that it is not widespread and may be NT if not VU; a precautionary approach suggests VU is appropriate (IUCN S&PS 2011); not reserved
Corymbia dallachiana	-	VU	A2b	Index of clearing = 33.7%
Corymbia erythrophloia	-	VU	A2b	Index of clearing = 42.7%
Corymbia leptoloma	VU	VU	D2	EOO = 138 km^2 so we have assumed AOO < 20 km^2; index of clearing = 0%, reservation index 48.3%
Corymbia paractia	P1 (WA)	VU	B1ab(ii,v)	EOO = 647 km^2, known from c. 7 locations, may be threat of clearing due to proximity to Broome, reservation status 0%. There is uncertainty in the no. of locations because the publicly-available records have been generalised to the nearest 0.1 degree - we have counted each combination of 0.1 d as one location
Corymbia sp. Pentland Hills	-	VU	D2	EOO << 20 km^2 (known from a single location that is not reserved)
Corymbia sp. Springsure	-	VU	D2	EOO << 20 km^2 (known from a single location that is not reserved)
Corymbia torelliana	-	VU	A2b	Index of clearing = 34.1% (reservation index 26.1%)
Eucalyptus exserta	-	VU	A2b	Index of clearing = 32.3%; occurs in NSW as well so index will be underestimate as based on total records
Eucalyptus farinosa	-	VU	D2	EOO = 3 km^2 (known from a single location that is not reserved)
Eucalyptus kenneallyi	P1 (WA)	VU	D2	EOO << 20 km^2 (known from a single location that is not reserved)
Eucalyptus koolpinensis	NT (NT)	VU	D2	Examination of records strongly suggests AOO < 10 km^2, notwithstanding recent range extension that has greatly expanded the EOO to 992 km^2 (reservation index = 100%)
Eucalyptus nudicaulis	-	VU	B1a,b(ii,v)	EOO = 2,131 km^2, known from 7 locations, none reserved, may be threat of clearing due to proximity to Mt Isa

Table 12 *continued*

Taxon	Official status	Our assessment	IUCN Criterion	Supporting information
Eucalyptus paedoglauca	VU	VU	B1a,b(ii,v)	EOO = 6,590 km^2 but is greatly inflated by a single outlier; known from 9 locations; Index of clearing 3.3%, reservation index 0%; threat of clearing due to proximity to Townsville
Eucalyptus platyphylla	-	VU	A2b	Index of clearing = 31.4% (reservation index 13.8%)
Eucalyptus tenuipes	-	VU	A2b	Index of clearing = 36.3%
Corymbia lamprophylla	-	NT	A2b	Index of clearing = 20.0% (reservation index 16.4%)
Corymbia watsoniana subsp. *capillata*	-	NT	A2b	Index of clearing = 23.7%
Corymbia xanthope	VU	NT	A2b	Index of clearing = 23.2% (reservation index 5.4%; EOO = 9479 km^2)
Eucalyptus ammophila	-	NT	A2b	Index of clearing = 27.0%
Eucalyptus brownii	-	NT	A2b	Index of clearing = 22.2% (reservation index 3.0%)
Eucalyptus cloeziana	-	NT	A2b	Index of clearing = 23.3%
Eucalyptus persistens	-	NT	A2b	Index of clearing = 23.8% (reservation index 7.5%)
Eucalyptus sp. Mt Hope Homestead	-	NT	A2b	Index of clearing = 27.3% (reservation index 0%)
Eucalyptus suffulgens	-	NT	A2b	Index of clearing = 20.9%
Corymbia clandestina	VU	DD	D2	EOO = 17,341 km^2 but locations are widely scattered and AOO appears to be small so it may qualify as VU under D2; index of clearing = 0%, reservation status 0%
Eucalyptus mooreana	VU	DD	D2	EOO = 6,385 km^2, known from 13 locations, no threat of clearing, reservation status 80%; AOO might be small because restricted to high peaks in the King Leopold and Lady Forrest Ranges in central Kimberley
Corymbia rhodops	VU	LC		EOO = 4,732 km^2; index of clearing 1.6%, reservation index 6.3%; occurs on elevated hills where the main if not sole risk of clearing is with localised mining operations; restricted range, but insufficient to qualify unless much more severely at risk of decline
Eucalyptus ceracea	VU	LC		EOO = 445 km^2, known from c. 7 locations, no threat of clearing, reservation index 6.1%. It is conceivable (but we think unlikely) that the AOO is close to or less than 20 km^2, in which case VU or NT might apply. Otherwise, rarity is insufficient to qualify in the absence of identifiable risk of decline. Remote location (north-east Kimberley) may mean this species is under-reported; also there is uncertainty in the no. of locations because the publicly-available records have been generalised to the nearest 0.1 d - we have counted each combination of 0.1 d as one location

Table 12 *continued*

Taxon	Official status	Our assessment	IUCN Criterion	Supporting information
Eucalyptus costuligera	P1 (WA)	LC		EOO = 2,176 km^2, known from 7 locations, index of reservation 27.3%, unlikely to be any threat of clearing; rarity is insufficient to qualify in the absence of threats
Eucalyptus cupularis	NT (NT)	LC		EOO = 49,876 km^2, known from many locations (WA & NT), no threat of clearing
Eucalyptus distans	P1 (WA)	LC		Wide distribution in the NT & Qld (EOO = 540,326 km^2)
Eucalyptus fitzgeraldii	P2 (WA)	LC		Few records (21) may reflect remote location in Kimberley but EOO = 32,523 km^2 and has no known threats (reservation index 57.1%, all private)
Eucalyptus gregoriensis	DD	LC		With EOO of 5,047 km^2 and no known threats (reservation index = 86.7%), the only conceivable basis for listing would be if population and/or EOO were extremely small (D1, D2)
Eucalyptus limitaris	DD (NT)	LC		Wide distribution in WA & NT (EOO = 111,865 km^2), moderate number of records (81) and no known threat
Eucalyptus ordiana	P2 (WA)	LC		EOO= 7,440 km^2, >10 locations and its occurrence on rocky hills precludes major threat of land-clearing notwithstanding proximity to Ord River development and reservation index of 0%

Our appraisal indicates a far wider and deeper distribution of threatened taxa in Queensland than that officially recognised (Fig. 28A *cf.* 28C), a pattern that is reinforced by our assessment of taxa as Near Threatened or Data Deficient (Fig. 28D). This is almost entirely due to our assessment of threat due to land-clearing on relatively widespread taxa, i.e. taxa that demonstrate a severe decline such that they need not and do not also qualify on the basis of rarity (Fig. 29A).

Our assessment of threat on the basis of rarity with or without decline (Fig. 29B,C) also differs substantially from official status (though official assessments do not spell out the criteria, so this is implicit). However, both assessments suggest just a few, widely scattered taxa qualify under these criteria.

We did not find evidence to support concern (at the level of IUCN assessment) about the considerable number of other taxa illustrated in Fig. 28B and listed in Table 8. This list of species comes from a variety of sources and, in particular, features a variety of taxa that were listed under ROTAP (Briggs & Leigh 1996) on the basis of rarity or being poorly known.

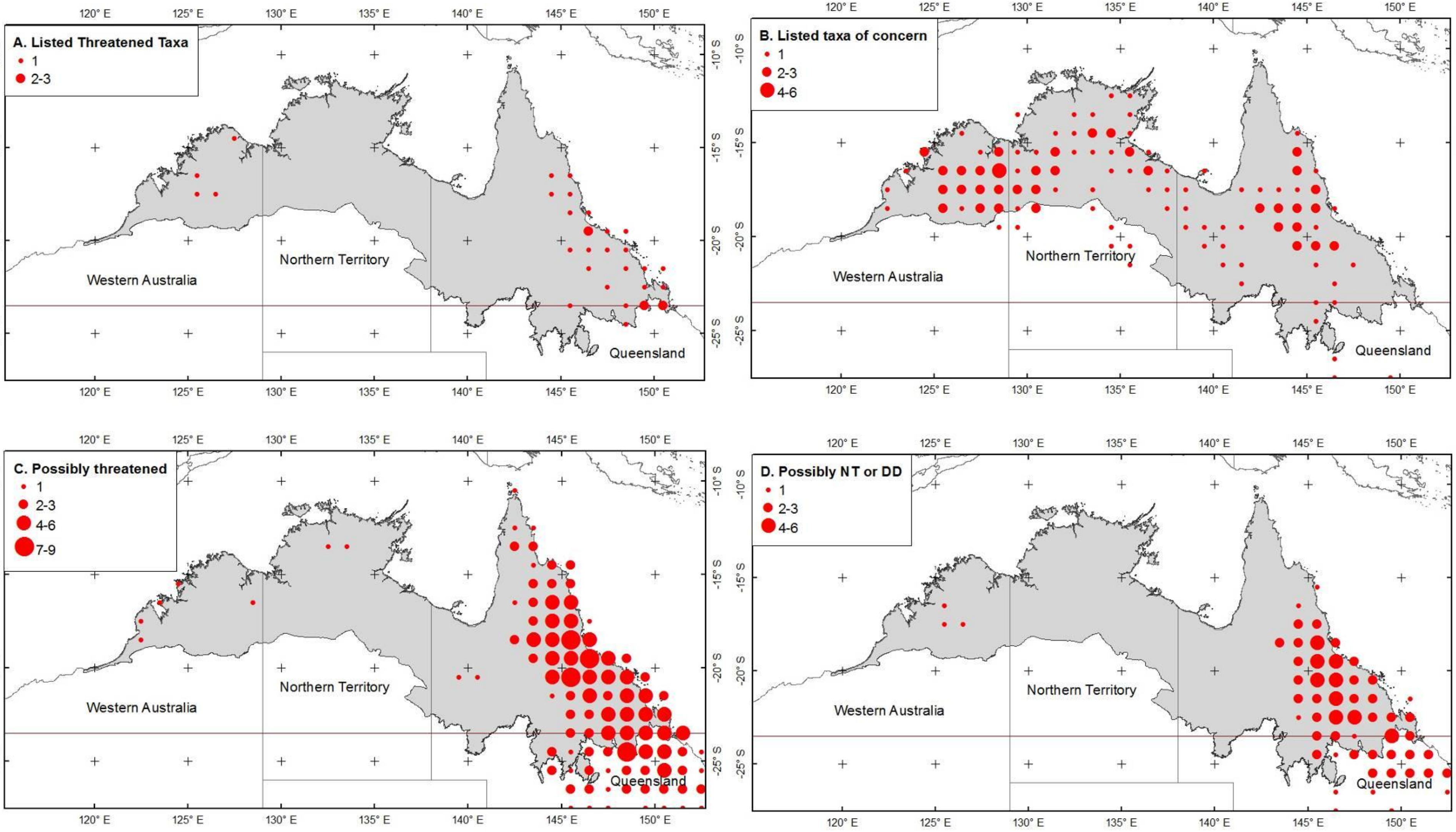


Figure 28. Number of north Australian eucalypt taxa in degree cells: A. listed as threatened; B. listed as of concern; C. rated by us as threatened; and D. rated by us as Near Threatened or Data Deficient.

Taxa are as per Tables 8 and 12.

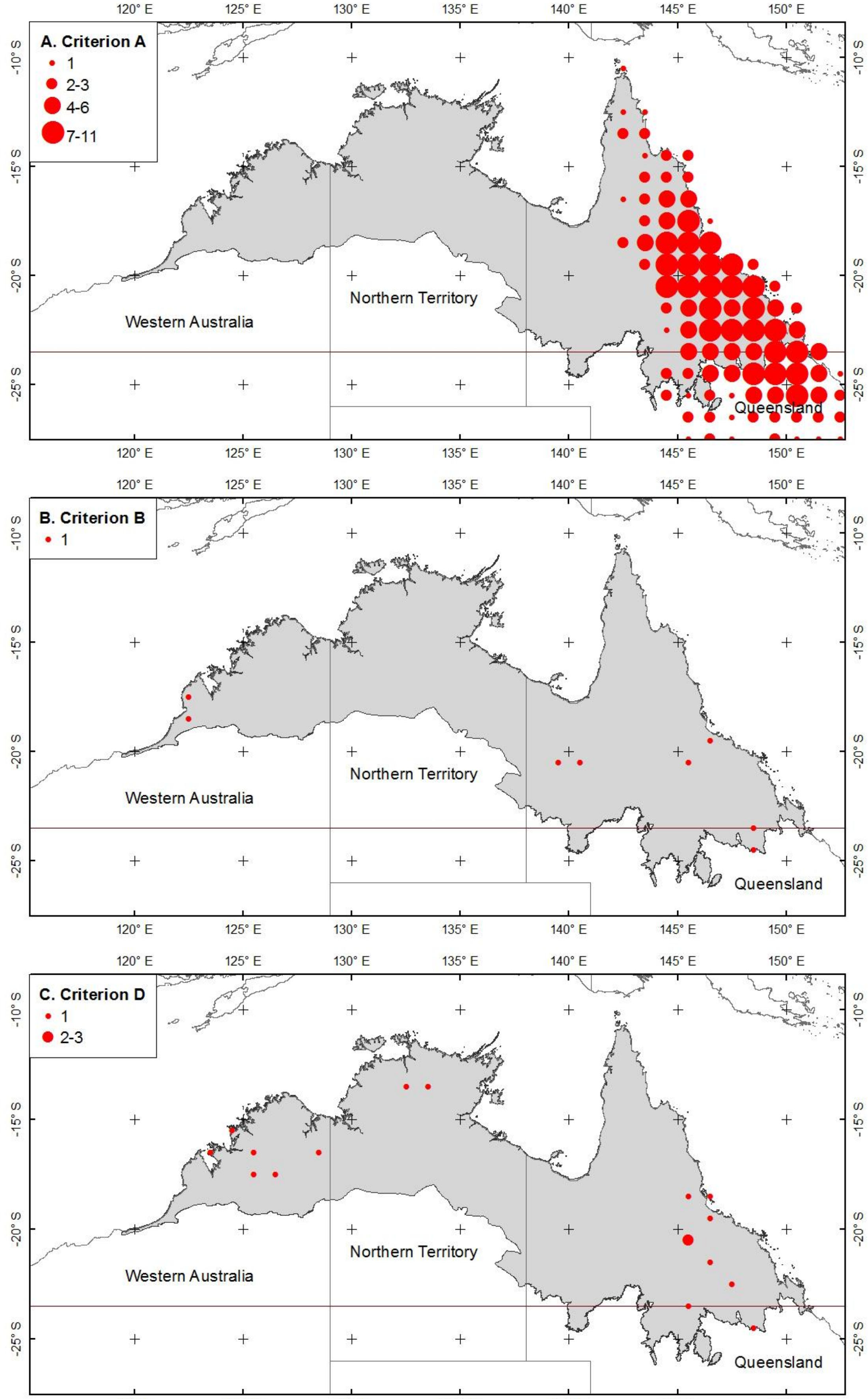


Figure 29. Frequency distribution in degree cells of north Australian eucalypt taxa by threat criteria: A. land-clearing alone (criterion A); B. rarity and threat of land-clearing (criterion B); C. extreme rarity alone (criterion D).

CHAPTER 6: EUCALYPT COMMUNITIES

Important caveats for this chapter:

- **the data are for the tropical savanna region of northern Australia but without the "rainforest" bioregions (i.e. as in Fig. 6B but with the areas in green excluded).**
- **we do not have access to information about the extent of vegetation types that also occur outside the tropical savanna region. Thus, for example, a map unit that is rare or poorly reserved in the tropical savanna study area could feasibly be widespread or well-reserved elsewhere**

Background

In ecology, a community is a group of organisms comprising more than one species that co-occur *and* interact (Lincoln *et al.* 1998). Because interspecific competition for resources such as moisture, nutrients and light are characteristic of vegetation, plant species that co-occur are appropriately termed plant communities; many other types of interactions may also occur between plant species. Subject to definitions of spatial scale, a plant community is the vegetation at a site, and in the broadest geographic sense a plant community forms a vegetation type. It is in this latter sense that we appraise the eucalypt communities of northern Australia.

The vegetation types of the tropical savanna portion of our study area have been described, mapped and made available in GIS format by Fox *et al.* (2001). This is the product of extensive fieldwork, analysis and evaluation of remotely-sensed images across the three states combined with a complex process of merging the resulting state-based classifications; it is widely accepted as a benchmark for northern Australia. It reflects the pre-European state of the vegetation in the sense of mapping where vegetation types occurred at that time (i.e. before land clearing) but with important qualifiers that there may have changes to vegetation since then such as thickening or thinning of the trees that are not systematically known. In recognition that classification of vegetation types is strongly dependant on the scale of the available data, how site data are aggregated up to types, and how decisions are made about the measurement, inclusion and weighting of floristics, vegetation structure, soils and geomorphological setting, Fox *et al.* (2001) use the prosaic but accurate term "map units" rather than vegetation types or communities; when referring to their classification, we will do likewise.

Fox *et al.*'s 125 map units are aggregated into 10 land units which are characterised by soils, geomorphology and underlying geology. Alternatively and somewhat independently, map units are aggregated into 26 Broad Vegetation Groups which more strongly reflect the characteristic species of the dominant stratum. Here are two examples:

> Map Unit D27: *Eucalyptus leucophloia* (Snappy Gum) low open-woodland and/or shrubland with *Triodia pungens* (Soft Spinifex) and *T. bitextura* (curly spinifex) hummock grasses
> - occurs on Land Unit D (sand deposits) and is in Broad Vegetation Group 7 (monsoon low open-woodlands dominated by *Eucalyptus brevifolia* or *E. leucophloia*)
> These two eucalypt species are an allopatric pair – close relatives occupying similar environments but in different locations.
>
> Map Unit K4: *Eucalyptus miniata* (Darwin Woollybutt) grassy woodland
> - occurs on Land Unit K (ancient volcanics including granites) and is in Broad Vegetation Group 5 (monsoon woodlands and open-woodlands dominated by *Eucalyptus tetrodonta* and *E. miniata*)

It is evident from the above that Map Units are not necessarily characterised by the eucalypt species in them and that a species may be characteristic of more than one map unit. An example of the latter is the widespread *E. tetrodonta* (Darwin Stringybark) that occurs in the brief description of 10 Map Units on 3 Land Units. In addition, though nine of these Map Units fall into Broad Vegetation Group 5 (monsoon woodlands and open-woodlands dominated by *Eucalyptus tetrodonta* and *E. miniata*), one (in which it is less dominant) falls into Group 2 (open-forests dominated by *Eucalyptus* spp. and *Corymbia* spp.). It is possible that the latter is in fact *E. megasepala*, a species that has been split off from *E. tetrodonta* by Bean (2006) since the work of Fox *et al*. (2001) was completed.

The opposite scenario is that a Map Unit may be described in terms of a few widespread tree species but contain localised stands of other species which may even be endemic to it. For example, the trees of Map Units J8 and K6, eastern Queensland hill woodlands occurring on metamorphic and granite soils respectively, are both listed as *Eucalyptus* spp. (ironbarks) ± *Corymbia* spp., but also contains stands of taxa of conservation interest such as *E. pachycalyx* subsp. *pachycalyx* (Pumpkin Gum) (Fig. 30) and *E. lockyeri* (Northern Peppermint) which are not even mentioned in the detailed description of associated species. This illustrates the problem of scale. Stands of tree species or mixtures of species that occur in patches of less than 1,000 ha, and mostly less than 2,000 ha, are not mapped by Fox *et al*. (2001), and if all patches are less than these thresholds then the stand is not described as a unique Map Unit. This illustrates the scale-dependence of all vegetation mapping exercises. The map units of Fox *et al.* (2001) are an excellent representation of the vegetation of the Australian tropical savannas at the vast scale at which they occur but do not negate the need for site-based assessments and consideration of local diversity when considering proposals for development and conservation. For Queensland, greater detail is available in the form of Regional Ecosystem mapping (http://www.dnrm.qld.gov.au/land/vegetation-management/vegetation-maps, downloaded 7 Jan. 2014).

Figure 30. Stand of Pumpkin Gum (*Eucalyptus pachycalyx* subsp. *pachycalyx*) – the pale-barked trees – within Fox *et al.*'s (2001) Map Unit K6. Small stands such as these have not been identified as Map Units. Some stands are identified, however, in Queensland's Regional Ecosystem mapping. The subspecies has a *very restricted* range (*sensu* Table 6) and is thus of conservation concern.

Summary of the eucalypt communities of northern Australia

We consider a Map Unit of Fox *et al.* (2001) to be a eucalypt community if one or more eucalypt species are listed in the short description of the unit. Short descriptions include the species that characterise the unit but also the most prominent secondary species. Fox *et al.* identify 125 Map Units of which 72 (58%) are dominated by eucalypts and an additional 12 (10%) feature eucalypts secondarily, 84 (67%) Map Units in total. These cover 69% of their study area (Fig. 31) and occur across eight of ten land units (Table 13). Fourteen Broad Vegetation Groups are characterised by eucalypts, a further four feature eucalypts as minority species whilst two whose description does not include eucalypts include Map Units in which eucalypts feature as secondary species.

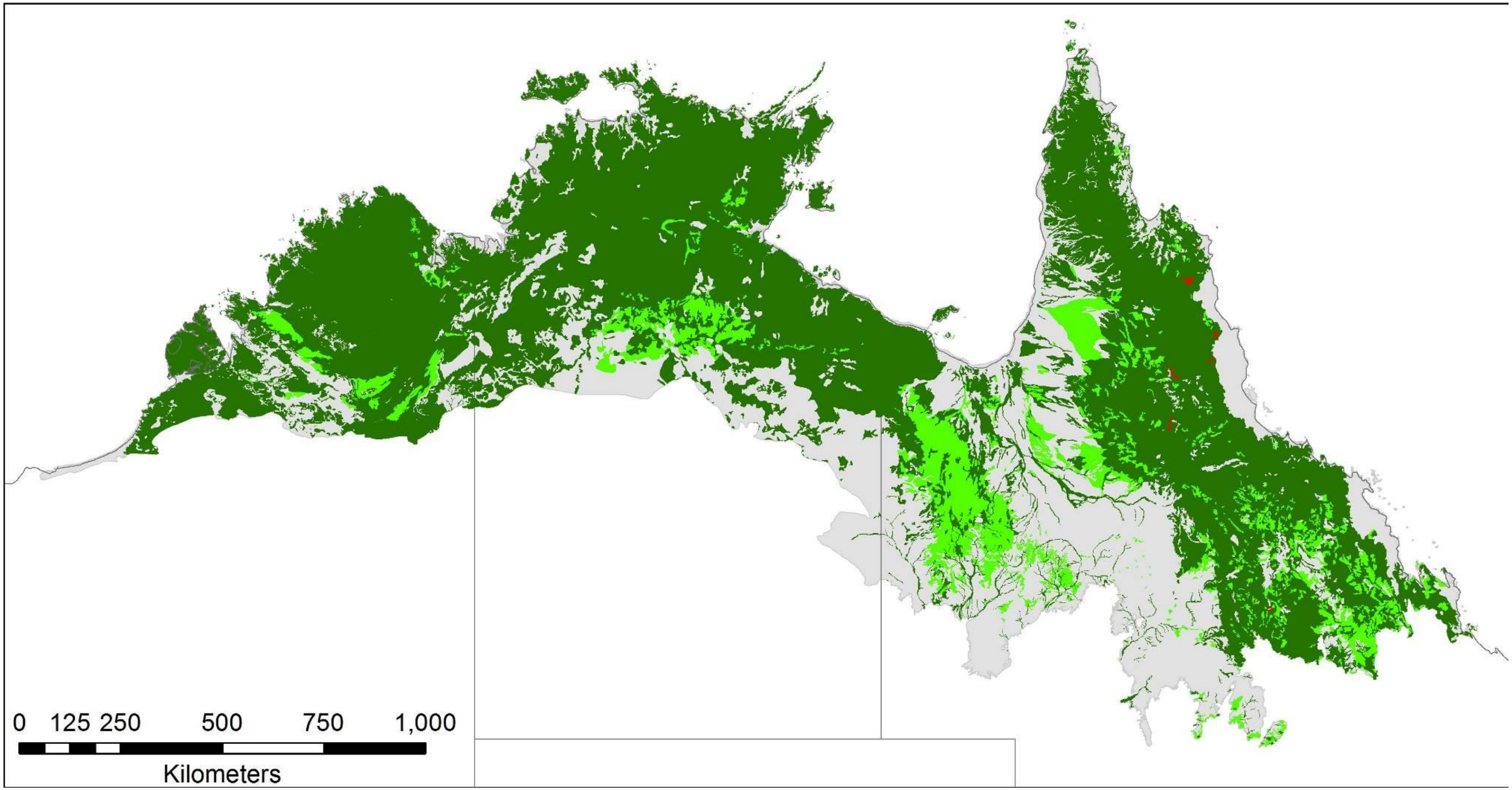


Figure 31. Distribution of Map Units (vegetation types) from Fox *et al.* (2001) that feature eucalypts.
Dark green areas are dominated by eucalypts; light green are those featuring eucalypts secondarily; red areas (in Queensland) are two restricted range eucalypt Map Units (see text), both of which are dominated by eucalypts. Grey areas are vegetation types that do not feature eucalypts as primary or key secondary species and/or are rainforest bioregions; the latter do, however, contain areas of eucalypt forest and woodland which are thus not mapped here.

Table 13. Summary of Land and Map Units described for the north Australian savanna region by Fox *et al.* (2001).
Land Unit I is not present in northern Australia. Land Unit characterisations have been simplified greatly from Fox *et al.* (2001). Time scales are geographic: "recent" means in the last 1.8 million years, "modern" the last 65 million years and "ancient" means more than 65 million years old.

Land Unit	Characterisation of Land Units	No. of Map Units	No. (%) of eucalypt Map Units
A	recent marine deposits	3	0 (0)
B	recent coastal deposits	2	0 (0)
C	modern alluvial deposits	20	7 (35)
D	modern sand deposits	36	27 (75)
E	modern duricrusts	4	3 (75)
F	modern volcanics	9	7 (78)
G	rocks derived from fine-grained sediments*	11	6 (55)
H	rocks derived from coarser sediments*	18	14 (78)
J	ancient metamorphics	13	12 (92)
K	ancient volcanics including granites	9	8 (89)
Total		**125**	**84 (67)**

* age variable, modern to ancient

Conservation assessment

Most eucalypt Map Units have a mapped area within the tropical savannas of between 1,000 and 100,000 km^2 (Fig. 32). Of the seven with a smaller mapped area (Table 14), only two (F3, F5) are genuinely of restricted range (Fig. 31). Of the remaining five, two (G6, H11) occur more extensively outside the study area, two (H2, H12) occur in numerous stands too small to be mapped, and one (J2) has both these qualifiers.

Figure 32. Frequency distribution of the area of eucalypt Map Units (from Fox *et al.* 2001) within northern Australia.

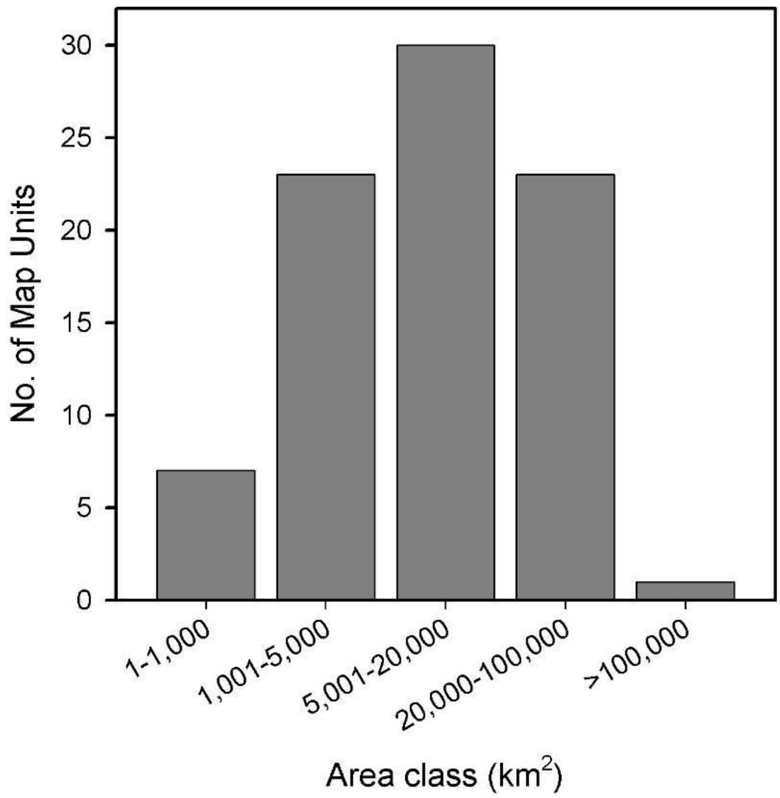
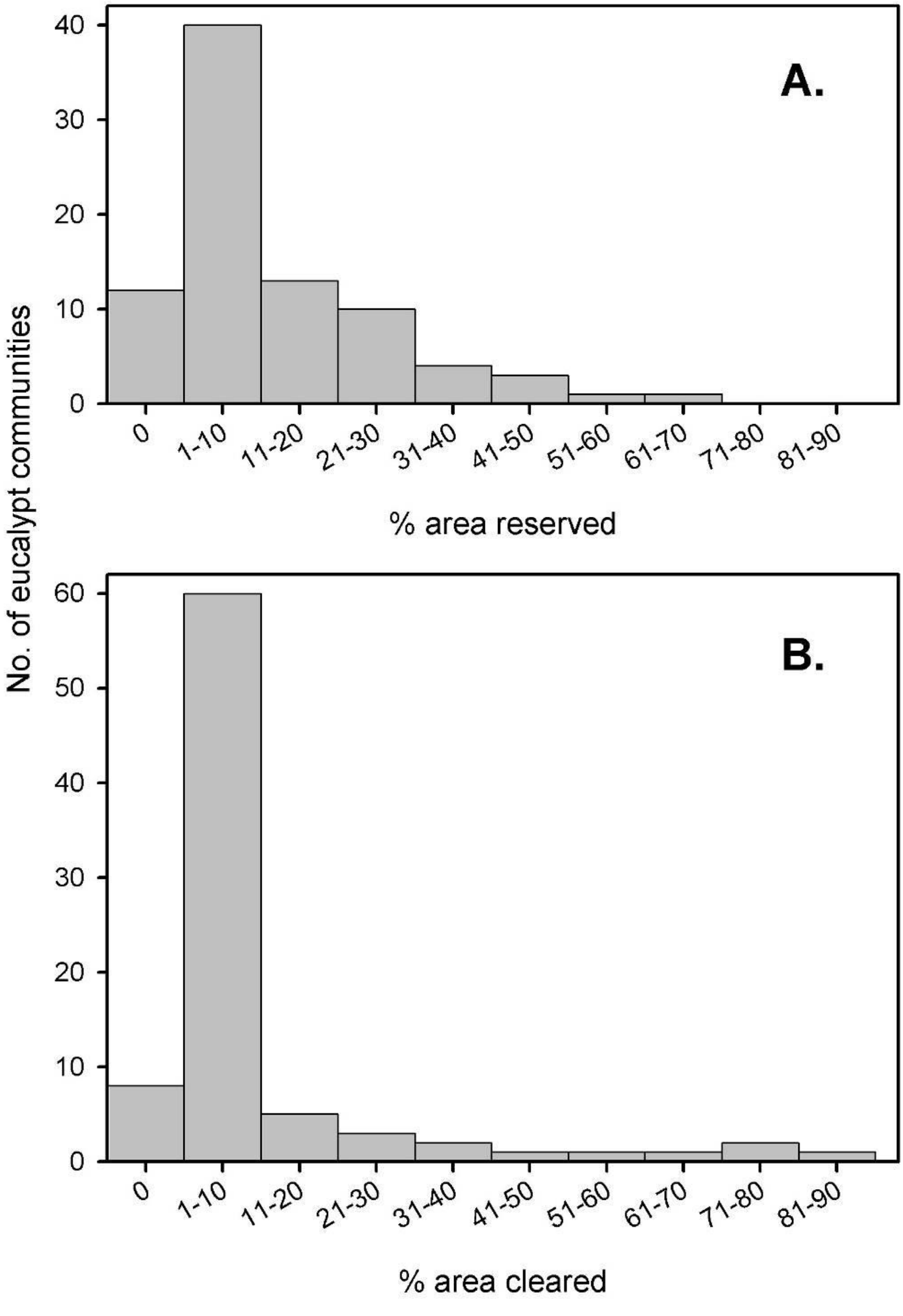


Table 14. Details of the seven Map Units with a mapped area of less than 1,000 km^2 within northern Australia.
BVG = Broad Vegetation Group. Characterisations modified from Fox *et al.* (2001), and quotes in the Notes field are from the same source.

Map unit	Abbreviated characterisation	BVG	Area (km^2)	Notes
H11	*Eucalyptus decorticans* (Gum-topped Ironbark) open-woodland	13	19	Marginal to study area (Desert Uplands bioregion, Qld) but "much larger in extent in areas [to the] south"
H12	*Eucalyptus persistens* (Knotted Box) and/or *Eucalyptus shirleyi* (Silver-leaved Ironbark) open-woodland	13	43	"small patches in the Einasleigh Uplands [Qld], … similar communities are fairly widespread in the north Queensland sandstone country, but rarely of a size that can be mapped at this scale"
G6	*Corymbia terminalis* (bloodwood) low open-woodland	8	210	"a minor occurrence of a unit that extends into the map area from the south" (NT)
F5	*Eucalyptus microneura* (Gilbert River Box) open-woodland	15	227	"Restricted to the western Einasleigh Uplands in the Georgetown area [Qld]."
J2	*Corymbia* spp. and/or *Eucalyptus* spp. open-forest on metamorphic slopes	2	228	"Occurs more extensively as very small communities which are restricted to the wetter east coast of Queensland. Also occurs more extensively in the Wet Tropics and Central Queensland Coast bioregion. ... Many of the communities contain the naturalised shrub *Lantana camara**, which can dominate the understory."
H2	*Acacia shirleyi* (Lancewood) and/or *Acacia catenulata* (Bendee) open-forest +/- emergent *Eucalyptus* spp. and *Corymbia* spp.	17	366	"This widespread community occurs in patches that are frequently too small to be mapped. Closely associated with unit E1"
F3	*Eucalyptus leptophleba* (Molloy Red Box) and/or *Corymbia* spp. woodland	15	603	"A restricted unit confined to the Einasleigh Uplands and southern Cape York Peninsula with an isolate in the southern Desert Uplands. … In the Lakeland Downs area … much of this unit has been cleared for cropping (Neldner 1999)" (Qld)

Twelve Map Units are not represented in any crown or private conservation reserve, while less than 10% of the area (and often less than 1%) of a further 40 Map Units are reserved (Fig. 33A). These are strongly concentrated in Queensland and in inland parts of northern Western Australia and the Northern Territory (Fig. 34A). In contrast, well-reserved Map Units (arbitrarily, >30% by area) are a small minority (Fig. 33A) and are concentrated mainly in the central and north Kimberley, in the Northern Top End and Gulf uplands of the Northern Territory (Fig. 34A).

Figure 33. Frequency distribution of eucalypt Map Units in northern Australia by % area reserved (A) and cleared (B).



The considerable majority of eucalypt Map Units have had little clearing (<10% but mostly <1%) (Fig. 33B). However, five Map Units have been more than 50% cleared and a further three have been 30–50% cleared. Heavily cleared Map Units are strongly concentrated in the south-east of the study area and further north in eastern Queensland (Fig. 34B).

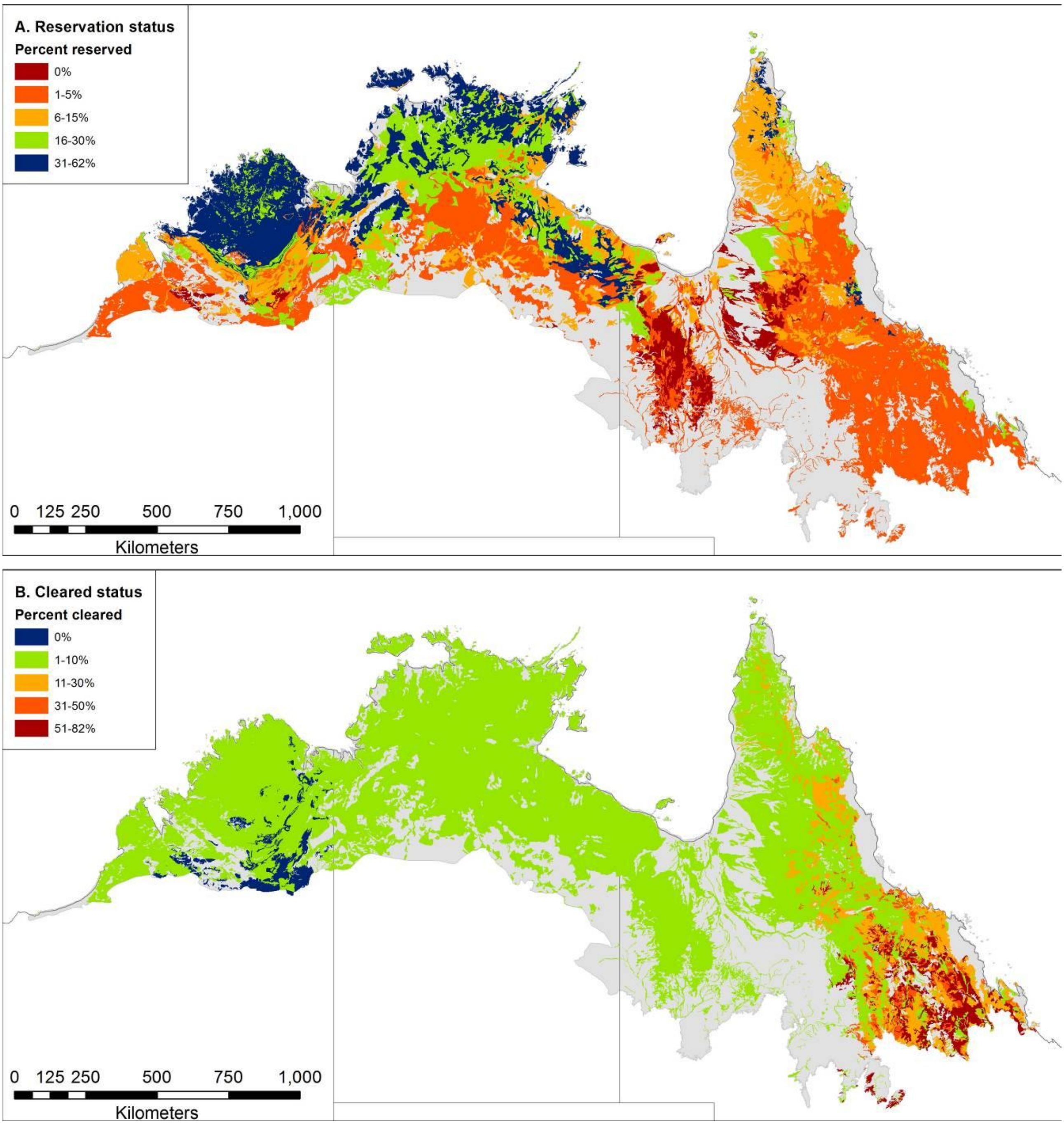


Figure 34. Distribution of eucalypt Map Units (after Fox *et al.* 2001) in northern Australia by % area reserved (A) and cleared (B).
Grey areas are vegetation Map Units that do not feature eucalypts as dominants.

The relationship between clearing status and reservation is mostly negative, i.e. Map Units that have been subject to clearing are poorly reserved, and *vice versa*, even though combined totals for reservation and clearing are less than 50% for 77 of the 84 Map Units (Fig. 35). Only three units subject to moderate clearing are also moderately reserved (labelled in the green area of Fig. 35; combined area reserved and cleared all less than 32%). Four Map Units are neither reserved nor cleared, and a further 12 have combined totals of less than 1%.

Crown and private reserves provide some complementarity in their coverage of ecological communities (Fig. 36).

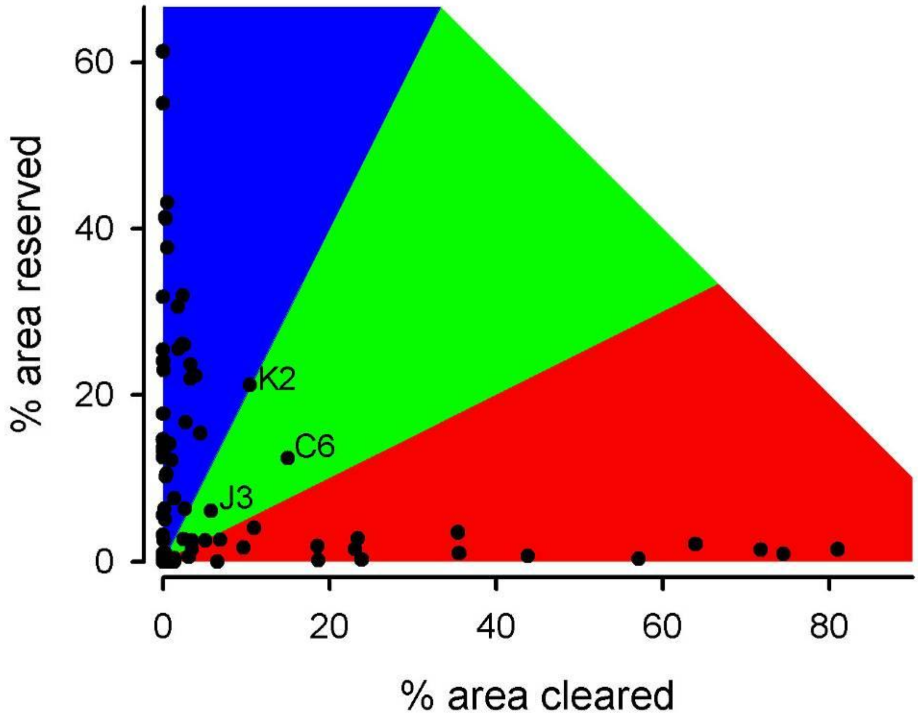


Figure 35. Relationship between clearing and reservation of the 84 eucalypt communities in northern Australia.
Communities are the Map Units of Fox *et al.* (2001) and labels correspond to those in that report. Green shading represents those areas in which clearing is matched (arbitrarily 50 – 200%) by reservation. Thus, Map Units in the red shading lack matching reservation whilst those in the blue shading are well-reserved *relative to clearing* – though some are scarcely reserved at all. The diagonal upper right boundary to the shaded areas represents the 100% limit to the sum of reservation and clearing.

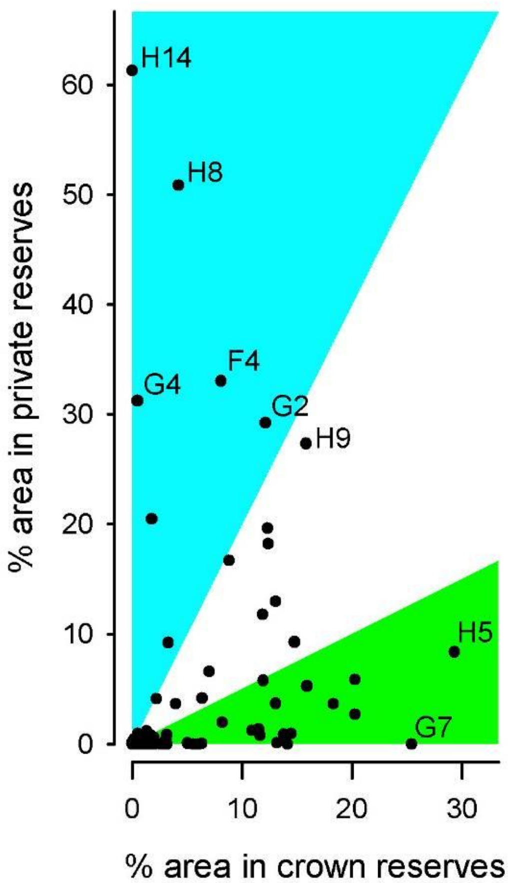


Figure 36. Relationship between crown and private reservation of 84 eucalypt communities in northern Australia.
Communities are the Map Units of Fox *et al.* (2001) and labels correspond to those in that report. Green shading represents Map Units with more 2/3 of reservation in crown reserves; light blue Map Units with more than 2/3 of reservation in private reserves.

Greenhouse gases and land clearing

Carbon is the building block of life and is thus abundant in vegetation. When vegetation is cleared, carbon is released into the atmosphere in the form of carbon dioxide (CO_2); with revegetation and regrowth, carbon is sequestered (withdrawn from the atmosphere). An increase in carbon dioxide in the atmosphere (along with much smaller amounts of other greenhouse gases) over recent decades is the major driver of climate change (IPCC 2007) and has obvious implications for the management of the tropical savannas of northern Australia. The savannas of northern Australia contain carbon stocks averaging 79 t/ha (Douglass *et al.* 2011) which, over the approximately 1.9 million km^2 of these savannas, amounts to about 15 billion tonnes (15 thousand million tonnes) of carbon and 55 billion tonnes of CO_2-equivalents (CO_2-e). To give some sense of scale to this, Australia's CO_2-e emissions for the year to March 2013 have been estimated at 557 million tonnes (DOE 2013) and so the tropical savannas contain the equivalent to 99 years of emissions at current rates. The considerable majority of the tropical savanna carbon stock is held by eucalypt communities, as a majority of the non-eucalypt vegetation of the region is grassland (Fox *et al.* 2001), which has relatively small carbon stocks per unit area (Law & Garnett 2011).

Whilst some carbon is held above the ground and some in roots, in tropical savanna most carbon is held as organic matter in the soil. For open forest of *E. tetrodonta* and *E. miniata* near Darwin, Chen *et al.* (2003) estimated that 74% is held as soil organic matter. Carbon stocks vary between sites and vegetation types and there is considerable uncertainty in measurements. In a field study in eucalypt open forests near Darwin, Chen *et al.* (2003) estimated carbon stocks to be 204 ± 53 t/ha. Based on Australian FullCAM modelling (Richards & Evans 2008), Law & Garnett (2011) calculated carbon stocks to be 158 ± 23 t/ha for eucalypt open forests of the Northern Territory in general. Carbon stocks are broadly proportional to above-ground biomass; vegetation that is shorter and/or more open supports lower stocks (Table 15).

Table 15. Estimates of carbon stocks and emissions due to clearing (including other greenhouse gases measured as CO_2) with a follow-up fire for eucalypt Major Vegetation Groups in northern Australia. Major Vegetation Groups are broad structural formations – level III in the National Vegetation Information System. Data are means ± SD from Law & Garnett (2011).

Major Vegetation Group	Carbon stock (tC/ha)	Emissions from clearing (tCO_2/ha)
eucalypt open forest	158 ± 23	415 ± 59
eucalypt woodland	62 ± 19	136 ± 42
eucalypt open woodland	40 ± 15	88 ± 34
tropical eucalypt woodlands/grasslands	79 ± 20	195 ± 44

Clearing of wooded vegetation (i.e., its conversion to grassland) results in the loss of much of the carbon held, but the amount depends somewhat on what happens to the felled trees. On the assumption that the felled trees are burned, emissions in the eucalypt open forests of portions of the tropical savanna region with higher rainfall and better soils (favoured for clearing) may exceed 400 tCO_2/ha (Table 15).

Greenhouse gases and fire

The greenhouse effects of savanna fires are more complicated. Fire releases carbon into the atmosphere, but with recovery of vegetation after fire, carbon is resorbed (IPCC 2006). In fire-adapted tropical eucalypt savannas, the net effect of any one fire on the carbon stock of vegetation is thus potentially neutral. However, the cumulative effect over time of a fire regime may be to cause either vegetation thickening or thinning, thus increasing or decreasing the carbon stock (Table 16). A general but weak thickening trend appears to be occurring across Australian savannas (Murphy *et al.* 2014), though this is not necessarily the result of fire regimes. In the vicinity of Darwin, vegetation thinning is driven by high-intensity fires fuelled by invasive Gamba Grass (*Andropogon gayanus*) (Brooks *et al.* 2010).

Table 16. Estimates of carbon sequestration potential for north Australian eucalypt major vegetation groups.

Based on Law (2011). Major Vegetation Groups are broad structural formations – level III in the National Vegetation Information System. NBP and NEP refer to Net Biome Productivity and Net Ecosystem Productivity. NEP is the carbon that is left in the ecosystem after plant respiration, herbivory and decomposition processes are accounted for. NBP additionally accounts for the effect of disturbances such as fire and is thus a more realistic value for disturbance-prone ecosystems such as tropical savannas (Rob Law, pers. comm.). (Note that estimates are negative because sequestration reduces the amount of CO_2 in the atmosphere).

Major vegetation group	Estimate (tC/ha/yr)	Source
eucalypt open forest	-3.8 (NEP)	Chen *et al.* (2003)
eucalypt open forest	-2.3 (NBP)	Chen *et al.* (2003)
eucalypt open forest	-1.0 (NBP)	Williams *et al.* (2004)
eucalypt open forest	-2.8 (NEP)	Eamus *et al.* (2001)
eucalypt open forest	-2.0 (NBP)	Beringer *et al.* (2007)
eucalypt woodland – eucalypt open forest	-0.1	Beringer *et al.* (2007)
eucalypt woodland – eucalypt open forest	-0.06	Murphy *et al.* (2009)
eucalypt open forest (above-ground only)	-0.5	Cook *et al.* (2005)
eucalypt woodland (above-ground only)	-0.53	Burrows *et al.* (2002)

Fires also release other greenhouse gases, notably methane and nitrous oxide, and it is these that are proving central to the carbon economy of northern Australia (Heckbert *et al.* 2012; Russell-Smith *et al.* 2013). As greenhouse gases, the global warming potential of methane is 25 times more powerful than CO_2 and nitrous oxide 298 times more powerful (Forster *et al.* 2007), so small amounts notwithstanding, the consequences of these emissions are large. Methane and nitrous oxide are an accountable part of emissions under international protocols and are measured as CO_2-e in terms of their greenhouse consequences. Methods for estimation of these emissions from savanna fires have been provided by Russell-Smith *et al.* (2009) and Meyer *et al.* (2012) and a savanna burning methodology for reduction of these emissions has been approved by the Commonwealth Department of Environment (http://www.climatechange.gov.au/reducing-carbon/carbon-farming-initiative/methodologies/methodology-determinations/savanna-burning; accessed 3 January 2014). Abatement of these emissions occurs with a reduction in area burnt and a reduction in combustion efficiency (Meyer *et al.* 2012). Strategic early dry season burns are used to reduce the potential for extensive late dry season fires (Price *et al.* 2007, 2012). Early burns may also have lower combustion efficiency than late fires, but only if fuels have not fully cured (dried) (Meyer *et al.* 2012). In general, annual grasses cure even before early fires, thus mitigating any efficiency benefits (Meyer *et al.* 2012), but perennial grasses cure more slowly (and spinifex does not cure at all) (Allan *et al.* 2003).

CHAPTER 7: DISCUSSION

The eucalypts of northern Australia are speciose and taxonomically diverse, have high levels of endemism and exhibit strong spatial patterning. Even at the relatively broad-brush scale of the vegetation mapping of Fox *et al.* (2001), the eucalypt communities of northern Australia are also diverse. This provides a clear and pressing basis for an assessment of their conservation status – and efforts to attend to the issues identified. We have provided multiple perspectives to facilitate identification of conservation priorities, and in this discussion we draw out the main messages to be obtained therefrom.

Knowledge and gaps

It is clear from the records in Australia's Virtual Herbarium that a concerted effort has been made to locate eucalypt taxa even in remote regions, and that the distribution of species and subspecies is, in broad outline, quite well known. As a result, we are confident that the analyses presented in this report are robust in their generality. However, the finer detail will undoubtedly be subject to considerable change over time. Key uncertainties include that some rare taxa almost certainly remain to be located and/or recognised, many taxonomic issues – in particular resolution of species complexes – remain unresolved, there is a remarkable dearth of detailed occurrence data for rare and threatened taxa, and our ecological knowledge of almost every species and community is staggeringly scant.

Some additional collection effort is likely to be informative, particularly in remote areas of the Kimberley. We have also identified a relative paucity of eucalypt collections per unit area from inland portions of the study area, but it is unclear from our data to what extent this reflects less collection effort in these areas in general or less focus on eucalypts because the species present are generally widely dispersed.

More generally, however, further taxonomic resolution of the eucalypt flora of the region appears constrained as much by the availability of taxonomists and geneticists as of herbarium collections. We note with concern that state herbaria have been squeezed by recent budget cuts (especially so in the Northern Territory), further constraining their already limited capacity to address taxonomic questions.

At the level of species and subspecies, taxonomic development in eucalypts remains primarily morphological and we eagerly await a greater contribution from geneticists and specifically the merging of morphological and genetic perspectives to provide more robust resolution of difficult questions. It is often unclear how "significant" morphological variation and differences are, and genetic analysis offers some prospect of shedding light on these issues. We also counsel against the popular frustration over name changes and "lumpers and splitters". Whilst this frustration has some basis (i.e. there are unquestionably personal idiosyncrasies among taxonomists), it is an almost inevitable process during what is still a relatively early stage of taxonomic refinement for many species groups. In the broader context, the process may usefully be interpreted as one of setting up hypotheses which may subsequently be accepted, rejected or revised. The process may be illustrated by the white mahogany group of species (section *Amentum* sensu Brooker 2000) of eastern Australia. Prior to 1999, five species of white mahogany were recognised (two in our study area), of which one, *E. acmenoides*, embraced a range of morphologies and environments that invited further consideration. In an attempt to provide resolution for the complex, Hill (1999) described seven new species, bringing the total to 12 (seven in the study area). In CPBR (2006), it is argued that "this revision [is] partly unworkable because some species delineations seem to be weakly founded in morphology", and the number of species reduced to eight (four in our study area). The Queensland Herbarium (Bostock & Holland 2010) appears to have adopted an intermediate position, recognising one of the study area species rejected by CPBR (2006) – *E. portuensis* – though the basis for this has apparently not been published. The Australian Plant Census appears to have adopted the same position as CPBR (2006), so that is the position adopted in this report. As CPBR (2006) is the most recent justified review of the complex, we are comfortable with this position, but clearly further examination of members of this complex is required. Previous analyses will surely facilitate future clarification by providing hypotheses and evidence.

This identifies a frustration of our own; that State/Territory checklists produced by jurisdictional herbaria often pre-empt taxonomic resolution, i.e. are based on judgements for which there is no published justification. This has generated many headaches for us that we have minimised by the use of the Australian Plant Census as a national standard; without such a standard, fortuitously updated recently (2011) this study would scarcely have been possible.

An alternative approach to directly focussing on taxonomic resolution, and one that has potentially profound implications for conservation management, is to focus on the identification of Evolutionary Significant Units (ESUs) (Ryder 1986). These are sometimes more loosely referred to as Conservation Units, and in the context of harvested populations, as Management Units. ESUs are populations representing more or less discrete evolutionary potential. In practice, they may be defined as isolated populations, as genetically differentiated groups of individuals, or as locally-adapted phenotypes (http://en.wikipedia.org/wiki/Evolutionarily_Significant_Unit, downloaded 8 March 2014), definitions that will vary in their applicability in different circumstances (Crandall *et al.* 2000; Fraser & Bernatchez 2001). ESUs may or may not align well with species and subspecies. They may result in recognition of populations for conservation purposes that cannot be differentiated morphologically (and possibly even genetically). Conversely, it is feasible that some morphological differences recognised by taxonomists as appropriate to differentiate subspecies and even species may not correspond to ecological, genetic or adaptive differentiation. Identification of ESUs has an obvious urgency in areas under theat, for example from land-clearing, and in particular from an adaptive perspective, in the face of climate change.

Of more immediate concern is the scarcity of data to inform decisions about threatened and potentially threatened taxa. The former is illustrated by *E. sicilifolia*, the taxon we assessed as Endangered on the basis of five isolated populations within an Extent of Occurrence of 41 km^2 and a clearing index of 25.8%. The species is listed as Vulnerable by the Queensland government, but has no threat rating nationally. Is there more suitable habitat in the area which has not yet been surveyed? How large (in numbers and or area) are the five populations? We searched the scientific literature and government files on-line including Qld DNRM vegetation maps and the Qld REDD file (v8, downloaded 1 Jan. 2014) and learnt nothing more than the brief description of its habitat detailed in this report.

Our ignorance of ecological processes that are key to conservation in the face of development is equally alarming. What do we know about reproduction and seedling recruitment in north Australia eucalypts? General observations (but no data) suggest that many if not most species are masting, i.e. they flower synchronously but not every year, creating questions about pollination and thus seed production. Are the few vertebrates capable of responding at these spatial and temporal scales – the Little Red Flying-fox (*Pteropus scapulatus*) and the Varied Lorikeet (*Psitteuteles versicolor*) (see Franklin 1996) – critical to pollination? And if so, what degree of habitat retention and landscape connectivity is necessary to retain their services? How do fire regimes and other disturbances influence seedling establishment? We can only hazard guesses about these questions, for the available research from northern Australia to inform these issues is – zero – and that for eucalypts from other places scarcely any better. The scant information available about lifespans and generation lengths and the time taken to reach maturity in north Australian eucalypts has already been reviewed in this report, and further illustrates the depths of our ignorance. And so one could go on.

These black holes of ecological information are not unique to eucalypts. Australia is ill-informed and thus ill-prepared for the land-use planning needed to minimise adverse consequences from the widespread land-clearing that has already occurred in the south-east of the study area, is on-going in Queensland in particular (see below), and which senior politicians in both state and federal governments advocate takes place on a greater scale throughout the study area.

Spatial patterns and hot spots

Strong spatial patterning in the occurrence of eucalypts within the study area is most strikingly evident in our identification of 12 biogeographic clusters of taxa (Table 4). Although the level of similarity within groups was quite low (Fig. 15), the groupings were nevertheless strongly supported statistically by randomisation tests. We attribute the low levels of similarity within groups to frequently incomplete and idiosyncratic patterns of distribution of species within group core areas. In other words, a species may belong to Group C (Top End endemics) but its occurrence within the Top End may be limited to a sub-set of the degree cells that characterise the group's distribution (Fig. 16C). Observed patterns of species richness (Fig. 12) are also indicative of strong spatial patterning, though there is some uncertainty about the relative contributions of actual richness and survey effort to these findings. Patterns of richness of restricted range taxa provide an additional perspective in which patterns emerge with progressive inclusion of a broader view of "restricted" (Fig. 23); with inclusion of all four tiers of restrictedness, the emergent pattern is strikingly similar to that of observed species richness overall.

Our biogeographic analyses are consistent with the broad conclusion obtained from a wider variety of taxa that, whilst the Kimberley and Top End have somewhat discrete floras, their joint biogeographic separation from eastern Queensland is greater (e.g. Bowman *et al.* 2010a). The eucalypts of eastern Queensland belong primarily to an eastern Australian evolutionary track that is quite distinct from that of north-western Australia (Ladiges *et al.* 2011). This is most clearly exemplified by the informal group of *Eucalyptus* species known as "monocalypts" which multiple genetic studies have nevertheless demonstrated to be a discrete lineage (e.g. Bayly *et al.* 2013). Monocalypts include species commonly known as stringybarks, peppermints and white mahoganies. They are a prominent component of the eucalypt flora of eastern Queensland extending well into inland areas and north to the Wet Tropics, but are absent from the Kimberley, the Top End and Cape York Peninsula (Gill *et al.* 1985).

Our more detailed identification of areas of endemism has striking parallels, but also notable differences, to the national analysis of Ladiges *et al.* (2011). Whereas Ladiges *et al.* identified areas of endemism (based on select groups of eucalypt taxa), we identified clusters of eucalypts based on their range which allows us the more profound perspective that the flora of a given area may belong to more than one biogeographic group. Thus, for instance, whereas Ladiges *et al.* identified the Kimberley as one area of endemism and the Top End including the Gulf of Carpentaria hinterland as another, we identified areas of endemism in the Kimberley (Group D) and Top End (Group C) but also that most of the associated Gulf hinterland eucalypt species occur in both (Group B). Similarly, whereas Ladiges *et al.* identified Cape York Peninsula as a single area of endemism, we identified both a local area of endemism with strong links to New Guinea (Group H) but also significant sharing of species with the Kimberley and Top End (Group B). Importantly, both studies identified an area of inland north-west Australia as biogeographically significant (our Group E), along with a notable area in inland north Queensland that approximately equates with inland portions of the Einasleigh Uplands bioregion ± the Desert Uplands (our Group F), and also a Wet Tropics region that includes the eastern (higher and moister) portions of the Einasleigh Uplands (our Group G). The latter group includes the most speciose area of eucalypts in northern Australia, with a major concentration of taxa in the dry sclerophyll forests and woodlands of the western Atherton Tablelands and adjacent western slopes, along with a few species associated with moist and wet sclerophyll forest and rainforest fringes. Our brigalow belt group J appears to be a sub-set of Ladiges *et al.*'s "Inland South-East Queensland" group, different delimitation of southern limits possibly reflecting their inclusion of species that do not occur in our study area.

The spatial perspectives presented in this report provide alternative perspectives on conservation. Patterns of overall species richness and of richness of restricted range taxa place emphasis on biodiversity hot spots. In contrast, the biogeographic analysis identifies additional areas of interest, for example the "hot country specialists" of inland north-western Australia and the brigalow belt endemics of inland south-east Queensland, which may be of particular concern given limited reservation and (in some cases) extensive land clearing. The implications of these biogeographic groups are explored further under the headings of

"Reservation status" and "Land-clearing as a threat" below. The remainder of this section is devoted to a brief discussion of biodiversity hot spots in the study area.

The distinctness of the flora and fauna of the Kimberley and the Top End has long been recognised (e.g. Cracraft 1991; Crisp *et al.* 1995; Woinarski *et al.* 2006). Richness is not necessarily tied to distinctness, and while these regions are rich in some taxa, they are poor in others. For example, the Kimberley region is moderately rich in species of *Acacia* but with an exceptionally high level of endemism (González-Orozco *et al.* 2011), but rather poor in species and exceptionally poor in endemic butterfly taxa (Braby 2008). In comparison only with other parts of northern Australia, the eucalypt flora of these regions is both rich and distinct, with many taxa endemic to one or the other or the two combined. Biogeographic affinities between these regions are generally associated with dissected sandstone landscapes, and it is likely that a combination of topography and altitude in these landscapes has provided refugia for species especially during more arid periods (Freeland *et al.* 1988; Bowman *et al.* 2010a). The dissected landscapes of the central Kimberley ranges and Arnhem Land Plateau are particularly rich in localised eucalypt species. However, a number of other species are associated with non-dissected and lowland habitats, for example *E. argillacea* with grassy plains and savannas in the Kimberley, and *C. foelscheana* (Wide-leaved Bloodwood) with lowland plains and footslopes in the Top End.

Much less is known about the biogeographical history of eucalypts leading to local endemism in Queensland. It may reasonably be inferred that areas immediately inland of the Wet Tropics rainforests have served as refugia for eucalypts during arid periods, and indeed there is evidence to this effect (Hopkins *et al.* 1993). The elevation of the area, considerable by Australian standards with many peaks over 1,000 m, is likely to have attracted moisture and reduced evapotranspiration at these times. More generally, the Great Dividing Range in north Queensland extends well inland – the Einasleigh Uplands – with areas above 500 m elevation up to 300 km from the Pacific coast, for example the Newcastle Range near Forsayth south-east to the White Mountains near Burra. The combination of elevation and topography is likely to have provided refugia that have facilitated the retention of diversity through climatic vacillations (AHC 2001). Special mention should be made of the White Mountains – Pentland Hills area on the southern edge of these highlands, a largely unheralded area of exceptional eucalypt diversity and also localised endemicity (*C.* sp. Pentland Hills, *E. farinosa*, *E. quadricostata*). Referring to the vertebrate diversity of the area, Kutt *et al.* (2005) wrote that these mountains lie "at the confluence of multiple major landscape features and the composition of the fauna assemblage reflects this position at climatic and biogeographic crossroads in the semi-arid tropical savannas. The mesic gorges and tall high altitude *Eucalyptus* forests provide habitat for species with typical distributions tending further east and south." The White Mountains also support an endemic species of butterfly (Braby 1996).

Threatened species and subspecies

Eight north Australian eucalypt taxa are rated as threatened under Commonwealth legislation and one additional species (*E. sicilifolia* in Qld) under state legislation; all of these are officially rated as Vulnerable. In contrast, we rated only four of these as threatened (2 Endangered, 2 Vulnerable) (Table 12). Of the remaining five rated officially as Vulnerable, we rated one as Near Threatened, two as Data Deficient and two as Least Concern. Fifteen taxa not listed officially as threatened were rated by us as threatened – one as Endangered and 14 as Vulnerable. We believe the differences are attributable to two causes.

The first is that Commonwealth listings in particular are clearly quite out of date. Indeed, all eight listed eucalypts were carried over into the EPBC Act from prior listings and only one (*E. raveretiana*) has been formally re-assessed under EPBC Act criteria. That EPBC Act listings of threatened species were seriously out of date was noted by the Australian National Audit Office in 2007 (McVay *et al.* 2007), was the subject of serious criticism at a recent Senate committee hearing into the Act, and has been noted publicly (Garnett & Woinarski 2012). The consequences of this situation are two-fold. On the one hand, development proponents may not be required to consider taxa that are genuinely threatened, and management plans will inevitably not be developed for these taxa (though there is no obligation on the relevant Minister to develop plans under the Act, and no plan has been developed for any listed north Australian eucalypt). On the other hand, proponents of development may be required to consider and take potentially costly actions for taxa that are not genuinely threatened (Stephen Garnett, pers. comm.). In the case of eucalypts, it appears that most taxa were listed on the grounds of rarity alone (*E. raveretiana* almost certainly excepted); subsequent surveys have, in a number of cases shown that the species is not rare enough to meet IUCN criterion D (rarity alone) or B (rarity plus threat). However, new taxa have been discovered and identified, and some of these are extremely rare.

The second cause, we believe, is a reluctance to list eucalypts under criterion A2b on the basis of decline due to land clearing over the last three generations when the taxon may remain widespread and perhaps common. We are aware that many eucalypts of woodlands in south-eastern and south-western Australia qualify as threatened under this criterion, but have not been listed. This reluctance is, we argue, quite lacking in justification. The "three generations" timeframe has been included in the IUCN criteria quite specifically to ensure the demographic appropriateness of consideration of rates of decline across a wide range of organisms (IUCN S&PS 2011). No such reluctance has been evident in applying the three-generation timeframe to long-lived vertebrates such as marine turtles. Further, listing of applicable eucalypts in order to highlight and prevent a continuation of their clearing is precisely the point of the criterion and its application.

There is inevitable uncertainty in the information basis upon which we have based our threat ratings. This is, in itself, no reason to hold back on assessment (IUCN S&PS 2011). However, there is little doubt that additional information exists about many of the taxa concerned, perhaps particularly among state and territory Herbarium staff and local conservation staff and naturalists. This information should be incorporated – and placed in the public arena – before any formal re-assessments of the threat status of taxa are undertaken. Further, some taxa will doubtless prove amenable to targetted additional surveys. Our ratings should be taken as a clarion call to collate the available information (and make it public), and to undertake targetted surveys, as a matter of considerable priority.

In particular, more detailed assessment of the impact of clearing on populations is appropriate. Our index of clearing, based as it is on the intersection of herbarium records with land clearing, is a useful approximation that could in some cases be readily refined with local knowledge. The accuracy of the coordinates of some herbarium records, particularly older ones, is questionable and may generate error but not bias - either an over- or under-estimation of the impact of clearing is possible in consequence. Further, the interpretation of a record as representative of a population that has been cleared – or not cleared – may contain biases in the direction of either over- or under-estimation of impacts. For example, records may have been selectively collected along roadsides in cleared land because the uncleared land is not readily accessible or there are sensitivities about collecting in reserves, or conversely collections may be biased towards uncleared land because of restrictions to access to private property or simply that there are few or no individuals remaining because they have already been cleared. The same caveats apply to our reservation index and to the application of both indices to non-threatened as well as threatened taxa.

We make a plea for much greater transparency and consistency in the assessment of the threatened status of eucalypt and other taxa. Of the Commonwealth, two states and one territory relevant to our study area, only the Northern Territory provides explicit documentation of the basis for listings (Woinarski *et al.* 2007b; http://www.lrm.nt.gov.au/plants-and-animals/home/specieslist#, accessed 5 Jan. 2014). Arguably, the Commonwealth does likewise (http://www.environment.gov.au/cgi-bin/sprat/public/sprat.pl, accessed 5 Jan. 2014). However, in the case of eucalypts we note that all but one taxa have never been assessed under EPBC Act criteria – technically a result of being out-of-date rather than reflecting an unwillingness to provide information. For the one taxon that has received formal assessment under the Commonwealth's EPBC Act, *E. raveretiana*, we feel that the assessment is quite superficial because we had no difficulty generating evidence strongly suggesting that the taxon is Endangered based on decline due to clearing, whereas with reference to possible decline the SPRAT assessment for the species states "Insufficient data …

there are no quantitative population data available, and therefore there are insufficient data to determine whether this species has or is likely to undergo future reductions in numbers". This leads to the rather absurd conclusion that "Although there are insufficient data to assess the species against the criteria, the Committee recommends a precautionary approach be applied and hence that **no amendment** be made to the list referred to in section 178 of the EPBC Act and that *Eucalyptus raveretiana* remains eligible for inclusion in the **vulnerable** category of the list" [bold is in original].

We note also that, whilst jurisdictional criteria for listing taxa as threatened bear some resemblance to those of the IUCN, only those of the Northern Territory are an exact match to them. Indeed, if the assessment of *E. raveretiana* had complied with IUCN standards, the result is likely to have been different. Firstly, IUCN S&PS (2011) explicitly caution against the sort of rigid evidentiary approach quoted in the previous paragraph ("no quantitative population data … therefore there are insufficient data …") when alternatives are available. However, even if it is accepted that there was insufficient evidence about clearing, then the relevant conclusion might have been different and the explanation of it certainly quite different:

- if the evidence was deemed sufficient that *E. raveretiana* was *at least* Near Threatened on the basis of clearing (i.e. >20% decline) but insufficient to determine which category it was correctly placed in, then it should have been placed in the category deemed most likely *and* an explicit statement of the underlying reasoning and qualifications spelt out; or
- if the evidence was deemed insufficient to rule out the possibility that the species might be of Least Concern, then it should have been classified as Data Deficient.

Finally, we note that all taxa assessed as threatened in this report are endemic to Australia, and nearly all are restricted to a single state, so that state, territory, national and IUCN assessments should be global by definition and thus consistent (but for possible differences in official threat criteria). The sole exception is *E. exserta*, which occurs in both Queensland and New South Wales – we found evidence of sufficient clearing in Queensland alone to warrant a global assessment of Vulnerable for this species.

Reservation status

Notwithstanding considerable complementarity between the crown and private reserve systems, the geographical distribution of conservation reserves in northern Australia, and thus their coverage of eucalypt taxa and communities, is extremely uneven. In the Kimberley and Top End, reserves are concentrated in the higher rainfall and more topographically-dissected regions and remarkably scant in the pastoral districts of the inland. In Queensland, a somewhat similar pattern is apparent, with a concentration of reserves on Cape York Peninsula, in the Wet Tropics, and in the form of a series of small reserves along the length of the east coast, but remarkably little coverage on inland, predominantly pastoral districts.

This unevenness has some advantages as well as major drawbacks. Almost by definition, topographically varied areas support more eucalypt (and other) species and, in particular, more localised endemics, and frequent rocky terrain renders them of limited value for pastoralism. With the notable exception of the Einasleigh Uplands of north Queensland, these areas are generally well-reserved. Yet even in eucalypt-rich areas, much better matching of reserves to eucalypt taxa and communities could be achieved. For example, the eucalypt hotspot in the White Mountains – Pentland Hills area south-west of Charters Towers in Queensland features the 112,000 ha White Mountains National Park, yet the rarer two of the three eucalypts endemic to the area – *C*. sp. Pentland Hills and *E. farinosa* – apparently do not occur in the Park.

This unevenness in the development of a reserve system for northern Australia is a malaise whose implications extend well beyond eucalypts. Poor representation of eucalypt communities that are favoured for low-intensity pastoralism that does not involve land clearing has implications for a wide range of biodiversity (e.g. granivorous birds; Franklin 1999). Ironically, it may however, have limited implications for eucalypts because in general eucalypts are remarkably resilient to grazing and variation in fire regimes. However, this malaise extends to poor (or no) reservation of eucalypt communities favoured for land clearing for higher-intensity pastoralism and agricultural development (Fig. 35). Eucalypts are not resilient to land clearing and we have shown that a number of eucalypts in northern Australia are already threatened by it. Australia is yet to demonstrate that it can intelligently intensify food production in northern Australia by matching that intensification with development of a reserve system that is appropriate to the ecological compromises and challenges that intensification generates.

Land-clearing as a threat

Land clearing is the ultimate threat to eucalypts, eucalypt communities and all natural ecosystems in northern Australia. The intactness of much of the north Australian landscape is an extraordinary boon and one that should be maintained in the face of impending northern development. However, past and current practice, particularly in the south-east of the study area does not inspire confidence in the development process. Land that is favourable for intensification of land use has been developed, and conservation efforts largely confined to land that is not favourable for intensification, with resultant selective loss of species and communities that occur on more fertile soils. This selectivity can have additional unforeseen consequences, for example causing disproportionate loss of bird populations from a landscape because options for survival during stressful periods such as drought are reduced (Watson 2011).

Land clearing in Queensland is on-going at concerning rates (Table 17) notwithstanding the ban on broad-scale land-clearing introduced in 2006 (Kehoe 2006). These rates are, we acknowledge, diminished by an order of magnitude from those of the late 20th century and early in the first decade of the 21st century. Much of this exposure is and was to communities dominated by Brigalow (*Acacia harpophylla*) (Fensham *et al.* 1998), but we have shown that a number of eucalypts and eucalypt communities have also been heavily exposed. Compensatory conservation measures such as reservation of the species and communities threatened by clearing remain to be put in place. We note also that the major threshold for concern under Queensland's Vegetation Management Act 1999 appears to be the loss of 70% of a community (Qld. regional ecosystem, http://www.ehp.qld.gov.au/ecosystems/biodiversity/regional-ecosystems/how_to_download_redd.html, downloaded 1 Jan. 2014). This is clearly and markedly insufficient to avoid taxa whose occurrence is tied to key regional ecosystems from being listed as threatened under IUCN criteria. We note also with concern recent amendments to the Act that relax some of its provisions.

Table 17. Annual rates of land-clearing in the Queensland portion of the study area since the prohibition of broad-scale land clearing in 2006.
Data extracted by intersection of our study area with SLATS shapefiles - official Qld government shapefiles of vegetation change. More recent data are not available publicly.

Year	Area (ha)
2007-08	41,706
2008-09	38,239
2009-10	35,671
Average	**38,539**

The problem is incipient in other parts of northern Australia. Even though the area of clearing in the Northern Territory and the Kimberley region of Western Australia remains small, it is focussed on particular ecosystems that are suitable for agricultural development. The potential risks are illustrated by our finding of an index of clearing of 17.7% for *C. foelscheana*, a eucalypt endemic to the north-west of the Northern Territory.

Climate change: threat & opportunity

Climate change as threat

The most certain implication of climate change for northern Australia is that it will get even hotter. Inland northern Australia, already the hottest part of Australia, is predicted to experience the greatest increase in temperatures nationally (Suppiah *et al.* 2007).

The outlook for change to rainfall is less clear and more regionally varied. In recent decades, rainfall in the Top End and Kimberley has increased, contrary to the predictions of general global climate models. Reconciliation of models with actual trends has now been achieved by the inclusion of increases to atmospheric particulate matter (Rostayn *et al.* 2012) – pollution brought south from Asia by the summer monsoon that is, in effect, seeding rain. However, the interplay of opposing forces – greenhouse gases and air pollution – yields uncertain predictions for the coming century. There is greater certainty in Queensland, where rainfall has already decreased and is predicted to decrease further (CSIRO 2007), least so in the Wet Tropics (Suppiah *et al.* 2009) though global predictions of a rise in cloud elevations in tropical montane areas (Still *et al.* 1999) are a major concern. Global climate models that have only just become available suggest a far more severe drying of Cape York Peninsula than previously predicted (Franklin *et al.* in press a). More generally, the northern wet season may be abbreviated but more intense in a higher proportion of years (Taschetto *et al.* 2009; Yeh *et al.* 2009), potentially enhancing the severity of the dry season.

There are many other facets of climate change that have implications for biodiversity – see Franklin *et al.* (in press b) for a major review in an Australian context. Of these, the one that may have most implications for eucalypts is that elevated levels of CO_2 in the atmosphere influence plant growth and alter vegetation independently of climate by three pathways (Murphy & Bowman 2012): by elevating tree growth rates, by increasing carbon assimilation differentially more in C_3 (mostly woody) than C_4 (mostly grassy) plants, and by changes to water use efficiency that should favour deeper-rooted species. These lead to the general prediction for tropical regions of vegetation transitions from grassland to treed savanna and from savanna to monsoon forest or rainforest. These predictions are consistent with observed tropical trends in vegetation change globally (Bond & Midgley 2012) and in northern Australia (Murphy & Bowman 2012).

Eucalypt taxa tend strongly to occupy relatively narrow climatic bands as measured by temperature and rainfall (Hughes *et al.* 1996). Unsurprisingly, therefore, climate envelope models that are projected into the future yield rather dire predictions for the fate of eucalypts including those of northern Australia (Butt *et al.* 2013). We do not unequivocally endorse this finding as predictions based on projections of climate envelope models alone have justifiably received much criticism (e.g. Low 2011). Criticisms centre on two arguments: *a*. the underlying assumption that a taxon's range is constrained by climate is often incorrect; and *b*. they don't consider the ability of taxa to adapt, for example by dispersal, phenotypically or evolutionarily. A special case of *a.* is that interspecific interactions are often key to biological responses and these are not considered in climate space models. Of these criticisms, the first is most relevant to eucalypts, with distributions often defined by substrates and geographical history and probably also interspecific interactions. We note that long-generation times (this report) severely constrain the ability of eucalypts to adapt evolutionarily to rapid change, and lack of adaptation to long-distance dispersal of seed (House 1997) limits their capacity to track shifting climate envelopes through space. Wallace *et al.* (2008) demonstrated an unusual exception – dispersal of seed of Cadaghi (*C. torelliana*) by bees.

A somewhat more optimistic outlook for eucalypts in Queensland was predicted by Low (2011):

> Eucalypts may show considerable resilience to climate change, having distributions that often do not reflect climatic limits (4.1, 6.1), and pollination systems and growth forms that facilitate survival under changing conditions (4.1). But deaths of dominant ironbarks (for example *E. crebra*, *E. melanophloia*) and boxes and their replacement over large areas by subordinate bloodwoods (*Corymbia* species) seem likely (4.1), because dominant eucalypts often have 'high risk' growth

> strategies. Contractions of range at western margins are likely, especially for species with large ranges."

Low's suggestion of change in local community composition is driven partly by the observation of widespread death during prolonged severe drought of some north Queensland eucalypts (Fensham 1998; Bowman *et al.* 1999; Fensham & Holman 1999; Fensham *et al.* 2003, 2009; Fensham & Fairfax 2007). In this case at least, the negative effect of drought over-rode any improvement in water-use efficiency attributable to elevated levels of atmospheric CO_2 (Fensham *et al.* 2009). Clearly, some eucalypts are already at their climatic limit.

Low (2011) also explored the evidence that some eucalypts persisted in refugia through the prolonged dryness of the last glaciation ("Ice Age"), some species persisting only in those refugia to this day and others dispersing out from these refugia as the climate subsequently ameliorated. He also suggested that many Australian taxa (not necessarily eucalypts) evolved during hotter periods.

Under climate change, we may anticipate that some eucalypts will thrive, some merely persist, and some decline (potentially severely so), but predictions about which and where are beyond the scope of this report – and at the moment at least, largely beyond the realms of scientific possibility.

Greenhouse gas management as opportunity

We have briefly reviewed the possibilities for reduction, sequestration and abatement of greenhouse gas emissions in northern Australia. The potential contribution of these processes to the conservation and management of eucalypt communities is great but contingent on the price of carbon, and on retention, revegetation and management of vegetation being factored into national carbon inventories. Current moves by the Commonwealth government away from a carbon price are most regrettable, but are perhaps best viewed as a short-term political imperative that is almost bound, sooner or later, to be overridden by overwhelming concerns about a changing climate. The Western Arnhem Land Fire Abatement Project (WALFA) has been funded by an international company willing to pay for carbon offsets (Fitzsimons *et al.* 2012) that are not required of it under any national carbon pricing scheme.

The carbon emitted when eucalypt forests and woodlands are cleared is substantial. If there was a carbon pricing mechanism in Australia which offered a substantial incentive to landholders not to clear land, then landholders may choose to forego clearing in return for sales of carbon credits. This is unlikely in the foreseeable future, and was not addressed under the Carbon Farming Initiative which was implemented by the previous Federal government (http://www.climatechange.gov.au/, accessed 16 January 2014).

Abatement of emissions of methane and nitrous oxide by reducing areas burnt and/or shifting the balance of fire towards the early dry season in northern Australia offers a nexus of benefits:

1. greenhouse gas abatement (Russell-Smith *et al.* 2009, 2013);
2. biodiversity benefits (Andersen *et al.* 2005; Woinarski *et al.* 2009);
3. economic benefits especially including employment opportunities for Aboriginal people living in remote communities where employment options are scarce (Whitehead *et al.* 2008); and
4. cultural and health benefits in generating opportunities for traditional owners to remain or become involved in management of their land (Garnett *et al.* 2009; Fitzsimons *et al.* 2012)

Summary of threats

As discussed already in this chapter, land clearing is the pre-eminent existential threat to those eucalypts and eucalypt communities that occur on soils favourable to agriculture and in districts with intense settlement somewhat regardless of soils. Climate change may well prove to be an existential threat to some taxa and populations (including Evolutionary Significant Units). In contrast, eucalypts are remarkably resilient to a range of fire regimes, weed invasion and to grazing, though these management issues have major ramifications for other aspects of biodiversity. Exceptions to this resilience have local rather than existential significance. One of these is the impact of rainforest invasion (to which changes in fire regimes may have contributed, most likely in tandem with climate change) adversely affecting several eucalypts in the Wet Tropics of north Queensland (notably Rose Gum *E. grandis* but also Red Mahogany *E. resinifera*) – see comments and literature referred to in Chapters 1 & 5. Another is the impact of frequent, severe fire driven by invasive Gamba Grass (*Andropogon gayanus*) in transforming intact stands of eucalypts of higher-rainfall savannas/open forests of the Top End of the Northern Territory into a degraded state and perhaps ultimately to grassland (Brooks *et al.* 2010). Affected eucalypts include Darwin Woollybutt *E. miniata* and Darwin Stringybark *E. tetrodonta* and a range of co-occurring species such as Glossy-leaved Bloodwood *C. bleeseri*. A third locally-significant threat is large-scale harvesting of eucalypts for the manufacture of didgeridus. This risks compromising the integrity of populations of several species (e.g. Darwin Woollybutt *E. miniata*, Darwin Stringybark *E. tetrodonta*, and Gnaingar *E. phoenicea*) by removing individuals that would otherwise have high growth and survival rates *cf.* traditional practices which tended to remove weak individuals (Werner *et al.* 2008).

Conservation assessment

We provide three shapefiles to facilitate the assessment of development proposals:

1. threatened taxa. This corresponds to Fig. 28A-D (Files: *Threatened_taxa.shp* and ESRI ArcGIS file: *Eucs-NthAust_2013-9_Threatened.mxd*). Attributes are the no. of taxa per degree (in classes as mapped) for A. listed threatened taxa; B. listed taxa of concern; C. possibly threatened taxa (i.e. our assessment); and D. possibly Near Threatened or Data Deficient (our assessment). For a list of the taxa concerned, consult worksheet *threatened* in our supplementary file;
2. reservation status of eucalypt communities. Corresponds to Fig. 34A (Files: *nveg_polygon_GDA94_Zone52_Eucalypt_formations.shp* and ESRI ArcGIS file: *Eucs-NthAust_2013-Euc_classes_reserved-deliverable.mxd*). Attributes of communities are the % reserved in classes as mapped. For more precise data on % reservation including the proportions in crown and private reserves, consult worksheet *communities* in our supplementary file; and
3. cleared status of eucalypt communities. Corresponds to Fig. 34B (Files: *nveg_polygon_GDA94_Zone52_Eucalypt_formations.shp* and ESRI ArcGIS file: *Eucs-NthAust_2013-Euc_classes_cleared-deliverable.mxd*). Attributes of communities are the % cleared in classes as mapped. For more precise data on % cleared, consult worksheet *communities* in our supplementary file.

Each of these shapefiles can be interrogated through ESRI's ArcGIS 'Identify tool' or using the attributes table 'select by attributes' or 'Query builder'.

Metadata for our supplementary file are provided in Appendix 4.

ACKNOWLEDGEMENTS

This project was funded by the Bjarne K Dahl Trust (http://dahltrust.org.au/) via a grant to the Environment Centre of the Northern Territory (http://ecnt.org/) . We are most grateful to Clare Taylor, Stuart Blanch and Jess Abrahams of the ECNT for the supportive environment they generated for this work.

A number of Herbarium staff from around the country responded generously with their time and expertise notwithstanding almost widespread tight budgetary constraints on their availability. We are particularly grateful to Andree Slee of CSIRO Australian National Herbarium, Ian Cowie (NT Herbarium), Frank Udovicic and Alison Vaughan (Victorian Herbarium), Barry Conn (NSW Herbarium) and Peter Bostock and Rod Fensham (Queensland Herbarium). David Martin, Niels Klazenga and Nick Dosremedios provided support with Australia's Virtual Herbarium.

Gay Crowley, David Gillieson and Kym Dungey provided helpful advice on GIS issues.

Rob Law provided key advice, assistance and data relating to carbon stocks, emissions and sequestration.

Stephen Garnett provided valuable advice on the application of IUCN criteria to assessment of the threatened status of species and subspecies.

Clare Taylor, Darren Crayn, Paul Gioia and Andrew Slee provided helpful comments on an earlier draft.

Digital datasets

IUCN digital datasets: IUCN and UNEP-WCMC (2013), *The World Database on Protected Areas (WDPA)* [On-line]. Cambridge, UK: UNEP-WCMC. Available at: www.protectedplanet.net [Accessed 23 November 2013].

IPA Source data acknowledgements: We acknowledge the Indigenous Protected Areas Section, Parks Australia, Department of the Environment as the custodian of the data © Department of the Environment, 2013.

1:250,000 mapping used © Copyright Commonwealth of Australia (Geoscience Australia) 2006. The GEODATA TOPO 250K Series 3 User Guide can be found at http://www.ga.gov.au/image_cache/GA8349.pdf.

This Eucalypt mapping product incorporates Data which is © Copyright Commonwealth of Australia (2009). The Data has been used in the Eucalypt mapping project with the permission of the Commonwealth. The Commonwealth has not evaluated the Data as altered and incorporated within the Eucalypt mapping project, and therefore gives no warranty regarding its accuracy, completeness, currency or suitability for any particular purpose.

Digital dataset of Australian Wildlife Conservancy properties is © Copyright Australian Wildlife Conservancy 2011. It has been provided by Tani Cooper and Sarah Legge of AWC and is used with permission.

Digital datasets of Bush Heritage properties © Copyright Bush Heritage Australia (2013). Provided by Murray Haseler of BHA and used with permission.

Northern Territory Parks and Reserves Spatial Dataset was supplied by Department of Land Resource Management © Northern Territory of Australia (2013) and used with permission.

Northern Territory vegetation cover data were supplied by the Department of Land Resource Management. Data supplied by this Department is licensed under the Creative Commons Attribution 3.0 Australia License

(CC BY 3.0). Data supplied by Department of Land Resource Management. Copyright Northern Territory of Australia. Used with permission.

Australia - Present Major Vegetation Groups - NVIS Version 4.1 (Albers 100m analysis product):
Source data acknowledgements:
This raster product is modelled from data originally supplied by the states and territories. DSEWPaC (Commonwealth Department of Environment) acknowledges the following departments/organisations -
- ACT Environment and Sustainable Development Directorate
- NSW Office of Environment and Heritage and Department of Primary Industries
- NT Department of Natural Resources, Environment, The Arts and Sport
- QLD Department of Science, Information Technology, Innovation and the Arts (Queensland Herbarium)
- SA Department of Environment and Natural Resources
- TAS Department of Primary Industries, Parks, Water and the Environment
- VIC Department of Sustainability and Environment
- WA Department of Agriculture and Food- Geoscience Australia

Statewide landcover and trees study 1988 to 2010 Queensland is licensed under a Creative Commons - Attribution 3.0 Australia licence. State of Queensland (Department of Science, Information Technology, Innovation and the Arts) 2013. Updated data available at http://dds.information.qld.gov.au/dds/

Queensland remnant vegetation cover 2009 version 7 - August 2012 is licensed under a Creative Commons - Attribution 3.0 Australia licence.

The Department of Science, Information Technology, Innovation and the Arts requests attribution in the following manner:
© State of Queensland (Department of Science, Information Technology, Innovation and the Arts) 2013. Updated data available at http://dds.information.qld.gov.au/dds/.

Protected areas of Queensland digital dataset is licensed under a Creative Commons - Attribution 3.0 Australia licence.

The Department of National Parks, Recreation, Sport and Racing requests attribution in the following manner:
© State of Queensland (Department of National Parks, Recreation, Sport and Racing) 2013. Updated data available at http://dds.information.qld.gov.au/dds/.

The Vegetation of the Australian Tropical Savannas (Scale 1:1,000,000) by I.D. Fox, V.J. Neldner *et al.* 2001 dataset was supplied by the Queensland Herbarium, Department of Environment and Heritage. Used under licence.

Interim Biogeographic Regionalisation for Australia (IBRA), Version 7 (Regions) digital dataset was obtained from the Dept of Environment (formerly SEWPAC). Data are available in the Public Domain under Creative Commons by Attribution Licensing Agreement. We attribute the Department of Sustainability, Environment, Water, Population and Communities (now Dept of Environment) as the data provider.

References

Australian Heritage Commission. 2001. *White Mountains National Park and Resources Reserve, Pentland Qld*. Register of the National Estate, Australian Heritage Commission: Canberra.

Allan G, Johnson A, Cridland S, Fitzgerald N. 2003. Application of NDVI for predicting fuel curing at landscape scales in northern Australia: can remotely sensed data help schedule fire management operations? *International Journal of Wildland Fire* 12: 299-308.

Andersen AN, Cook GD, Corbett LK, Douglas MM, Eager RW, Russell-Smith J, Setterfield SA, Williams RJ, Woinarski JCZ. 2005. Fire frequency and biodiversity conservation in Australian tropical savannas: implications from the Kapalga fire experiment. *Austral Ecology* 30: 155-167.

Anonymous. 1996. Where are the tropical savannas? *Savanna Links* 2: 10.

Ash J. 1988. The location and stability of rainforest boundaries in north-eastern Queensland, Australia. *Journal of Biogeography* 15: 619-630.

Australian Surveying and Land Information Group. 1990. *Atlas of Australian Resources. Third Series. Volume 6. Vegetation*. Department of Administrative Services: Canberra. 64 pp.

Barrett RL. 2007. *Corymbia cadophora* subsp. *polychroma* (Myrtaceae): a new subspecies from the east Kimberley region of Western Australia. *Nuytsia* 17: 32-35.

Bayly MJ, Rigault P, Spokevicius A, Ladiges PY, Ades PKA, Charlotte, Bossinger G, Merchant A, Udovicic F, Woodrow IE, Tibbits J. 2013. Chloroplast genome analysis of Australian eucalypts - *Eucalyptus*, *Corymbia*, *Angophora*, *Allosyncarpia* and *Stockwellia* (Myrtaceae). *Molecular Phylogenetics and Evolution* 69: 704-716.

Bean AR. 1991. Two new species of red gum (*Eucalyptus* L'Herit., Myrtaceae) from Queensland. *Austrobaileya* 3: 467-471.

Bean AR. 2006. *Eucalyptus megasepala* A.R.Bean (Myrtaceae), a new species from Queensland allied to *E. tetrodonta* F.Muell. *Austrobaileya* 7: 305-310.

Beringer J, Hutley LB, Tapper NJ, Cernusak LA. 2007. Savanna fires and their impact on net ecosystem productivity in North Australia. *Global Change Biology* 13: 990–1004.

Bond WJ, Midgley GF. 2012. Carbon dioxide and the uneasy interactions of trees and savannah grasses. *Philosophical Transactions of the Royal Society B-Biological Sciences* 367: 601-612.

Bostock PD, Holland AE, eds. 2010. *Census of the Queensland Flora 2010*. Queensland Herbarium, Department of Environment and Resource Management: Brisbane. 324 pp.

Bowman DMJS. 1998. The impact of Aboriginal landscape burning on the Australian biota. *New Phytologist* 140: 385-410.

Bowman DMJS. 2002. The Australian summer monsoon: a biogeographic perspective. *Australian Geographical Studies* 40: 261-277.

Bowman DMJS. 2003. Australian landscape burning: a continental and evolutionary perspective. In *Fire in ecosystems of south-west Western Australia*, ed. I Abbott, N Burrows, pp. 107-188. Backhys Publishers: Leiden.

Bowman DMJS, Dunlop CR. 1986. Vegetation pattern and environmental correlates in coastal forests of the Australian monsoon tropics. *Vegetatio* 65: 99-104.

Bowman DMJS, Wilson BA, Fensham RJ. 1999. Relative drought tolerance of evergreen-rainforest and evergreen-savanna species in a long unburnt *Eucalyptus* savanna, north Queensland. *Proceedings of the Royal Society of Queensland* 108: 27-31.

Bowman DMJS, Brown GK, Braby MF, Brown JR, Cook LG, Crisp MD, Ford F, Haberle S, Hughes J, Isagi Y, Joseph L, McBride J, Nelson G, Ladiges PY. 2010a. Biogeography of the Australian monsoon tropics. *Journal of Biogeography* 37: 201-216.

Bowman DMJS, Murphy BP, Banfai DS. 2010b. Has global environmental change caused monsoon rainforests to expand in the Australian monsoon tropics? *Landscape Ecology* 25: 1247-1260.

Brooks KJ, Setterfield SA, Douglas MM. 2010. Exotic grass invasions: applying a conceptual framework to the dynamics of degradation and restoration in Australia's tropical savannas. *Restoration Ecology* 18: 188-197.

Bureau of Meteorology. 1988. *Climate Atlas of Australia*. Department of Administrative Services: Canberra.

Braby MF. 1996. A new species of *Nesolycaena* Waterhouse and Turner (Lepidoptera: Lycaenidae) from northeastern Australia. *Australian Journal of Entomology* 35: 9-17.
Braby MF. 2008. Biogeography of butterflies in the Australian monsoon tropics. *Australian Journal of Zoology* 56: 41-56.
Briggs JD, Leigh JH. 1996. *Rare or Threatened Australian Plants*. CSIRO
Brooker MIH. 2000. A new classification of the genus *Eucalyptus* L'Hér. (Myrtaceae). *Australian Systematic Botany* 13: 79-148.
Brooks KJ, Setterfield SA, Douglas MM. 2010. Exotic grass invasions: applying a conceptual framework to the dynamics of degradation and restoration in Australia's tropical savannas. *Restoration Ecology* 18: 188-197.
Burgess IP, Bell JC. 1983. Comparative morphology and allozyme frequencies of *Eucalyptus grandis* Hill ex Maiden and *E. saligna* Sm. *Australian Forest Research* 13: 133-149.
Burrows GE. 2013. Buds, bushfires and resprouting in the eucalypts. *Australian Journal of Botany* 61: 331-349.
Burrows GE, Hornby SK, Waters DA, Bellairs SM, Prior LD, Bowman DMJS. 2008. Leaf axil anatomy and bud reserves in 21 Myrtaceae species from northern Australia. *International Journal of Plant Sciences* 169: 1174-1186.
Burrows WH, Henry BK, Back PV, Hoffmann MB, Tait LJ, Anderson ER, Menke N, Danaher T, Carter JO, McKeon GM. 2002. Growth and carbon stock change in eucalypt woodlands in northeast Australia: ecological and greenhouse sink implications. *Global Change Biology* 8: 769-784.
Butt N, Pollock LJ, McAlpine CA. 2013. Eucalypts face increasing climate stress. *Ecology and Evolution* 3: 5011-5022.
Carr SGM. 1972. Problems in the geography of the tropical eucalypts. In *Bridge and Barrier: the natural and cultural history of Torres Strait*, ed. D Walker, pp. 153-181. Australian National University Press: Canberra.
Chen XY, Hutley LB, Eamus D. 2003. Carbon balance of a tropical savanna of northern Australia. *Oecologia* 137: 405-416.
Clarke KR, Gorley RN. 2006. *PRIMER v6: User manual/Tutorial*. PRIMER-E: Plymouth, UK. 190 pp.
Cook GD, Liedloff AC, Eager RW, Chen X, Williams RJ, O'Grady AP, Hutley LB. 2005. The estimation of carbon budgets of frequently burnt tree stands in savannas of northern Australia, using allometric analysis and isotopic discrimination. *Australian Journal of Botany* 53: 621-630.
Centre for Plant Biodiversity Research. 2006. *EUCLID: Eucalypts of Australia. Third Edition.* CSIRO Publishing: Collingwood.
Cracraft J. 1991. Patterns of diversification within continental biotas: hierarchical congruence among the areas of endemism of Australian vertebrates. *Australian Systematic Botany* 4: 211-227.
Crandall KA, Bininda-Emonds ORP, Mace GM, Wayne RK. 2000. Considering evolutionary processes in conservation biology. *Trends in Ecology & Evolution* 15: 290-295.
Crisp MD, Linder HP, Weston PH. 1995. Cladistic biogeography of plants in Australia and New Guinea: Congruent pattern reveals two endemic tropical tracks. *Systematic Biology* 44: 457-473.
CSIRO. 2007. *Climate Change in Australia – Technical Report 2007*. Commonweath Scientific & Industrial Research Organisation.
Department of the Environment. 2013. *Australian National Greenhouse Accounts. Quarterly Update of Australia's National Greenhouse Gas Inventory. March Quarter 2013*. Department of the Environment, Commonwealth of Australia.
Douglass LL, Possingham HP, Carwardine J, Klein CJ, Roxburgh SH, Russell-Smith J, Wilson KA. 2011. The effect of carbon credits on savanna land management and priorities for biodiversity conservation. *PLoS ONE* 6: e23843.
Eamus D, Hutley LB, O'Grady AP. 2001. Daily and seasonal patterns of carbon and water fluxes above a north Australian savanna. *Tree Physiology* 21: 977-988.
Fensham RJ. 1998. The influence of cattle grazing on tree mortality after drought in savanna woodland in north Queensland. *Australian Journal of Ecology* 23: 405-407.
Fensham RJ, Bowman DMJS. 1992. Stand structure and the influence of overwood on regeneration in tropical eucalypt forest on Melville Island. *Australian Journal of Botany* 40: 335-352.

Fensham RJ, Fairfax RJ. 2007. Drought-related tree death of savanna eucalypts: species susceptibility, soil conditions and root architecture. *Journal of Vegetation Science* 18: 71-80.

Fensham RJ, Holman JE. 1999. Temporal and spatial patterns in drought-related tree dieback in Australian savanna. *Journal of Applied Ecology* 36: 1035-1050.

Fensham RJ, McCosker JC, Cox MJ. 1998. Estimating clearance of *Acacia*-dominated ecosystems in central Queensland using land-system mapping data. *Australian Journal of Botany* 46: 305-319.

Fensham RJ, Fairfax RJ, Butler DW, Bowman DMJS. 2003. Effects of fire and drought in a tropical eucalypt savanna colonized by rain forest. *Journal of Biogeography* 30: 1405-1414.

Fensham RJ, Fairfax RJ, Ward DP. 2009. Drought-induced tree death in savanna. *Global Change Biology* 15: 380-387.

Fitzsimons J, Russell-Smith J, James G, Vigilante T, Lipsett-Moore G, Morrison J, Looker M. 2012. Insights into the biodiversity and social benchmarking components of the Northern Australian fire management and carbon abatement programmes. *Ecological Management & Restoration* 13: 51-57.

Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, Haywood J, Lean J, Lowe DC, Myhre G, Nganga J, Prinn R, Raga G, Schulz MD, R. 2007. Changes in atmospheric constituents and in radiative forcing. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. S Solomon, D Qin, M Manning, Z Chen, M Marquis*, et al*, pp. 129-134. Cambridge University Press: Cambridge, United Kingdom.

Fox ID, Neldner VJ, Wilson GW, Bannink PJ. 2001. *The Vegetation of the Australian Tropical Savannas*. Environment Protection Agency: Brisbane. 329 pp.

Franklin D. 1996. A massive aggregation of the Varied Lorikeet. *Eclectus* 1: 6-7.

Franklin DC. 1999. Evidence of disarray amongst granivorous bird assemblages in the savannas of northern Australia, a region of sparse human settlement. *Biological Conservation* 90: 53-68.

Franklin DC. 2013. *Towards an Appropriate Fire Regime for Threatened Regional Ecosystem 7.12.22 in the Tumoulin Forest Reserve*. Unpublished report to Tablelands National Park Volunteers21 pp.

Franklin DC, Ehmke G, Garnett ST. in press a. The vulnerability of Australian birds to climate change. In *Climate Change Adaptation Plan for Australian Birds*, ed. ST Garnett, DC Franklin. CSIRO: Collingwood.

Franklin DC, Ehmke G, VanDerWal J, Garnett ST. in press b. The exposure of Australian birds to climate change. In *Climate Change Adaptation Plan for Australian Birds*, ed. ST Garnett, DC Franklin. CSIRO: Collingwood.

Franklin DC, Noske RA. 2000. Nectar sources used by birds in monsoonal north-western Australia: a regional survey. *Australian Journal of Botany* 48: 461-474.

Fraser DJ, Bernatchez L. 2001. Adaptive evolutionary conservation: towards a unified concept for defining conservation units. *Molecular Ecology* 10: 2741-2752.

Freeland WJ, Winter JW, Raskin S. 1988. Australian rock-mammals: a phenomenon of the seasonally dry tropics. *Biotropica* 20: 70-79.

Gardner CA. 1960. Trees of Western Australia. Eight *Eucalyptus* trees from the tropical north. *Journal of Agriculture of Western Australia, Series 4* 1: 212-222.

Garnett ST, Sithole B, Whitehead PJ, Burgess CP, Johnston FH, Lea T. 2009. Healthy country, healthy people: policy implications of links between Indigenous human health and environmental condition in tropical Australia. *Australian Journal of Public Administration* 68: 53-66.

Garnett S, Woinarski J. 2012. Endangered species: what makes the list? *The Conversation*, http://theconversation.com/endangered-species-what-makes-the-list-11073, downloaded 20 Jan. 2014.

Gasteen WJ. 1985. The brigalow lands of eastern Australia - agricultural impact and land use potential verses biological representation and stability. In *Agriculture and Conservation in Inland Queensland*, ed. J Gasteen, D Henry, S Page, pp. 45-49. Wildlife Preservation Society of Queensland: Brisbane.

Gaston KJ, Fuller RA. 2009. The sizes of species' geographic ranges. *Journal of Applied Ecology* 46: 1-9.

Gill AM, Belbin L, Chippendale GM. 1985. *Phytogeography of Eucalyptus in Australia*. Bureau of Flora and Fauna: Canberra. 53 pp.

González-Orozco CE, Laffan SW, Miller JT. 2011. Spatial distribution of species richness and endemism of the genus Acacia in Australia. *Australian Journal of Botany* 59: 600-608.

Goosem S, Morgan G, E KJ. 1999. Wet tropics. In *The Conservation Status of Queensland's Bioregional Ecosystems*, ed. P Sattler, R Williams, pp. 7/1-7/73. Environmental Protection Agency, Queensland Government: Brisbane.

Harrington GN, Sanderson KD. 1994. Recent contraction of wet sclerophyll forest in the wet tropics of Queensland due to invasion by rainforest. *Pacific Conservation Biology* 1: 319 -327.

Heckbert S, Russell-Smith J, Reeson A, Davies J, James G, Meyer C. 2012. Spatially explicit benefit–cost analysis of fire management for greenhouse gas abatement. *Austral Ecology* 37: 724-732.

Heinsohn R, Cermak M. 2008. *Life in the Cape York Rainforest*. CSIRO: Melbourne. 104 pp.

Hill KD. 1997. New taxa in *Eucalyptus* (Myrtaceae) from New South Wales and Queensland. *Telopea* 7: 187-198.

Hill KD. 1999. A taxonomic revision of the White Mahagonies, *Eucalyptus* series Acmenoideae (Myrtaceae). *Telopea* 8: 219–247.

Hill KD, Johnson LAS. 1991. Systematic studies in the eucalypts - 4. New taxa in *Eucalyptus* (Myrtaceae). *Telopea* 4: 321-349.

Hill KD, Johnson LAS. 1995. Systematic studies in the eucalypts. 7. A revision of the bloodwoods, genus *Corymbia* (Myrtaceae). *Telopea* 6: 185-504.

Hill KD, Johnson LAS. 1998. Systematic studies in the eucalypts. 8. A review of the Eudesmioid eucalypts, *Eucalyptus* subgenus *Eudesmia* (Myrtaceae). *Telopea* 7: 375-414.

Hill KD, Johnson LAS. 2000. Systematic studies in the eucalypts. 10. New tropical and subtropical eucalypts from Australian and New Guinea (*Eucalyptus*, Myrtaceae). *Telopea* 8: 503-539.

Holmes JM. 1966. *Australia's Open North. A Study of Northern Australia Bearing on the Urgency of the Times*. Angus and Robertson: Sydney. 505 pp.

Hopkins MS, Ash J, Graham AW, Head J, Hewett RK. 1993. Charcoal evidence of the spatial extent of the *Eucalyptus* woodland expansions and rain-forest contractions in north Queensland during the late Pleistocene. *Journal of Biogeography* 20: 357-372.

House SM. 1997. Reproductive biology of eucalypts. In *Eucalypt Ecology: Individuals to Ecosystems*, ed. JE Williams, JCZ Woinarski, pp. 30-55. Cambridge University Press: Cambridge.

Hughes L, Cawsey EM, Westoby M. 1996. Climatic range sizes of eucalyptus species in relation to future climate change. *Global Ecology and Biogeography Letters* 5: 23-29.

Hutley LB, Beringer J, Isaac PR, Hacker JM, Cernusak LA. 2011. A sub-continental scale living laboratory: Spatial patterns of savanna vegetation over a rainfall gradient in northern Australia. *Agricultural and Forest Meteorology* 151: 1417-1428.

Intergovernmental Panel on Climate Change. 2007. *Climate change 2007: Synthesis Report*. Intergovernmental Panel on Climate Change: Geneva. 52 pp.

Intergovernmental Panel on Climate Change. 2006. *IPCC Guidelines for National Greenhouse Gas Inventories*. National Greenhouse Gas Inventories Programme; Institute for Global Environmental Strategies: Kanagawa, Japan.

IUCN. 2001. *IUCN Red List Categories and Criteria: Version 3.1*. IUCN Species Survival Commission: Gland, Switzerland and Cambridge, UK. ii + 30 pp. pp.

IUCN. 2013. *The IUCN Red List of Threatened Species. Version 2013.1*. IUCN

IUCN Standards and Petitions Subcommittee. 2011. *Guidelines for Using the IUCN Red List Categories and Criteria. Version 9.0 (September 2011)*. IUCN87 pp.

Kehoe J. 2006. Land-clearing in Queensland. *Environmental and Planning Law Journal* 23: 148-157.

Kershaw AP. 1985. An extended late Quaternary vegetation record from north-eastern Queensland and its implications for the seasonal tropics of Australia. *Proceedings of the Ecological Society of Australia* 13: 179-189.

Kutt AS, Kemp JEM, K R, Williams Y, Williams SE, Hines HB, Hero J-M, Torr G. 2005. Vertebrate fauna survey of White Mountains National Park in the Desert Uplands Bioregion, central-north Queensland. *Australian Zoologist* 33: 17-38.

Lacey CJ, Whelan PI. 1976. Observations on the ecological significance of vegetative reproduction in the Katherine-Darwin region of the Northern Territory. *Australian Forestry* 39: 131-139.

Ladiges PY, Udovicic F, Nelson G. 2003. Australian biogeographical connections and the phylogeny of large genera in the plant family Myrtaceae. *Journal of Biogeography* 30: 989-998.

Ladiges P, Parra-O C, Gibbs A, Udovicic F, Nelson G, Bayly M. 2011. Historical biogeographical patterns in continental Australia: congruence among areas of endemism of two major clades of eucalypts. *Cladistics* 27: 29-41.

Lawes MJ, Richards A, Dathe J, Midgley JJ. 2011. Bark thickness determines fire resistance of selected tree species from fire-prone tropical savanna in north Australia. *Plant Ecology* 212: 2057-2069.

Lehmann CER, Prior LD, Bowman DMJS. 2009. Fire controls population structure in four dominant tree species in a tropical savanna. *Oecologia* 161: 505-515.

Law R, Garnett ST. 2011. Mapping carbon in tropical Australia: Estimates of carbon stocks and fluxes in the Northern Territory using the national carbon accounting toolbox. *Ecological Management & Restoration* 12: 61-68.

Law RM. 2011. *Greenhouse Gas Management in Northern Australian Savannas: Opportunities and Risks for Indigenous Land Management*. Charles Darwin University MTEM thesis: Darwin. 65 pp.

Lincoln R, Boxshall G, Clark P. 1998. *A Dictionary of Ecology, Evolution and Systematics*. Cambridge University Press: Cambridge.

Low T. 2011. *Climate Change and Terrestrial Biodiversity in Queensland*. Department of Environment and Resource Management, Queensland Government: Brisbane.

Martin B, Cossalter C. 1977. *The Eucalyptuses of the Sunda Isles*. New Zealand Forest Service: Wellington.

McVay P, Mathie C, Crossley D. 2007. *The Conservation and Protection of National Threatened Species and Ecological Communities*. Australian National Audit Office: Barton, ACT. 166 pp.

Meyer CP, Cook GD, Reisen F, Smith TEL, Tattaris M, Russell-Smith J, Maier SW, Yates CP, Wooster MJ. 2012. Direct measurements of the seasonality of emission factors from savanna fires in northern Australia. *Journal of Geophysical Research-Atmospheres* 117: Art. No. D20305.

Monk KA, De Fretes Y, Reksodiharjo-Lilly G. 1997. *The Ecology of Nusa Tenggara and Maluku*. Periplus Editions: Hong Kong. 966 pp.

Murphy BP, Bowman DMJS. 2012. What controls the distribution of tropical forest and savanna? *Ecology Letters* 15: 748-758.

Murphy BP, Lehmann CER, Russell-Smith J, Lawes MJ. 2014. Fire regimes and woody biomass dynamics in Australian savannas. *Journal of Biogeography* 41: 133-144.

Murphy BP, Russell-Smith J, Watt FA, Cook GD. 2009. Fire management and woody biomass carbon stocks in mesic savannas. In *Culture, Ecology and Economy of Fire Management in North Australian Savannas: Rekindling the Wurrk Tradition*, ed. J Russell-Smith, P Whitehead, P Cooke, pp. 361-378. CSIRO Publishing: Collingwood, Vic.

Neldner VJ. 1999. Cape York Peninsula. In *The Conservation Status of Queensland's Bioregional Ecosystems*, ed. P Sattler, R Williams. Environmental Protection Agency, Queensland Government: Brisbane.

Nicolle D. 2006. A classification and census of regenerative strategies in the eucalypts (*Angophora*, *Corymbia* and *Eucalyptus*—Myrtaceae), with special reference to the obligate seeders. *Australian Journal of Botany* 54: 391–407.

Nicolle D, Kleinig DA. 2011. *Eucalyptus melanophloia* subsp. *nana* D.Nicolle & Kleinig, a new mallee ironbark (*E.* series Siderophloiae; Myrtaceae) from central Australia and north western Queensland. *Austrobaileya* 8: 347-355.

Notaro M, Wyrwoll K-H, Chen G. 2011. Did aboriginal vegetation burning impact on the Australian summer monsoon? *Geophysical Research Letters* 38: L11704.

Preece ND. 2013. Tangible evidence of historic Australian indigenous savanna management. *Austral Ecology* 38: 241-250.

Price OF, Edwards AC, Russell-Smith J. 2007. Efficacy of permanent firebreaks and aerial prescribed burning in western Arnhem Land, Northern Territory, Australia. *International Journal of Wildland Fire* 16: 295-307.

Price OF, Russell-Smith J, Watt F. 2012. The influence of prescribed fire on the extent of wildfire in savanna landscapes of western Arnhem Land, Australia. *International Journal of Wildland Fire* 21: 297-305.

Pryor LD, Williams ER, Gunn BV. 1995. A morphometric analysis of *Eucalyptus urophylla* and related taxa with descriptions of two new species. *Australian Systematic Botany* 8: 57-70.

Richards GP, Evans DMW. 2008. *Full Carbon Accounting Model (FullCAM), National Carbon Accounting System*. Australian Greenhouse Office: Canberra.

Rotstayn LD, Jeffrey SJ, Collier MA, Dravitzki SM, Hirst AC, Syktus JI, Wong KK. 2012. Aerosol- and greenhouse gas-induced changes in summer rainfall and circulation in the Australasian region: a study using single-forcing climate simulations. *Atmospheric Chemistry and Physics* 12: 6377-6404.

Russell-Smith J, Price OF, Murphy BP. 2010. Managing the matrix: decadal responses of eucalypt-dominated savanna to ambient fire regimes. *Ecological Applications* 20: 1615-1632.

Russell-Smith J, Cook GD, Cooke PM, Edwards AC, Lendrum M, Meyer CP, Whitehead PJ. 2013. Managing fire regimes in north Australian savannas: applying Aboriginal approaches to contemporary global problems. *Frontiers in Ecology and the Environment* 11: E55-E63.

Russell-Smith J, Murphy BP, Meyer CP, Cook GD, Maier S, Edwards AC, Schatz J, Brocklehurst P. 2009. Improving estimates of savanna burning emissions for greenhouse accounting in northern Australia: limitations, challenges, applications. *International Journal of Wildland Fire* 18: 1-18.

Ryder OA. 1986. Species conservation and systematics: the dilemma of subspecies. *Trends in Ecology & Evolution* 1: 9-10.

Sale MM, Potts BM, K WA, Reid JB. 1993. Relationships within *Eucalyptus* using chloroplast DNA. *Australian Systematic Botany* 6: 127-138.

Setterfield SA. 1997. The impact of experimental fire regimes on seed production in two tropical eucalypt species in northern Australia. *Australian Journal of Ecology* 22: 279-287.

Setterfield SA, Williams RJ. 1996. Patterns of flowering and seed production in *Eucalyptus miniata* and *E. tetrodonta* in a tropical savanna woodland, northern Australia. *Australian Journal of Botany* 44: 107-122.

Stanton P, Stanton D, Stott M, Parsons M. 2014. Fire exclusion and the changing landscape of Queensland's Wet Tropics Bioregion 1. The extent and pattern of transition. *Australian Forestry* 77: 51-57.

Steinbauer MJ. 2010. Latitudinal trends in foliar oils of eucalypts: Environmental correlates and diversity of chrysomelid leaf-beetles. *Austral Ecology* 35: 204-213.

Still CJ, Foster PN, Schneider SH. 1999. Simulating the effects of climate change on tropical montane cloud forests. *Nature* 398: 608-610.

Suppiah R, Hennessy K, Whetton PH, McInnes K, Macadam I, Bathols J, Ricketts J, Page CM. 2007. Australian climate change projections derived from simulations performed for the IPCC 4th Assessment Report. *Australian Meteorological Magazine* 56: 131-152.

Suppiah R, Bathols J, Macadam I, Whetton PH. 2009. Past and future climates in the tropical rainforest region of north Queensland. In *18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009*, ed. RS Anderssen, RD Braddock, LTH Newham, pp. 2064-2070. Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics and Computers in Simulation

Taschetto AS, Ummenhofer CC, Sen Gupta A, England MH. 2009. Effect of anomalous warming in the central Pacific on the Australian monsoon. *Geophysical Research Letters* 36: L12704.

Thackway R, Cresswell ID, eds. 1995. *An interim biogeographic regionalisation for Australia: a framework for setting priorities in the national reserves system cooperative program. Version 4.0*. Australian Nature Conservation Agency: Canberra.

Tng DYP, Murphy BP, Weber E, Sanders G, Williamson GJ, Kemp J, Bowman DMJS. 2012b. Humid tropical rain forest has expanded into eucalypt forest and savanna over the last 50 years. *Ecology and Evolution* 2: 34-45.

Tng DYP, Williamson GJ, Jordan GJ, Bowman DMJS. 2012a. Giant eucalypts - globally unique fire-adapted rain-forest trees? *New Phytologist* 196: 1001-1014.

Trainor CR. 2011. New island records of *Eucalyptus alba sensu lato* for Damar and Romang, Lesser Sundas, Indonesia. *Northern Territory Naturalist* 23: 45-53.

Tropical Savannas CRC. 2001. *What is healthy country in Australia's tropical savannas?* Tropical Savannas CRC: Darwin. 21 pp.

Turton SM, Duff GA. 1992. Light environments and floristic composition across an open forest-rainforest boundary in northeastern Queensland. *Australian Journal of Ecology* 17: 415-423.

Udovicic F, Mcfadden GI, Ladiges PY. 1995. Phylogeny of *Eucalyptus* and *Angophora* based on 5S rDNA spacer sequence data. *Molecular Phylogenetics and Evolution* 4: 247-256.

Unwin GL. 1989. Structure and composition of the abrupt rain-forest boundary in the Herberton Highland, North Queensland. *Australian Journal of Botany* 37: 413-428.

Wallace HM, Howell MG, Lee DJ. 2008. Standard yet unusual mechanisms of long-distance dispersal: seed dispersal of *Corymbia torelliana* by bees. *Diversity and Distributions* 14: 87-94.

Walsh NG, Albrecht DE. 1998. A new species of *Eucalyptus* (series Subexsertae) from the Northern Territory. *Muelleria* 11: 41-44.

Watson DM. 2011. A productivity-based explanation for woodland bird declines: poorer soils yield less food. *Emu* 111: 10-18.

Werner PA. 2012. Growth of juvenile and sapling trees differs with both fire season and understorey type: Trade-offs and transitions out of the fire trap in an Australian savanna. *Austral Ecology* 37: 644-657.

Werner PA, Cowie ID, Cusack JS. 2006. Juvenile tree growth and demography in response to feral water buffalo in savannas of northern Australia: an experimental field study in Kakadu National Park. *Australian Journal of Botany* 54: 283–296.

Werner PA, Franklin DC. 2010. Resprouting and mortality of juvenile eucalypts in an Australian savanna: Impacts of fire season and annual sorghum. *Australian Journal of Botany* 58: 618-628.

Werner PA, Prior LD. 2007. Tree-piping termites and growth and survival of host trees in savanna woodland of north Australia. *Journal of Tropical Ecology* 23: 611-622.

Werner PA, Prior LD. 2013. Demography and growth of subadult savanna trees: interactions of life history, size, fire season, and grassy understory. *Ecological Monographs* 83: 67-93.

Werner PA, Prior LD, Forner J. 2008. Growth and survival of termite-piped *Eucalyptus tetrodonta* and *E. miniata* in northern Australia: Implications for harvest of trees for didgeridoos. *Forest Ecology and Management* 256: 328-334.

Whitehead PJ, Purdon P, Russell-Smith J, Cooke PM, Sutton S. 2008. The management of climate change through prescribed savanna burning: emerging contributions of indigenous people in northern Australia. *Public Administration and Development* 28: 374-385.

Williams JE, Woinarski JCZ, eds. 1997. *Eucalypt Ecology. Individuals to Ecosystems*. Cambridge University Press: Cambridge.

Williams RJ. 1997. Fire and floral phenology in a humid tropical savanna at Kapalga, Kakadu National Park, northern Australia. In *Bushfire 97: Proceedings of the 6th Australian Bushfire Conference Darwin, N.T.*, ed. BJ McKaige, RJ Williams, WM Waggitt, pp. 54-59. CSIRO Tropical Ecosystems Research Centre: Darwin.

Williams JE, Brooker IH. 1997. Eucalypts: an introduction. In *Eucalypt Ecology: Individuals to Ecosystems*, ed. JE Williams, JCZ Woinarski, pp. 1-15. Cambridge University Press: Cambridge.

Williams PR. 2009. Contrasting demographics of tropical savanna and temperate forest eucalypts provide insight into how savannas and forests function. A case study using *Corymbia clarksoniana* from north-eastern Australia. *Austral Ecology* 34: 120-131.

Williams RJ, Hutley LB, Cook GD, Russell-Smith J, Edwards A, Chen XY. 2004. Assessing the carbon sequestration potential of mesic savannas in the Northern Territory, Australia: approaches, uncertainties and potential impacts of fire. *Functional Plant Biology* 31: 415-422.

Woinarski J, Mackey B, Nix H, Traill B. 2007a. *The Nature of Northern Australia. Natural Values, Ecological Processes and Future Prospects*. ANU E Press: Canberra. 128 pp.

Woinarski J, Pavey C, Kerrigan R, Cowie I, Ward S, eds. 2007b. *Lost from Our Landscape. Threatened Species of the Northern Territory*. Northern Territory Department of Natural Resources, Environment and The Arts: Palmerston. 284 pp.

Woinarski JCZ, Fisher A. 1995. Wildlife of lancewood (*Acacia shirleyi*) thickets and woodlands in Northern Australia. 2. Comparisons with other environments of the region (*Acacia* woodlands, *Eucalyptus* savanna woodlands and monsoon rainforests). *Wildlife Research* 22: 413-443.

Woinarski JCZ, Hempel C, Cowie I, Brennan K, Kerrigan R, Leach G, Russell-Smith J. 2006. Distributional pattern of plant species endemic to the Northern Territory, Australia. *Australian Journal of Botany* 54: 627–640.

Woinarski JCZ, Russell-Smith J, Andersen AN, Brennan K. 2009. Fire management and biodiversity of the western Arnhem Land Plateau. In *Culture, Ecology and Economy of Fire Management in North Australian Savannas: Rekindling the Wurrk Tradition*, ed. J Russell-Smith, P Whitehead, P Cooke, pp. 201-227. CSIRO Publishing: Collingwood, Vic.

Yeh S-W, Kug J-S, Dewitte B, Kwon M-H, Kirtman BP, Jin F-F. 2009. El Niño in a changing climate. *Nature* 461: 511-514.

APPENDIX 1: METHODS – CHECKLIST OF TAXA

Methods

State and territory checklists for the relevant IBRAs were obtained as followed:

- Western Australia: downloaded from FloraBase, http://florabase.dec.wa.gov.au/, 27 June 2013
- Northern Territory: checklist provided by NT Herbarium (Ian Cowie, pers. comm., 28 June 2013)
- Queensland: downloaded from Australia's Virtual Herbarium, http://avh.chah.org.au/, 8 July 2013, a resource of the Council of Heads of Australasian Herbaria and its member Herbaria listed at www.chah.gov.au; also, checklist provided by Qld Herbarium (Peter Bostock pers. comm., 10 July 2013)

The taxonomic standard adopted for this study is that of the Australian Plant Census (APC), which is the product of the Council of Heads of Australian Herbaria (CHAH). During late June and early July 2013, all plant names from state and territory checklists were cross-matched against the APC web-site list at http://www.anbg.gov.au/chah/apc/. Eucalypts on this list were updated by CHAH in August 2011 (http://www.anbg.gov.au/chah/apc/families-treated.html, downloaded 2 July 2013). Taxa not readily able to be reconciled were investigated further during late June and early July 2013 using a variety of sources including EUCLID (CPBR 2006) and the Australian Plant Name Index (http://www.cpbr.gov.au/apni/index.html) - a web-site maintained by the Australian National Herbarium. All taxa were also checked against EUCLID (CPBR 2006) and, as this is a key on-going source of information, details of taxonomic mis-matches kept.

We adopt just two changes to the APC list:

1. the taxon recognised by APC without formal description as *E. melanophloia* subsp. Dajarra (V.J.Neldner 1523) Qld Herbarium has since been formally described as *E. melanophloia* subsp. *nana* D.Nicolle & Kleinig (Nicolle & Kleinig 2011), so we have adopted the latter name
2. we have not recognised subspecies for *Eucalyptus chlorophylla*. Recognising them would have been problematic because there are no records in AVH of one (subsp. Archer River) and only a few records have been attributed to the other (subsp. *chlorophylla*). It would appear that the relevant Herbarium (Qld) no longer recognises subspecies in *E. chlorophylla* (John Clarkson pers. comm.).

In the taxonomy of wild plants, the categories subspecies and variety are functionally equivalent (Hamilton & Reichard 1992) and have been treated as equal in this study. As all but one infraspecific listing for the study area are subspecies (the exception is *E. alba* var. *australasica*), we use that generic term to include varieties.

The full checklist is available in the supplementary Excel file, worksheet *checklist*.

Reference for Appendix 1

Centre for Plant Biodiversity Research. 2006. *EUCLID: Eucalypts of Australia. Third Edition.* CSIRO Publishing: Collingwood.

Hamilton CW, Reichard SH. 1992. Current practice in the use of subspecies, variety, and forma in the classification of wild plants. *Taxon* 41: 485-498.

Nicolle D, Kleinig DA. 2011. *Eucalyptus melanophloia* subsp. *nana* D.Nicolle & Kleinig, a new mallee ironbark (*E.* series Siderophloiae; Myrtaceae) from central Australia and north western Queensland. *Austrobaileya* 8: 347-355.

APPENDIX 2: METHODS – LOCATION RECORDS

Georeferenced records of each north Australia eucalypt taxon were vetted and downloaded from Australia's Virtual Herbarium (AVH; http://avh.chah.org.au/) between 11 and 29 July 2013.

The main aim of the taxon-by-taxon vetting process was to check outlying records and eliminate duplicates. As Extent of Occurrence and Area of Occupancy, key conservation metrics, are highly sensitive to outliers, a fairly strict approach (below) was taken with these. Duplicate records (matched by location, date and collector) were eliminated to avoid spurious quantification of search effort. Vetting and culling (where necessary) took place in a series of stages.

The first stage was the elimination of some records using the record-selection tabs in AVH. Duplicate records were culled in this way, as were records flagged as being of uncertain identification, cultivated, questionably georeferenced, along with many gross outlying records. Gross outlying records were identified at the level of country, state and occasionally IBRA (Interim Biogeographic Regionalisation of Australia; Thackway & Cresswell (1995) with subsequent modifications) compared to baseline distribution maps for taxa, and are assumed to be either records of the species in cultivation or coordinate errors (a large proportion of these were cultivated plants from Canberra). Where taxon circumscriptions have not changed in recent years, maps and notes in EUCLID (CPBR 2006) were employed as a baseline, at times complemented by a range of other sources including Hill & Johnson (1995, 2000), FloraBase (http://florabase.dec.wa.gov.au/) for Western Australia, and Clarkson (2009) for Cape York Peninsula. Where taxon circumscriptions have changed, relevant taxonomic papers were consulted.

As both the flagging protocol in AVH is, and the preliminary culling of gross outliers was very incomplete, all remaining outliers were individually queried within AVH. Queried records were culled if they met any of the following criteria:

- were annotated (but not formally flagged) as cultivated, of uncertain identification or dubiously georeferenced
- the described location wasn't consistent with the coordinates (checked against maps in Readers Digest (1977) and occasionally other sources; where the nature of the coordinate error was obvious and readily corrected, the record was corrected rather than deleted)
- the described location was vague (mainly historical records)

In addition and more subjectively, remaining outlying records were appraised as to the likelihood of taxonomic or geolocational error, and culled if an error was deemed fairly likely. Treatment of a record as an outlier was a subjective combination of isolation from all records, and isolation and distance from the reported range as described above. Outliers of taxa known to have experienced taxonomic upheaval or to be difficult to identify were treated more stringently than those that are stable and readily identified. Isolated outliers were treated more stringently than clusters of non-duplicate outliers. Older records were treated more stringently than recent records, particularly if the record preceded taxonomic change. A few noteworthy cases were investigated further by enquiry to relevant botanists. All outliers that could reasonably be questioned were excluded. A second-round of checks for outliers was undertaken using maps generated in ArcGIS.

In some cases where subspecies occupied quite discrete geographic ranges, records not identified to subspecies level were attributed to subspecies on the basis of range. However, this was not always possible and in general we have made few assumptions about subspecific identification. This means that various parameter metrics and estimates for subspecies are underestimates and less reliable than for species. For restricted-range subspecies, we examined unattributed records of species on a case-wise basis for potential subspecific identification and incorporated these additional data at the point of analysis. However, in practice little extra information was obtained, probably because Herbaria may have taken extra care to update subspecific identifications for restricted-range subspecies.

References for Appendix 2

Centre for Plant Biodiversity Research. 2006. *EUCLID: Eucalypts of Australia. Third Edition.* CSIRO Publishing: Collingwood.

Clarkson J. 2009. *A Field Guide to the Eucalypts of the Cape York Peninsula Bioregion*. Qld Govt: Mareeba.

Hill KD, Johnson LAS. 1995. Systematic studies in the eucalypts. 7. A revision of the bloodwoods, genus *Corymbia* (Myrtaceae). *Telopea* 6: 185-504.

Hill KD, Johnson LAS. 2000. Systematic studies in the eucalypts. 10. New tropical and subtropical eucalypts from Australian and New Guinea (*Eucalyptus*, Myrtaceae). *Telopea* 8: 503-539.

Readers Digest Services Pty Limited, ed. 1977. *Reader's Digest Atlas of Australia*. Readers Digest Services Pty Limited: Sydney.

Thackway R, Cresswell ID, eds. 1995. *An Interim Biogeographic Regionalisation for Australia: A Framework for Setting Priorities in the National Reserves System Cooperative Program. Version 4.0*. Australian Nature Conservation Agency: Canberra.

APPENDIX 3: METHODS – GIS

Mapping methods

Species records

Point data were imported from Excel files of each species to ArcGIS (10.2) and displayed as x-y data, using lat/lon processed fields. They were then converted to a shape file. Errors and anomalies were identified at this stage, as some species files retained records from non-natural distributions. Shape files used the coordinate reference system of the Project layer, GDA94.

The shapefiles (.shp) were then imported into Quantum GIS (QGIS) and re-projected to WGS84 World Mercator projection to enable the shapefiles to be used to calculate extent of occurrence in square kilometres. The QGIS geometry function Delaunay Triangulation was used to create a complex polygon from the point data. Additional errors were picked up in this process, as if there were null records for coordinates, polygons could not be created. The null records were removed and the shapefile re-projected. The complex polygon was then simplified using the Geoprocessing tool 'Dissolve' and a new shapefile created. Distributions of the point records were overlaid by the simple polygon to check that the polygon mapped properly. The polygons map straight lines between extremity records, so gaps in distribution and across seas were included, as recommended by Gaston and Fuller (2009) for Extent of Occurrence (EOO) calculations.

The dissolved polygons were created as single polygons and opened in ArcGIS. A new field 'AREA' was created in the attributes tables, and then an editing session was opened and the 'calculate geometry' function was used to calculate areas as a long integer in square kilometres.

To determine how many records of each taxon fell within the savanna region, each point shapefile which extended beyond the region was clipped to the savanna region. The number of point records was then counted (from the attribute table) and the proportion of records falling within and outside the region calculated. Distribution of records was verified by mapping the clipped shapefile over the shapefile of the complete records of the species or subspecies.

Status of species

Calculations of the number of records in protected areas was done by using the vector analysis 'points in polygon' tool, which calculates the number of records in each polygon. Protected areas were separated into two main types – crown reserves which had been established for conservation purposes, and private reserves which do not necessarily have legislative protection. To the private reserves were added Indigenous Protected Areas, which have legislative protection, but are not necessarily protected for their conservation values.

Shapefiles of crown protected areas were obtained from the Northern Territory and Queensland. The protected areas for Western Australian section of the savanna region were obtained from the 1:250,000 digital datasets produced by GeoScience Australia, and individual polygons were merged into one file. For the whole savanna region, we used the IUCN conservation areas digital dataset (http://www.protectedplanet.net; accessed 15 October 2013), which is current to 2012.

Shapefiles of the private reserves were obtained from Bush Heritage Australia, Australian Wildlife Conservancy, and the Indigenous Protected Areas database (http://www.environment.gov.au/indigenous/ipa/map.html; accessed 15 October 2013). The three sets of private reserves were merged to one shapefile for the whole savanna region, and this was used to assess presence of species within private reserves.

Species which fell entirely within a state or territory were assessed using the state or territory protected areas shapefiles, whereas if species extended across two or three jurisdictions, they were assessed using the IUCN conservation areas dataset.

In all cases, the attributes tables of the shapefiles provided the numbers of records in each area, and the number of areas where they occurred.

Cleared areas were derived from the National Vegetation Information System (NVIS) Version 4.1. The digital data were obtained from the Department of the Environment as a raster dataset. The rasters were converted to vector format to enable calculations of areas. We cross-checked coverages of cleared areas in Queensland with the 'Statewide landcover and trees study' (SLATS) digital datasets obtained from the Queensland Government. These datasets cover the period 1988 to 2010.

Vegetation types were derived from the *Vegetation of the Australian Tropical Savannas (2001)* published by the Environmental Protection Agency, Brisbane and the Cooperative Research Centre for Sustainable Development of Tropical Savannas, Darwin. The digital dataset was mapped at 1:1,000,000 scale.

Reference for Appendix 3

Gaston KJ, Fuller RA. 2009. The sizes of species' geographic ranges. *Journal of Applied Ecology* 46: 1-9.

APPENDIX 4: METADATA FOR OUR SUPPLEMENTARY EXCEL FILE

A file, *eucalypts of northern Australia supplementary file.xlsx*, contains data supporting the outputs for this project. It contains five worksheets.

Worksheet *checklist*

A checklist of species, subspecies and varieties of eucalypt that occur in northern Australia as recognised by the Australian Plant Census (APC; https://www.anbg.gov.au/chah/apc/) with two changes noted in Appendix 1.

field *Taxon master list*: the checklist
field *Authority*: taxonomic authorities for the checklist consistent with APC but for the one update
field *Common name*: one per taxon, generally that which is in most widespread use, commonly from CPBR (2006) but with additions
fields *Species*, *Subspecies*, *Ultrataxon*: taxonomic level of taxon; an *ultrataxon* is the lowest officially-recognised taxonomic level
fields *Qld*, *NT*, *WA*: the states or territory within which the taxon occurs *within our study area*.
field *EUCLID*: how the taxon is incorporated into EUCLID (CPBR 2006). Differences between EUCLID and APC are highlighted in green.

Worksheet *taxon assessments*

Contains taxon-specific data derived in this study.

fields *Taxon master list*, *Species*, *Subspecies*: as in worksheet *checklist*
fields *EOO*, *No. 1° cells*, *N records*: data derived in and used to described restricted range
field *Endemicity group*: codes as in Table 2 of this report
field *Biogeographic group*: codes as in Table 4 of this report. Bracketed codes are *post-hoc* attributions. See associated text for explanation of "excluded" and "not classified"
fields *Tier(EOO)*, *Tier(cells)*, *Tier(records)*, *Tier(overall)*: rankings based on individual metrics (EOO, cells, records), and the lowest of these rankings (overall) based on thresholds reported in Table 6 of this report. 1 = extremely restricted; 2 = very restricted; 3 = restricted; 4 = somewhat restricted; 5 = not restricted.
fields *crown*, *private*, *combined*: % of unique herbarium records that are in the respective nature reserves as defined in the text of the report. The combined total is the *reservation index*. NA = not available; we calculated reservation rates for taxa endemic to the study area.
field *index of clearing*: % of unique herbarium records that are in cleared areas. NA = not available; we calculated the index of clearing for select taxa deemed to be potentially at risk based on their distribution – see text of report for details.

Worksheet *restricted range*

A matrix of restricted range taxa (tiers 1–4 from Table 6 of this report) by the degree cells in which they have been recorded. Tiers are reported in the field *Tier* and also notated in the matrix. Cells are designated by the whole degree latitude and longitude of the north-west corner of the cell combined; thus, for example, the cell centred at 13°30′ South by 131°30′ East is designated as 13131. Cells are arranged left to right in ascending numerical order of their designation.

Summary data per cell for tiers and priorities are provided below the main matrix (orange and yellow highlights). Priorities are as mapped in Fig. 23, and are the cumulative sum of tier totals. Thus, for instance, priority 3 contains taxa in tiers 1, 2 and 3.

Worksheet *threatened taxa*

A matrix of taxa that are listed as threatened, listed of concern, possibly threatened and possibly NT or DD (as listed in Tables 8 & 12 of this report) and the IUCN criterion under which we assessed them, by the degree cells in which they have been recorded (as mapped in Fig. 28 of this report). Cells are designated by the whole degree latitude and longitude of the north-west corner of the cell combined; thus, for example, the cell centred at 13°30' South by 131°30' East is designated as 13131. Cells are arranged left to right in ascending numerical order of their designation.

Summary data per cell are provided below the main matrix (yellow highlights).

Worksheet *communities*

Summary data for all the Map Units of Fox *et al.* (2001), with analytical metrics for eucalypt communities.
- field *Map Unit*: map unit codes as in Fox *et al.* (2001)
- field *BVG*: the Broad Vegetation Group to which the Map Unit belongs, following Fox *et al.* (2001)
- fields *Eucalypt primary*, *Eucalypt secondary*: Map Units coded 1 in either of these fields are the eucalypt Map Units of this report. See text of report for definitions.
- field *Area*: the area of the Map Unit within northern Australia as detailed by Fox *et al.* (2001)
- fields *%crown*, *%private*, *%reserved %cleared*: the percentage of unique herbarium records that are in the respective land tenure/land use categories as described in the report, for eucalypt communities only.

References for Appendix 4

Centre for Plant Biodiversity Research. 2006. *EUCLID: Eucalypts of Australia. Third Edition.* CSIRO Publishing: Collingwood.

Fox ID, Neldner VJ, Wilson GW, Bannink PJ. 2001. *The Vegetation of the Australian Tropical Savannas*. Environment Protection Agency: Brisbane. 329 pp.