Ironwood *Erythrophleum chlorostachys* in the Northern Territory: aspects of its ecology in relation to timber harvesting.

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CONTENTS

1. Summary

This report covers some aspects of the ecology of Cooktown ironwood *Erythrophleum chlorostachys* that are related to determining the sustainability of harvesting of this species for timber. Ironwood is a favoured timber species in the Northern Territory due to its termite resistance, high density and its appearance (a mixture of pale yellow and dark red-brown). Little information has previously been available to inform the development of regulations to govern harvesting and hence provide for the ecologically sustainable use of this resource. This report was commission by Agriculture, Fisheries and Forestry, Australia to assist in their achieving national coverage in relation to their reporting of the sustainability of forest management for the national State of the Forests report and internationally under the Montreal Process.

Distribution and biomass was modelled at a Territory scale to assess the extent of the timber resources provided by ironwood. Further modelling was undertaken at a catchment level to utilise more accurate data available at this scale to predict distribution. Sampling of distribution patterns at a local scale was also undertaken. The examination of the occurrence of hollows in timber species allowed some assessment of the potential affects of harvesting on hollow dwelling fauna. Regeneration in logged and unlogged areas allowed an assessment of the impacts of harvesting and on the future recruitment levels in logged areas. Statistics relating to the extent of logging are presented as is data on the selection of trees on the property where most of the ironwood logging has occurred. Finally, a review of data required to assess sustainability is presented. Relevant information relating to sustainability that was not covered in other parts of the report are detailed and gaps in our knowledge highlighted. Recommendations on changes to regulations governing timber harvesting are also made to assist in the process of working towards sustainable practices.

Key Findings

Distribution and biomass across the Northern Territory

The distribution and environmental association of ironwood was examined through review of literature and through analysis of a large vegetation data base, comprising information from 16,271 sample plots across the Northern Territory.

Ironwood is shown to have an extraordinarily broad environmental range across the Northern Territory north of 20°S. At 1:1,000,000 scale, 74 vegetation types are recognised for this region, and our records include ironwood from 49 of these (with a further 18 vegetation types considered inadequately sampled).

Ironwood occurs across almost all of this region, but has highest incidence and greatest basal area in a lowland belt between Katherine and Darwin, on the Tiwi Islands and on Cobourg Peninsula.

While ironwood is an important component in many forests and woodlands in the region, it is rarely dominant. Of all sites where ironwood was present, only 2.1% of sites had a basal area of >5 m^2/ha, and mean basal area of ironwood across this set of sites was 1.4 m^2/ha.

Based on extrapolation from a limited calibration of biomass to basal area, the total woody biomass of ironwood in the Northern Territory (north of 20°S) is estimated at 95 million tonnes. Of this total 11.2% is contained within conservation reserves.

Ironwood incidence, basal area, and basal area of trees >20 cm DBH only, was modeled using (a) environmental data recorded in plots at the time of sampling, and (b) using geographic, climatic, topographic and edaphic variables interpolated from GIS layers. The quadrat-based models described a highly significant association with soil texture, with a strong preference for sandy-loam soils. There was also a weaker positive association with soil depth and slope, and a weak negative association with rock cover. Although these models were highly significant, the deviance explained was only 11-16%. Basal area models using GIS-derived data were generally better, with 5-6 factor models explaining 19-30% of the deviance. Factors included in these models included rainfall, temperature, moisture index, latitude and (a coarse assessment of) surficial geology. Many of the locational and climatic variables are highly intercorrelated in this region, because of very simple but pronounced climatic gradients. This renders it difficult to tease apart which of these factors are environmental determinants of the distribution of ironwood.

The distributional models are partly compromised by the very pronounced response of ironwood to fire regimes. Frequent fires are associated with a stand structure of ironwood that is characterised by few trees and saplings but a high density of suppressed suckers. Fire exclusion produces a higher basal area, with more, larger trees and far more saplings. Thus, any estimation of basal area and biomass of ironwood from environmental variables that are fixed at any site will be noisy, as the actual values may be determined far more by local fire history.

Local distribution patterns

Modelling of the distribution of larger (>20 cm DBH) ironwoods was also undertaken at a regional scale using the Mary River catchment. In this catchment data on occurrence was available from a detailed botanical survey and GIS layers on geology and drainage were available at a finer scale than those available for many other areas. This was undertaken to enable a more accurate assessment to be made of the impacts of regulations relating to riparian reserves. For the presence/absence model of large ironwood three factors (surficial geology, distance from water and an index of green vegetation) explained 31% of the deviance and for the basal area model for large ironwoods seven factors (primarily surficial geology, and Landsat variables related to rock type and vegetation and soil moisture) explained 41% of the deviance. Sampling of transects in areas of differing slope around drainage lines showed that larger and taller trees occurred on creek flats compared with slopes. Volume and number of commercially acceptable trees was also greater in riparian areas. This appears to generally apply in most other areas. However a few studies have found that the basal area of ironwood is not greatest in riparian areas. Soil type may be determining these differing results.

Occurrence of hollows

The occurrence of hollows in eucalypts and ironwood was examined in different habitats in Limmen National Park in the Gulf Falls and Uplands bioregion of the Northern Territory. A hollow index was calculated for each tree from the numbers of small (width of entrance <5 cm), medium (5 ñ 10 cm) and large (>10 cm) hollows. *Eucalyptus camaldulensis* dominated in riparian areas with larger trees occurring along permanent billabongs compared with sections of the river that dried out during the dry season. There were no differences between the three eucalypt species in riparian areas (*E. camaldulensis*, *Corymbia confertiflora* and *Corymbia polycarpa*) in the relationship between diameter at breast height (DBH) and the hollow index. Eucalypts in riparian areas had a similar relationship between DBH and the hollow index to those occurring on rocky hills (*Eucalyptus leucophloia* and *Corymbia ferruginea*) but eucalypts in riparian areas were larger and hence had more hollows on average. *Eucalyptus miniata* on sandy flats had a lower hollow index for a given DBH compared with eucalypts in other habitats but had a comparable number of large hollows/tree to that of the most abundant species on rocky hills (*E. leucophloia*) due to the larger size of the *E. miniata*. In this area ironwood is a smaller tree than many of the eucalypts and it had a low number of medium and large hollows. Ironwood is a preferred timber species. Given its low number of hollows, timber harvesting here is unlikely to have an impact on the availability of hollows to fauna, even on a local scale. However whether this would also be the case in wetter areas with larger ironwoods needs examination. Also, in Kakadu National Park a previous study of a population of ironwoods with a similar size distribution to that of the present study area found that this species ranked third amongst 17 tree species in terms of hollow availability. This finding is at odds with that of the present study and the known termite resistance of ironwood.

Regeneration in logged and unlogged sites

Regeneration of ironwood and *Eucalyptus* / *Corymbia* was examined in logged and unlogged sites from two areas (OíNeil and Eureka Creeks) on Mary River East Station. Six plots in logged sites and five in unlogged sites were scored for the presence of juveniles (ie <10 cm DBH) in three height classes (<1.5 m, 1.5-3 m and >3 m). Plots were assigned a short-term fire rating. For ironwood stumps the number of coppice present was recorded, and, if DBH was >5 cm, DBH and height were also recorded. Excavations of root systems of ironwood seedlings indicated all those sampled could potentially have coppiced off the roots of adults. Coppice heights and numbers per ironwood stump were greater at Eureka Creek than at OíNeil Creek. Regeneration of both ironwood and *Eucalyptus* / *Corymbia* was dominated by woody sprouts with few saplings or poles. For ironwood there was significantly more woody sprouts, saplings and poles at Eureka Creek but no difference in regeneration between logged and unlogged areas with fire regimes appearing to be determining the level of regeneration. For *Eucalyptus* / *Corymbia* there was no difference in regeneration between the two areas or between logged and unlogged sites.

Timber harvesting in the Northern Territory

Ironwood is potentially one of the most important timber species native to northern Australia. Rapid depletion of ironwood occurred in the Darwin-Katherine region within the first few decades of European settlement. Information on permits issued for harvesting was collated for the period from 1995 to 2001. Ironwood was the most frequently harvested species (54% of stems) with smaller numbers of eucalypts (40%) and a wide range of other species taken. A total of 28 permits for 5125 stems of 30 species was issued over the period.

At the Mary River East Station harvesting has probably occurred for over 100 years. Harvesting was undertaken under permit from 1995 until 2000. Permit conditions for most of this time limited harvesting to trees with a DBH greater than 35 cm and more than 20 m from an incised watercourse. Evidence of logging was only found in riparian flats. In such areas there was an average of 7.5 ironwood and 1.2 eucalypt stumps per ha resulting from logging. This represented 59% of the commercially acceptable ironwood trees and 21% of the commercially acceptable eucalypt trees that would have been present prior to logging. For a sample of stumps in the field and logs at the Mary River East mill 4.5% of ironwood and 34% of eucalypts harvested were under the size limit of 35 cm DBH specified on the logging permit. Mean log length was 3.7 m for ironwood and 4 m for eucalypts. Log length was correlated with DBH for eucalypts but not for ironwoods.

Ecological sustainability

The calculation of sustainable yield requires a detailed knowledge of:

- standards for utilisation of logs required by industry;
- area of forest available for harvesting;
- inventory;
- growth;
- regeneration; and
- recruitment.

Growth of ironwoods from an undisturbed site at Kapalga in Kakadu National Park was very slow with trees 40 cm DBH estimated to be at least 110 years old and possibly over 360 years. However, growth at Mary River East in a cleared area and in logged areas was greater with a 40 cm DBH tree being a minimum of 30 years old. It is possible that removal of trees reduces competition and allows faster growth rates.

Given the small scale of the industry it is unlikely that the resources will ever be available to allow sustainable yield to be accurately calculated. Ensuring harvesting is ecologically sustainable requires that environmental and social values, as well as economic issues, are taken into account. A mechanism is proposed to regulate offtake of timber from native forest to try to ensure timber harvesting is ecologically sustainable. This involves the following:

- the issue of permits for specific areas of land that equate to an area suitable to supply the needs of a harvester for a year, rather than for the whole of a property as has often occurred in the past.
- Exclusion of harvesting from logged area for a time period sufficient to allow the regeneration of a sufficient number of trees to a commercial size.
- A condition of the permit be that suitable measures are undertaken to control fire regimes for 6 years after logging to ensure adequate regeneration.
- Permit conditions should be set in relation to size of trees harvested. This should be above the size at which the species first flowers to ensure a supply of seed. Size of trees taken can probably be reduced below the present limit of 35 cm DBH without impacting on ecological sustainability because of the low numbers of hollows in ironwood and the numbers of eucalypts rendered unsuitable for harvesting by termites.
- Issue of a permit should be dependant on the applicant demonstrating that they had consulted the appropriate authorities and taken account of environmental issues (e.g. soil erosion, water quality, riparian protection at stream crossings and protection of archaeological sites) that could arise as a result of timber harvesting activities. It is recommended that the requirement for riparian buffer widths for <u>selective</u> logging operations be increased from 20 to 30 m.

It is believed that the measures outlined above provide a better pathway towards the goal of ecologically sustainability than presently exists.

Future research priorities are outlined. Information relevant to Montreal indicators 2.1a, 2.1d and 2.1g is presented.

2. Introduction

Ironwood *Erythropleum chlorostachys* is a wide ranging hardwood tree found from northeast Queensland to the Kimberley area of Western Australia (Boland *et al.* 1984). Its mostly southerly distribution in the Northern Territory is south of Newcastle Waters where it borders the desert (Fensham and Kirkpatrick 1992). It is renowned as a source of timber that can withstand termite attack, an important characteristic in the Top End of Australia where termites can ravage timber structures. Initially during the colonization of the Top End any local timbers were harvested but termite damage soon led to the pursuit of timbers able to resist insect attack. Ironwood and cypress pine (*Callitris intratropica*) became favoured sources of timber (Hanssen and Wigston 1989) and were used in the establishment of European settlements and related infrastructure.

Despite it being the major timber species of the Northern Territory little is known about the resource levels of ironwood, its productivity or the sustainability of present practices. Australia is a part of the Montreal Process which involves 12 countries that have developed a list of criteria and indicators to assess the extent to which forest management practices are ecologically sustainable. A large amount of data have been amassed in the southern States in relation to assessing ecological sustainability and these have been reviewed and recommendations formulated to improve sustainability during the Regional Forest Agreement process. The Northern Territory being a very minor timber producer was not included in the Regional Forest Agreement process. However reporting of practices for the Northern Territory is considered desirable by the Commonwealth both in the Australian State of the Forests report and internationally under the Montreal Process. This report details various aspects of the ecology of ironwood and other timber species as a contribution towards the goal of achieving ecological sustainability of timber harvesting in the Northern Territory and assisting the Commonwealth in their reporting requirements.

The following topics are covered in the report:

- A summary of present knowledge of ironwood in the Northern Territory. This information forms a base of knowledge upon which the following chapters build.
- Distribution and biomass of ironwood in the Northern Territory. Data on the occurrence of ironwood is used to model the distribution of the species, assess the occurrence of larger sized trees and provide a very rough indication of the extent of the timber resource.
- Local distribution patterns. Modelling of the distribution of ironwood at a catchment level is undertaken to allow the influence of variables, such as distance from a watercourse and soil type, that were available at a finer scale of resolution at the catchment level to be examined in more detail. This also allowed the effect of different riparian reserve widths on timber volumes to be assessed. Sampling was also undertaken to assess the finer scale patterning of the occurrence of the species and different sized trees in relation to topography and drainage.

- Occurrence of hollows in ironwood and other timber species. This assessment was undertaken in order to determine how timber harvesting might impact on the availability of hollows. Assessment of ecological sustainability involves determining the impacts of management practices on a range of values, including biodiversity. This chapter thus assists in determining the possible effects of timber harvesting on hollow dwelling fauna.
- Regeneration of ironwood after logging. For timber harvesting to be sustainable adequate levels of regeneration have to occur after logging. Hence regeneration in logged areas was assessed and compared with that in unlogged areas.
- Timber harvesting. Data are provided on the numbers of permits issued for timber harvesting and the numbers of each different species harvested under those permits. A survey of sizes of trees taken and their topographic location was undertaken on the property where the highest intensity of timber harvesting has occurred.
- Towards sustainability. A review of data required to assess sustainability is presented. Relevant Information not covered in other parts of the report are detailed and gaps in our knowledge highlighted. Recommendations on changes to regulations governing timber harvesting are also made to assist in the process of working towards sustainable practices.

References

Boland, D.J., Brooker M.I.H, Chippendale, G.M., Hall, N., Hyland, B.P.M., Johnstone, R.D., Kleinig, D.A., and Turner, J.D. (1984). *Forest trees of Australia.* Fourth edition. (Thomas Nelson and CSIRO: Melbourne).

Fensham R.J. and Kirkpatrick J.B. (1992). Soil characteristics and tree species distribution in the savannah of Melville Island, Northern Territory. *Australian Journal of Botany* **40**:311-333.

Hanssen, N.L., and Wigston, D.L. (1989). Approaches to a forest history of the Northern Territory. In *Australiaís ever-changing forests.* (Eds: K.J. Frawley and N. Semple). (Department of Geography and Oceanography, University College, Australian Defence Force Academy: Campbell, ACT).

3. Ironwood: an ecological summary

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Erythrophleum chlorostachys is an endemic Australian species with the remaining eight (Ross 1998) or nine (Dunlop *et al*. 1995) species in the genus occuring in tropical regions of Africa, Madagascar, Asia and Malesia (Ross 1998).

Ironwood is an important traditional resource for Aboriginal people. Infusion from the bark is used to treat general body and stomach pains; root infusions are used for cuts; the wood, leaves and bark are used to ësmokeí a person suffering from constipation; infusions from leaves are used to treat scabies; the smoke from burning bark is used by women to produce sterility; the resin from roots is an important adhesive; the bark yields a red dye; extruded gum on the bark can be eaten raw; and probably most significantly the wood is highly valued for ceremonial carvings, spearheads, music and cooking sticks (Brock 1988; Dunlop *et al*. 1995).

Ironwood timber is very hard, termite resistant and durable. Boland *et al*. (1984) noted that it is ìone of Australiaís densest timbers with a density of 1200 kg/m^{3}ì. It was one of the first forest resources exported from Australia, with the wood being sought by Macassan trepang-fishermen for masts and anchors, probably since the seventeenth century (Macknight 1976). The timber is now used for railway sleepers, fence posts, furniture and other uses ìwhere strength and durability are prime requisitesî (Boland *et al*. 1984; Dunlop *et al*. 1995).

Far less positively, ironwood is also notable for possessing extremely toxic alkaloids (Chippendale and Murray 1963), with many records of livestock mortality due to foraging on ironwood foliage (Everist 1974).

Notwithstanding the claim that ìall parts of the tree are highly poisonous to mammalsî (Brock 1988), ironwood foliage has been shown to be the main and preferred food item for brushtail possums *Trichosurus vulpecula* in the Alligator Rivers region of the Northern Territory (Kerle 1985). At least partly because of its resistance to termite attack, ironwood is generally assumed to form few hollows and the tree is rarely used for roosting by arboreal mammals (Kerle 1985) and, presumably, by hollow-nesting birds. However, Braithwaite *et al*. (1985) counted tree hollows in a sample of 183 ironwood trees (>10 cm DBH) across a range of sites in Kakadu National Park, and estimated that ironwood trees supported an average of 1.5 small (1-20 cm diameter opening) and 0.21 large (>20 cm diameter opening) hollows per tree, the second highest average across 28 tree species considered.

Ironwood flowers are a moderately important nectar resource for nectarivorous birds (Woinarski *et al*. 2000), although Williams *et al.* (1999a) reported that flowering was relatively rare. Kerle (1985) recorded flowering in November and December and seed production in January to June.

Ironwood is semi-deciduous, with minimum canopy in September and new foliage produced mainly from August to November (Kerle 1985; Williams *et al*. 1997). The energy content of ironwood leaves was the highest of 24 species examined from eucalypt forests and monsoon rainforests (Bowman and Wilson 1988).

The water relations of ironwood are intermediate between the dominant eucalypts and deciduous subcanopy species (Myers *et al*. 1997), but, across a range of woody species considered in a study site near Darwin, ironwood had the largest seasonal variation and lowest values of pre-dawn leaf water potential, implying a relatively shallow root systems (Duff *et al*. 1997).

Ironwood reproduces both from seed (Russell-Smith *et al*. 1988) and vegetatively from root suckers (Lacey and Whelan 1976) or both lignotubers and root suckers (Fensham and Bowman 1992).

Especially compared to the dominant eucalypts with which it is associated, ironwood is relatively little affected by strong winds (Williams and Douglas 1995). It may be particularly affected by light availability and/or competition. At two sites on Melville Island, Fensham and Bowman (1992) found that ironwood showed the most pronounced response of all species to clear-felling the eucalypt overstorey, with massive increase in density of saplings at one site, but reduced proportion of ironwood in the understorey at the other site, with this disparity possibly due to differences in fire history.

The abundance, basal area, stand structure and relative importance of ironwood varies substantially with fire regimes. In frequently burnt woodland, the age/size structure of ironwood is very different to that of co-occurring eucalypts, with a preponderance of suppressed suckers (Figs 3.1, 3.2) (Fensham and Bowman 1992). However, this size distribution may vary substantially between different sites (Fig. 3.1), and is clearly related to disturbance (Russell-Smith *et al*. *ms*.).

In a single hot fire at Kapalga, Williams *et al*. (1999b) reported that ironwood had the lowest stem survival (10%) among the six dominant woody species, although whole plant survival was considerably better (88%). Survival was especially poor for smaller (DBH <20 cm) and larger (DBH >30 cm) stems (Williams *et al.* 1999b). At a different hot fire in Kapalga, Lonsdale and Braithwaite (1991) reported that mortality rates were highest in stems between 6 and 16 cm DBH (Fig. 3.2c), but few large trees were present in that study. They also reported that overall tree mortality for ironwood in this single fire was 26%, the fourth highest value among 29 species considered.

More so than any other co-occurring forest tree species, ironwood responds spectacularly to fire exclusion (Bowman *et al*. 1988a; Fensham 1990; Bowman and Panton 1995; Russell-Smith *et al*. *ms*.). At Munmarlary, Bowman and Panton (1995) reported that sites protected from fire for 20 years had far higher densities of ironwood saplings (>2 m high but <5 cm DBH) (735 cf 23/ha) and poles (5-10 cm DBH) (410 cf. 6.7/ha) than did nearby sites exposed to ambient fire regimes (generally fires every year or two). Similarly, Fensham (1990) reported far lower

Fig. 3.1. Fire regimes may create environments where ironwood is unrepresented in the tree layer but forms a dense shrubby understorey: *Eucalyptus miniata- E. tetrodonta* forest in central Arnhem Land.

abundance of ironwood saplings (>3 m high but <10 cm DBH) in sites burnt annually (10/ha) than at sites which were burnt less frequently with ìlight firesî (320/ha) or unburnt for 10 years (210/ha).

In some contrast, in central eastern Cape York Peninsula, Crowley and Garnett (1998) recorded no change in the frequency of occurrence of ironwood at sites over a 30 year period, in which fire frequency was apparently reduced. However, such apparent lack of change in distribution may not well reflect any change in stand structure or abundance.

Ironwood can grow to large size. Braithwaite *et al*. (1985) reported that the largest of 183 ironwood trees in sample plots in Kakadu National Park was 55 cm DBH. However OíGrady *et al*. (2000) considered that a 25.1 cm DBH tree was ìunusually largeî in their forest sites at Howard Springs.

Distribution of Ironwood

National distribution maps showing ironwood records are presented in Boland *et al*. (1984) and Ross (1998). Liddle *et al*. (1994) presents a map showing the occurrence of ironwood in sampled rainforest patches in the Northern Territory, with Herbarium records from a total of seventy 0.01° x 0.01° cells (from a total possible of well over 800 grid cells). Northern Territory Herbarium records are also

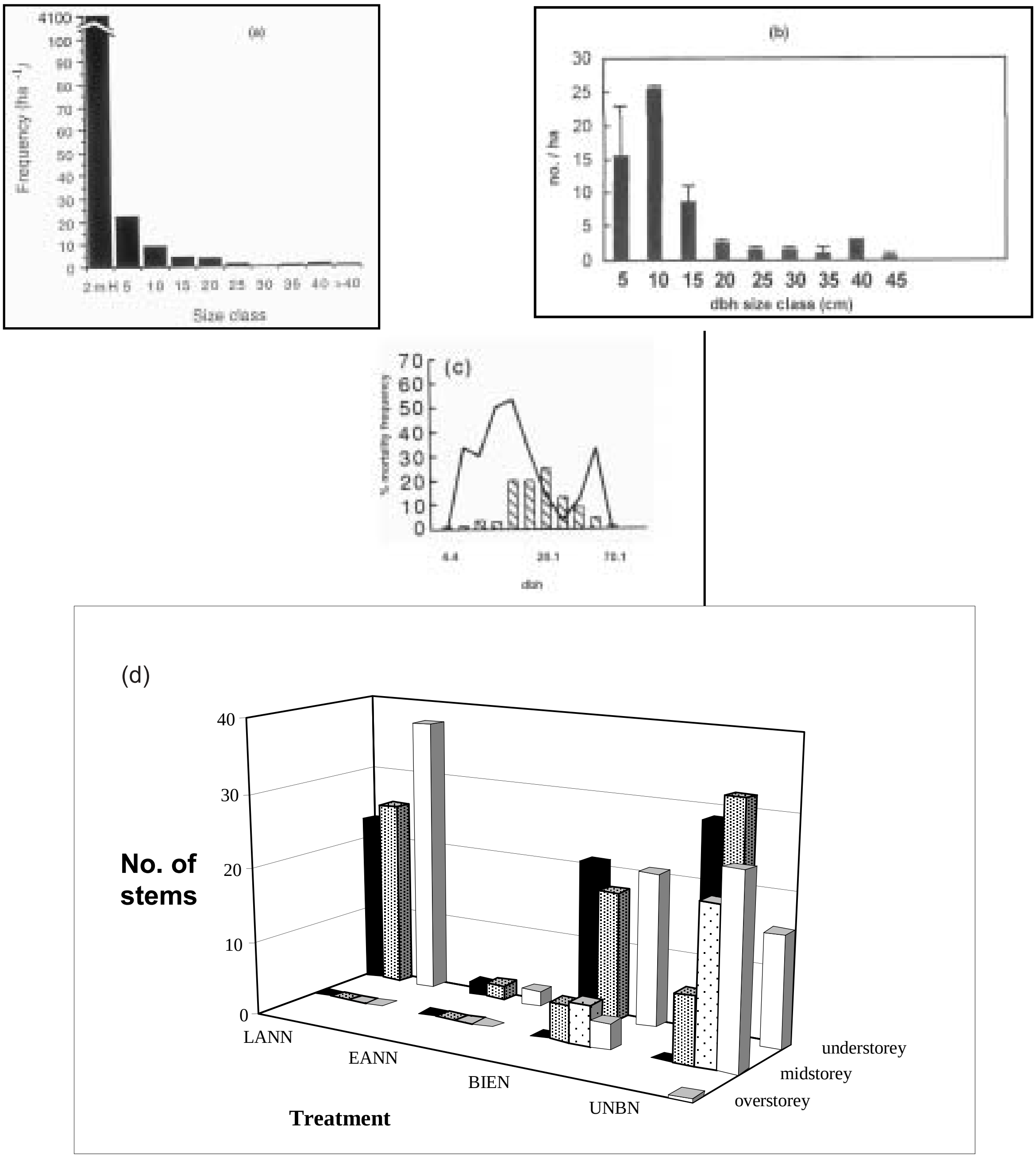

Fig. 3.2. Reported stand structures for ironwood from a range of published studies.
(a) open forest on Melville Island (Fensham and Bowman 1992). Smallest category is saplings <2 m height; all other categories show upperpoint of DBH (in cm);
(b) open forest, Gunn Point Peninsula, with stand structure possibly still recovering from cyclone 25 years previously (OíGrady et al. 2000). Size on axis gives upper level of DBH class;
(c) open forest, Kapalga (Lonsdale and Braithwaite 1991). Histogram shows % frequency rather than absolute no. of stems per hectare; size classes are indicated by the lower limit of DBH class (cm); and continuous line shows % mortality of stem classes;
(d) open forest at Munmarlary (Russell-Smith *et al.* ms.). No. of ironwood stems in four height classes: overstorey=stems >8 m tall (sampled in 50x10 m transect); midstorey=stems 2-8 m tall (sampled in 50x5 m transect); understorey=stems<2 m tall (sampled in 50x2 m transect); fire treatments - LANN=annual late dry season fires; EAN=annual early dry season fire; BIEN=biennial fire; UNBN=unburnt. Shading indicates sequential sampling during the fire regime experiment: black=sampled in 1973; grey 1976; spotted 1978; open 1994; but note that understorey was not sampled in 1978.

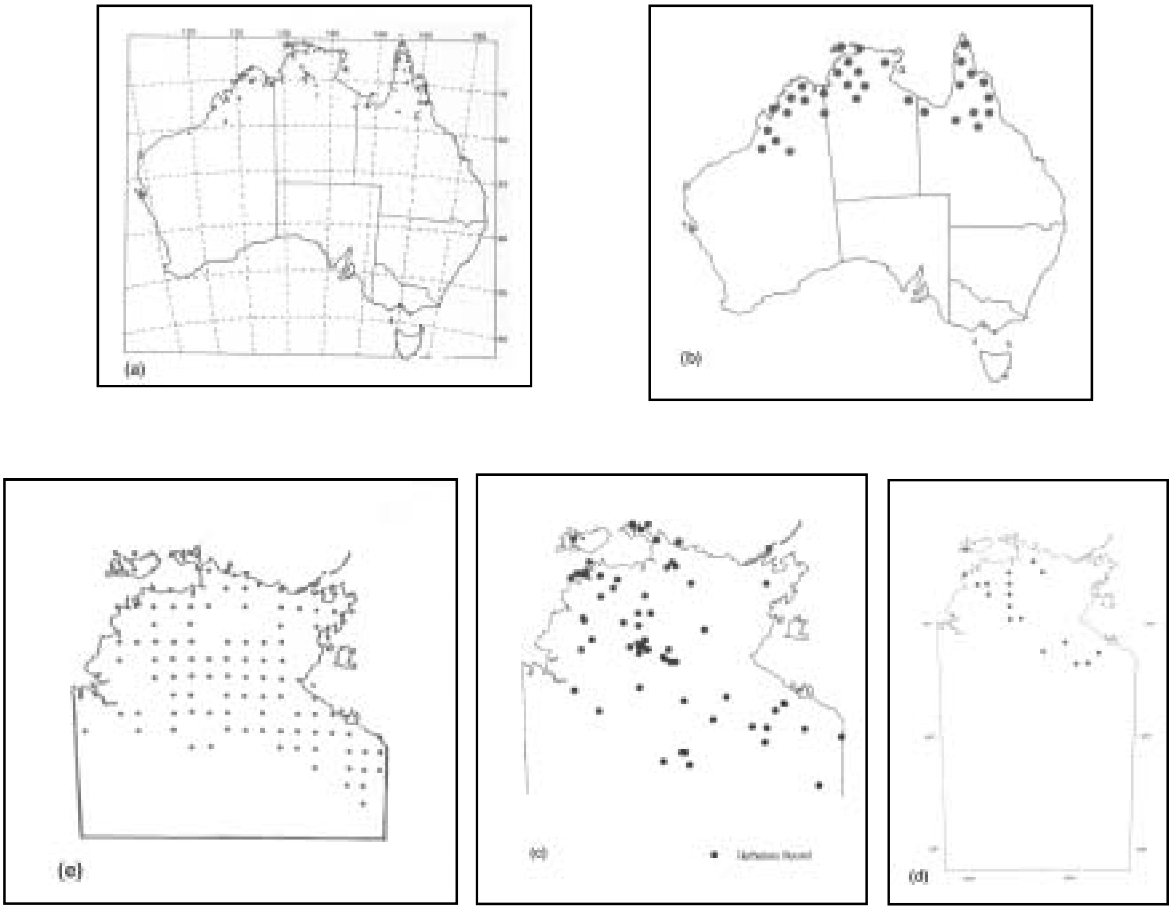

Fig. 3.3. Published point-based distribution maps for ironwood: (a) Boland *et al.* (1984); (b) Ross (1998); (c) Liddle *et al.* (1994), for NT rainforests only; (d) Dunlop and Bowman (1986), for NT Herbarium records only; and (e) Fensham and Kirkpatrick (1992).

plotted in Dunlop and Bowman (1986), and in Fensham and Kirkpatrick (1992) they are supplemented with additional unpublished records associated with Wilson *et al*. (1990) and unpublished records of Fensham. These maps are reproduced in Fig. 3.3.

Boland *et al*. (1984) provides the most comprehensive account of the broad geographical and ecological distribution of ironwood:

> *ì(it) has a wide distribution across northern Australia from northeastern Queensland to the Kimberley area of Western Australia, with a collection from the De Grey River further south. The range of latitude is about 11-20^{o}S and that of altitude about 100-1000 m. The distribution occurs in a wide range of climatic zones but is mainly in the hot sub-humid and hot semi-arid climatic zones. The mean maximum temperature of the hottest month is 30-39^{o}C and the mean minimum of the coldest month is 13-22^{o}C. Most of the area of occurrence is frost-free but the more inland sites would receive occasional frosts (1-2 per year). The mean annual rainfall is from 300 to 1700 mm. However, recorded annual rainfall figures may not reflect the water available to the species as it often grows on river flats where it*

> *would probably be able to obtain additional supplies. Rain falls mainly during the summer months.*
>
> *This tree grows on a wide variety of soil and rock types.* E. chlorostachys *is usually a component of the open-forests and woodlands and because it occurs over such a large area it is associated with a large number of eucalypt species. It grows on rocky hillsides but probably reaches its best development on creek and river flats*.î

These comments are reflected also in more regional accounts. For the Top End of the Northern Territory, Brock (1988) noted that ironwood is ì*common and widespread in open forest and woodland in sandstone or lowland country, on a wide range of well-drained soils*î. In the Darwin region, Dunlop *et al*. (1995) considered that it was ì*common Ö occurring in most vegetation types on a variety of soil types excluding heavy clays*.î In the Kimberley, Petheram and Kok (1983) considered it ì*widespread throughout the region in a variety of habitats*î. *Eucalyptus-Erythrophleum* woodlands are the dominant vegetation type over 64% of Cape York Peninsula, occupying the well-drained sandy interfluves and ranges (Story 1970; Neldner and Clarkson 1995; Crowley and Garnett 1998). In a report on Northern Territory forests, Jacobs (1933) calculated that ìuseableî ironwood trees made up 1% of the eucalypt woodlands.

More localised studies have also noted that it can be the dominant species or a major component of many forest and woodland types (Kirkpatrick *et al*. 1988; Bowman *et al*. 1991; Bowman 1992; Fensham and Kirkpatrick 1992), and that it has an extraordinary broad environmental range (Kirkpatrick *et al*. 1987; Bowman and Wightman 1985; Bowman *et al*. 1993), although notably avoiding some environments. For example, in a study of central eastern Cape York Peninsula, Crowley and Garnett (1998) reported that ironwood was the fourth most frequently occurring major woody plant, occurring in 22 of 64 grassland and grassy woodland sites. In the Jabiluka area around Kakadu National Park, ironwood occurred as a dominant in 10 of 15 vegetation types defined across a very broad ecological gradient from sandstone plateau to floodplain, being absent only in 5 floodplain and floodplain fringe sites (mostly seasonally inundated clays) (Burgman and Thompson 1982). In the Alligator Rivers Region more generally, it was recorded in five of the 11 defined vegetation types, again being absent only in seasonally-inundated and/or cracking clay areas and floodplain margin woodlands (Taylor and Dunlop 1985). In Howardís Peninsula, north-west of Darwin, it occurred in 10 of 15 wooded vegetation units across a broad environmental gradient, the broadest environmental range of any of the 61 recorded woody species (Wilson and Bowman 1987). It was absent only from heavy cracking clay soils, mangroves, seasonally flooded *Melaleuca* forests, one of the two defined *Melaleuca* open woodlands, and one of the three monsoon rainforest types. In Gunn Point, it was recorded across a broad gradient, being absent only from ìpeneplainî, gully floor (rainforest), and an intertidal flat (Bowman and Wightman 1985). Across several sites on Groote Eylandt, ironwood was recorded in an open forest on sandstone (sandy brown earth) substrate, but not from an open forest on laterite (acid red sandy loam) nor a low open *Eucalyptus tetrodonta*-dominated woodland on lateritised manganese (dark brown sand) (Langkamp *et al*. 1981). In Gregory

National Park (Victoria River District), ironwood was the most important species in sandstone mesa sideslopes, and co-dominant (with *Eucalyptus dichromophloia*) on sandstone plateau (Bowman *et al*. 1988b).

Fensham (1990) reported that ironwood occurrence was unaffected by aspect, potentially a measure of available moisture in soils. Fensham and Kirkpatrick (1992) provided some assessment of the relationship of ironwood occurrence with soil features on Melville Island, with some correlation of increased abundance with increased levels of potassium, magnesium and calcium in the soil, and with increased pH.

At Berry Springs near Darwin ironwood was most abundant in medium-fine texture soils of medium fertility and moderate drainage (Bowman and Minchin 1987). Absence from poorly drained areas was also noted by Bowman and McDonough (1991) along a seasonally inundated gradient which included eucalypt woodland fringing floodplain in the Fogg Dam area. Fensham (1993) did not record it in a coastal mosaic from grasslands, through coastal vine thicket to paperbark woodlands on Bathurst Island. Several studies have reported it to be absent or minor in a range of sandstone habitats on the Arnhem Land massif, including some heathlands, eucalypt woodlands and monsoon rainforests (Bowman *et al*. 1990; Bowman 1991; Russell-Smith *et al.* 1993, 1998). Although it was considered within the Northern Territory rainforest flora (Liddle *et al.* 1994), it is generally uncommon in most rainforest types (Bowman *et al*. 1990; Russell-Smith 1991).

Results from some of these studies are summarised in Table 3.1, which lists all published records of basal area of ironwood across a range of environments in the Northern Territory. Additionally, Fensham and Kirkpatrick (1992) graphed continuous variation in basal area of ironwood along a set of eight forest and woodland transects on Melville Island, indicating values reaching about 4.5 m^2/ha.

There are far fewer reports of stem density and biomass for ironwood. In open forests dominated by *Eucalyptus miniata* and *E. tetrodonta* at Munmarlary, Bowman and Panton (1995) reported densities of ironwood trees (>10 cm DBH) of 8.3/ha and 13.3/ha at sites burnt every year or two, and sites protected from fire for 20 years, respectively. Across a series of sites at which ironwood was present in Kakadu National Park, Braithwaite *et al*. (1985) reported a mean density of ironwood trees (>10cm DBH) of 26.9/ha. In an open forest at Kapalga, Lonsdale and Braithwaite (1991) reported densities of ironwood trees (>2cm DBH) at 47.9/ha. In an open forest also dominated by *Eucalyptus miniata* and *E. tetrodonta* near Howard Springs, OíGrady *et al*. (2000) reported mean (from a total of 30 plots) stem densities of ironwood of 68.8 stems/ha, with this tally including any stems >1.5 m tall.

Based on measurement of eight trees, OíGrady *et al*. (2000) estimated above-ground biomass of ironwood at Howard Springs as 5.47 +/- 2.97 t/ha, and derived power relationships between tree basal area and biomass (for wood component, $y=0.03x^{2.64}$, and for total above-ground biomass $y=0.021x^{3.12}$, with $r^2=0.97$ in both cases, DBH in cm and biomass in kg).

Table 3.1. Published values of basal area of *Erythrophleum chlorostachys*.

Basal area (m^2/ha)	No. of sites	Environment
Location and Source		
North-west Australia (widely-spaced sites) (Bowman 1992)		
0.07	245	Wet monsoon forest
0.46	87	Wet ecotone
0.57	80	Wet savanna
0.19	433	Dry monsoon forest
0.42	94	Dry ecotone
1.00	178	Dry savanna
Edith Falls area (Bowman *et al*. (1991)		
7.1*	1	Stony hill woodland
Kakadu Stage III (Bowman *et al*. (1993)		
0.67	133	Gently sloping, rock-free, with dry sandy soils
0.53	74	Flat, relatively rock-free run-on, seasonally dry clay-pans
0.84	11	Plateau creek lines with low rock cover and wet sandy soils
0.04	24	Flat, largely rock-free, seasonally flooded clay soils on floodplain edges
0.68	85	Sandstone plateau edges with boulder-strewn steep slopes and dry sandy soils
1.72	48	Stony dry clay soils on rolling hills
0.25	5	Moist rocky sandy soils on steep slopes
Tabletop Mountain (Litchfield National Park) (Kirkpatrick *et al*. (1987)		
0.3	8	Flats adjacent to streams
0.2	8	Shallow gravelly soils over lateritic cap
1.2	20	Moderately deep to deep well-drained sandy-loam soils
0.8	12	Steep but not broken escarpment; shallow rocky soils
1.0	7	Non-lateritic sandy or rocky soils
0.1	17	Well-drained parts of highly-broken sandstone country; shallow rocky soils
Gunn Point (Bowman and Dunlop 1986)		
0.6	8	Lateritic gravelly red earth
Howards Peninsula (Wilson and Bowman 1987)		
1.2	11	Sandy seasonally waterlogged soils, without gravel
0.8	17	Sandy loam seasonally waterlogged soils, without gravel
0.2	17	Well-drained, sideslopes, creek lines, drainage basins
0.5	9	Well-drained, sideslopes, creek lines, drainage basins on loam and sandy loam soils
0.3	8	Well-drained, sideslopes, creek lines, drainage basins on loam and sandy loam soils
0.3	5	Sideslopes and plateau surface, well drained sandy loam or loamy sand soils
0.3	9	Sideslopes and plateau surface, well drained gravelly sandy loam or loamy sand soils
0.5	12	Sideslopes and plateau surface, well drained gravelly sandy loam or loamy sand soils
0.3	9	Sideslopes and plateau surface, well drained gravelly sandy loam or loamy sand soils
0.1	12	Sideslopes and plateau surface, well drained gravelly sandy loam or loamy sand soils
Howard Springs (OíGrady *et al*. 2000)		
1.16	30	Highly weathered sandy-clay laterites

* value appears to be an error

References

Boland, D.J., Brooker, M.I.H., Chippendale, G.M., Hall, N., Hyland, B.P.M., Johnston, R.D., Kleinig, D.A. and Turner, J.D. (1984). *Forest trees of Australia*. Fourth edition. (Thomas Nelson and CSIRO: Melbourne.)

Bowman, D.M.J.S. (1991). Environmental determinants of *Allosyncarpia ternata* forests that are endemic to western Arnhem Land, northern Australia. *Australian Journal of Botany* **39**, 575-589.

Bowman, D.M.J.S. (1992). Monsoon forests in North-western Australia. II. Forest-savanna transition. *Australian Journal of Botany* **40**, 89-102.

Bowman, D.M.J.S. and Dunlop, C.R. (1986). Vegetation pattern and environmental correlates in coastal forests of the Australian monsoon tropics. *Vegetatio* **65**, 99-104.

Bowman, D.M.J.S. and McDonough, L. (1991). Tree species distribution across a seasonally flooded elevation gradient in the Australian monsoon tropics. *Journal of Biogeography* **18**, 203-212.

Bowman, D.M.J.S. and Minchin, P.R. (1987). Environmental relationships of woody vegetation patterns in the Australian monsoon tropics. *Australian Journal of Botany* **35**, 151-169.

Bowman, D.M.J.S. and Panton, W.J. (1995). Munmarlary revisited: response of a north Australian *Eucalyptus tetrodonta* savanna protected from fire for 20 years. *Australian Journal of Ecology* **20**, 526-531.

Bowman, D.M.J.S. and Wightman, G.M. (1985). Small scale vegetation pattern associated with a deeply incised gully, Gunn Point, northern Australia. *Proceedings of the Royal Society of Queensland* **96**, 63-73.

Bowman, D.M.J.S. and Wilson, B.A. (1988). Fuel characteristics of coastal monsoon forests, Northern Territory, Australia. *Journal of Biogeography* **15**, 807-817.

Bowman, D.M.J.S., Wilson, B.A. and Hooper, R.J. (1988a). Response of *Eucalyptus* forest and woodland to four fire regimes at Munmarlary, Northern Territory, Australia. *Journal of Ecology* **76**, 215-232.

Bowman, D.M.J.S., Wilson, B.A. and Wilson, P.L. (1988b). Floristic reconnaissance of the northern portion of the Gregory National Park, Northern Territory, Australia. *Journal of the Royal Society of Western Australia* **70**, 57-67.

Bowman, D.M.J.S., Wilson, B.A. and Fensham, R.J. (1990). Sandstone vegetation pattern in the Jim Jim Falls region, Northern Territory, Australia. *Australian Journal of Ecology* **15**, 163-174.

Bowman, D.M.J.S., Wilson, B.A. and Woinarski, J.C.Z. (1991). Floristic and phenological variation in a northern Australian rocky *Eucalyptus* savanna. *Proceedings of the Royal Society of Queensland* **101**, 79-90.

Bowman, D.M.J.S., Woinarski, J.C.Z. and Menkhorst, K.A. (1993). Environmental correlates of tree species diversity in Stage III of Kakadu National Park, northern Australia. *Australian Journal of Botany* **41**, 649-660.

Braithwaite, R.W., Parker, B.S., Wood, J.T. and Estbergs, J.A. (1985). The distribution and abundance of termite-induced tree hollows in tropical forests of northern Australia. In *The Kakadu Fauna Survey: an ecological survey of*

Kakadu National Park. (ed. R.W. Braithwaite.) pp. 651-729. (CSIRO: Darwin.)

Brock, J. (1988). *Top End Native Plants*. (John Brock: Darwin.)

Burgman, M.A. and Thompson, E.J. (1982). Cluster analysis, ordination and dominance-structural classification applied to diverse tropical vegetation at Jabiluka, Northern Territory. *Australian Journal of Ecology* **7**, 375-387.

Chippendale, G.M. and Murray, L.R. (1963). *Poisonous plants of the Northern Territory*. Northern Territory Administration, Animal Industry Branch, Extension Article 2.

Crowley, G.M. and Garnett, S.T. (1998). Vegetation change in the grasslands and grassy woodlands of east-central Cape York Peninsula, Australia. *Pacific Conservation Biology* **4**, 132-148.

Duff, G.A., Myers, B.A., Williams, R.J., Eamus, D., OíGrady, A. and Fordyce, I.R. (1997). Seasonal patterns in soil moisture, vapour pressure deficit, tree canopy cover and pre-dawn water potential in a northern Australian savanna. *Australian Journal of Botany* **45**, 211-224.

Dunlop, C.R. and Bowman, D.M.J.S. (1986). *Atlas of the Vascular Plant Genera of the Northern Territory*. Australian Flora and Fauna Series no. 6. (Australian Government Publishing Service: Canberra.)

Dunlop, C.R., Leach, G.J. and Cowie, I.D. (1995). *Flora of the Darwin region, Volume 2*. (Conservation Commission of the Northern Territory: Darwin.)

Everist, S.L. (1974). *Poisonous Plants of Australia.* (Angus and Robertson: Sydney.)

Fensham, R.J. (1990). Interactive effects of fire frequency and site factors in tropical *Eucalyptus* forest near Darwin, northern Australia. *Australian Journal of Ecology* **15**, 255-266.

Fensham, R.J. and Bowman, D.M.J.S. (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, R.J. and Kirkpatrick, J.B. (1992). Soil characteristics and tree species distribution in the savannah of Melville Island, Northern Territory. *Australian Journal of Botany* **40**, 311-333.

Jacobs, M.R. (1933). *A Reconnaissance of the Timber Resources of the Northern Territory*. (Commonwealth Forestry Bureau: Canberra.)

Kerle, J.A. (1985). Habitat preference and diet of the northern brushtail possum *Trichosurus vulpecula* in the Alligator Rivers region, N.T. *Proceedings of the Ecological Society of Australia* **13**, 161-176.

Kirkpatrick, J.B., Bowman, D.M.J.S., Wilson, B.A. and Dickinson, K.J.M. (1987). A transect study of the *Eucalyptus* forests and woodlands of a dissected sandstone and laterite plateau near Darwin, Northern Territory. *Australian Journal of Ecology* **12**, 339-359.

Kirkpatrick, J.B., Fensham, R.J., Nunez, M. and Bowman, D.M.J.S. (1988). Vegetation-radiation relationships in the wet-dry tropics: granite hills in northern Australia. *Vegetatio* **76**, 103-112.

Lacey, C.J. and Whelan, P.I. (1976). Observations on the ecological significance of vegetative reproduction in the Katherine-Darwin region of the Northern Territory. *Australian Forestry* **39**, 131-139.

Langkamp, P.J., Ashton, D.H. and Dalling, M.J. (1981). Ecological gradients in forest communities on Groote Eylandt, Northern Territory, Australia. *Vegetatio* **48**, 27-46.
Liddle, D.T., Russell-Smith, J., Brock, J., Leach, G.J. and Connors, G.T. (1994). *Atlas of the Vascular Rainforest Plants of the Northern Territory*. Flora of Australia Supplementary Series no. 3. (Australian Biological Resources Study: Canberra.)
Lonsdale, W.M. and Braithwaite, R.W. (1991). Assessing the effects of fire on vegetation in tropical savanna. *Australian Journal of Ecology* **16**, 363-374.
Macknight, C.C. (1976). *The Voyage to Marege*. (Melbourne University Press: Melbourne.)
Myers, B.A., Duff, G.A., Eamus, D., Fordyce, I.R., OíGrady, A. and Williams, R.J. (1997). Seasonal variation in water relations of trees of differing leaf phenology in a wet-dry tropical savanna near Darwin, Northern Territory. *Australian Journal of Botany* **45**, 225-240.
Neldner, V.J. and Clarkson, J.R. (1995). *Cape York Peninsula Vegetation Mapping*. (Cape York Peninsula Land Use Strategy: Brisbane.)
OíGrady, A.P., Chen, X., Eamus, D. and Hutley, L.B. (2000). Composition, leaf area index and standing biomass of eucalypt open forests near Darwin in the Northern Territory, Australia. *Australian Journal of Botany* **48**, 629-638.
Petheram, R.J. and Kok, B. (1983). *Plants of the Kimberley Region of Western Australia.* (University of Western Australia Press: Nedlands, WA.)
Ross, J.H. (1998). Erythrophleum. In *Flora of Australia. Volume 12. Mimosaceae (excl. Acacia), Caesalpiniaceae*. (CSIRO: Melbourne.)
Russell-Smith, J. (1991). Classification, species richness, and environmental relations of monsoon rain forest in northern Australia. *Journal of Vegetation Science* **2**, 259-278.
Russell-Smith, J., Lucas, D.E., Brock, J. and Bowman, D.M.J.S. (1993). *Allosyncarpia*-dominated rain forest in monsoonal northern Australia. *Journal of Vegetation Science* **4**, 67-82.
Russell-Smith, J., Ryan, P.G., Klessa, D., Waight, G. and Harwood, R. (1998). Fire regimes, fire-sensitive vegetation and fire management of the sandstone Arnhem Plateau, monsoonal northern Australia. *Journal of Applied Ecology* **35**, 829-846.
Story, R. (1970). Vegetation of the Mitchell-Normanby area. In *Lands of the Mitchell-Normanby area Queensland*. CSIRO Land Research Series no. 26. (eds R.W. Galloway, R.H. Gunn and R. Story.) pp. 75-88. (CSIRO: Melbourne.)
Taylor, J.A. and Dunlop, C.R. (1985). Plant communities of the wet-dry tropics of Australia: the Alligator Rivers region, Northern Territory. *Proceedings of the Ecological Society of Australia* **13**, 83-127.
Williams, R.J. and Douglas, M. (1995). Windthrow in a tropical savanna in Kakadu National Park, northern Australia. *Journal of Tropical Ecology* **11**, 547-558.
Williams, R.J., Myers, B.A., Muller, W.J., Duff, G.A. and Eamus, D. (1997). Leaf phenology of woody species in a north Australian tropical savanna. *Ecology* **78**, 2542-2558.

Williams, R.J., Myers, B.A., Eamus, D. and Duff, G.A. (1999a). Reproductive phenology of woody species in a north Australian tropical savanna. *Biotropica* **31**, 626-636.
Williams, R.J., Cook, G.D., Gill, A.M. and Moore, P.H.R. (1999b). Fire regime, fire intensity and tree survival in a tropical savanna in northern Australia. *Australian Journal of Ecology* **24**, 50-59.
Wilson, B.A. and Bowman, D.M.J.S. (1987). Fire, storm, flood and drought: the vegetation ecology of Howards Peninsula, Northern Territory, Australia. *Australian Journal of Ecology* **12**, 165-174.
Wilson, B.A., Brocklehurst, P.S., Clark, M.J. and Dickinson, K.J.M. (1990). *Vegetation survey of the Northern Territory, Australia*. Technical report no. 49. (Conservation Commission of the Northern Territory: Darwin.)
Woinarski, J.C.Z., Franklin, D., and Connors, G. (2000). Thinking honeyeater: nectar maps for the Northern Territory, Australia, showing spatial and temporal variation in nectar availability. Pacific Conservation Biology **6**, 61-80.

4. Distribution and biomass of ironwood in the Northern Territory

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Introduction

The extensive savanna woodlands and open forests of tropical northern Australia are dominated by eucalypts, and particularly so by two species, Darwin Stringybark *Eucalyptus tetrodonta* and Darwin Woollybutt *E. miniata*. Either or both of these species are dominant across more than 180,000 km^2 in the Northern Territory (Wilson *et al*. 1990) and comparable areas in northern Queensland and Western Australia. Characteristic traits of these dominant eucalypts are pivotal in structuring the ecology of these extensive formations (Bowman 1986, 1988; Bowman and Panton 1995; Woinarski *et al*. 2000), and the autecology of these dominant eucalypts is now relatively well known, with substantial studies on phenological patterning (Williams *et al*. 1997, 1999*a*; OíGrady *et al*. 2000), water and soil relations (Bowman and Minchin 1987; Wilson and Bowman 1994; Myers *et al*. 1997; Prior *et al*. 1997; Hatton *et al*. 1998; Prior and Eamus 1999), allometry and biomass (OíGrady *et al*. 2000; Werner and Murphy 2001), and response to storm and cyclone (Williams and Douglas 1995), to elevated CO_2 (Eamus *et al*. 1995a,b), to fire (Bowman *et al*. 1988*a*; Bowman and Panton 1995; Williams *et al*. 1999*b*), to aspect and solar radiation (Kirkpatrick *et al*. 1988; Fensham 1990) and to overstorey removal (Fensham and Bowman 1992).

In addition to this autecological research, a series of studies has examined the patterning of forest and woodland vegetation across local and regional environmental gradients, and attempted to define factors controlling variation in floristic composition and/or vegetation structure at this scale (Langkamp *et al*. 1981; Burgman and Thompson 1982; Bowman and Wightman 1985; Bowman and Dunlop 1986; Bowman 1986, 1991; Kirkpatrick *et al.* 1987, 1988; Bowman and Minchin 1987; Bowman and McDonough 1991; Bowman *et al.* 1988c, 1990, 1991, 1993; Fensham 1993; Russell-Smith *et al*. 1993; Wilson and Bowman 1994). These have been complemented by broader-scale studies examining variation in forest structure, vegetation patterning and eucalypt dominance at a semi-continental scale (Bowman *et al*. 1988*b*; Bowman 1996; Bowman and Connors 1996).

Some non-eucalypt tree species associated with the eucalypt-dominated woodlands and forests have been included as an informative comparison in autecological studies focusing on the two dominant eucalypts, or incidentally in community studies, but few have been the particular focus of detailed study. The two most notable exceptions are Northern Cypress-Pine *Callitris intratropica*, due to its potential significance for commercial forestry and problematical conservation management (Bowman and Panton 1993; Price and Bowman 1994), and the relatively restricted myrtaceous tree *Allosyncarpia ternata*, because it is a biogeographic and ecological oddity and also has conservation management problems (Bowman *et al*. 1990; Bowman 1991, 1994; Russell-Smith *et al*. 1993; Fordyce *et al*. 1995, 1997ab).

In this chapter we consider the distributional ecology of Cooktown Ironwood *Erythrophleum chlorostachys* (F.Muell.) Baillon (Caesalpinaceae), an important non-eucalypt component of these forests and woodlands. This focus reflects its current status as the main timber-producing tree species in the Northern Territory, although recognising that this current level of exploitation is minor. Here, we attempt to model its distribution as a guide to resource availability and constraints for any ironwood forestry program.

Methods

Data sources

For this study, we collated all available sources of distributional records for ironwood in the Northern Territory. These records comprise two main sources: collected specimens held in the Northern Territory Herbarium (ìHoltzeî data base), and field-based records of plant species present at geo-referenced sites. As ironwood is an unmistakably distinctive plant, the field-based records provide, in this case, a data source that can be treated with as much confidence as that from vouchered records.

The field data sources include a variety of surveys and methodologies (Appendix 4A). In most cases, basal area of all woody species was recorded, typically using a Bitterlich variable-radius wedge (Mueller-Dombois and Ellenberg 1974), or calculated from DBH measurements. In other cases, only presence was recorded for either all species (in which case lack of ironwood record indicates a true absence) or only dominant species (in which case lack of ironwood record may not indicate absence). Sample plot (quadrat) size varied between data sources, but typically was either 0.04 or 0.25 ha. In some data sets, the height/stand structure was recorded for dominant woody species. Locational precision varied substantially between data sets, with most of the data sets from the last 5 years having precision of +/- 10 m. Environmental variables measured at plots were consistent for many data sets (Appendices 4B and 4C), different but capable of being calibrated for others, totally idiosyncratic for others, and not measured at all for some data sets.

The heterogeneity of these data sets constrains some analyses. Subsets of data were used where appropriate to ensure consistency. In only a very small proportion of data sets were floristic lists for plots exhaustive, thereby reducing the applicability of some presence/absence modelling. Fig. 3.1 illustrates an example where ironwood was not present in the tree layer, but had a high density of suckers and small saplings. In this case, despite being abundant, the species may have been unreported in procedures that recorded only basal area of woody plants.

For each georeferenced plot, we added a range of climatic, geographic and other attributes:

- land tenure;
- vegetation type (from the 1:1,000,000 vegetation map of the Northern Territory: Wilson *et al*. 1990);
- elevation, slope and local elevational range (calculated as the difference between the lowest and highest point within a 450 x 450 m moving window) (all from a 3 second digital elevation model);
- average NDVI value or greeness index. (calculated from a monthly time series of NOAA NDVI (Normalised difference vegetation index) images for the period 1993-1998);
- distance to nearest permanent fresh water (calculated as the linear distance from all perennial fresh water as mapped in the AUSLIG 250k Geodata drainage layers);
- annual mean temperature, mean diurnal temperature range, isothermality, temperature seasonality (CV), maximum temperature of warmest period, minimum temperature of coldest period, temperature annual range, mean temperature of wettest quarter, mean temperature of driest quarter, mean temperature of warmest quarter, mean temperature of coldest quarter, annual precipitation, precipitation of wettest period, precipitation of driest period, precipitation seasonality (CV), precipitation of wettest quarter, precipitation of driest quarter, precipitation of warmest quarter, precipitation of coldest quarter, annual mean radiation, highest period radiation, lowest period radiation, radiation seasonality (CV), radiation of wettest quarter, radiation of driest quarter, radiation of warmest quarter, radiation of coldest quarter, annual mean moisture index, highest period moisture index, lowest period moisture index, moisture index seasonality (CV), mean moisture index of highest quarter, mean moisture index of lowest quarter, mean moisture index of warmest quarter, and mean moisture index of coldest quarter (all from the climate surface program ANUCLIM);
- surficial geology, as either [sand, silt, clay and gravel: alluvial, lacustrine, colluvial +/- marine] or [quartz sand: aeolian and residual; +/- minor ferruginous, aluminous, siliceous duricrust] or [clay, silt, minor sand: residual some alluvial] or [ferruginous, aluminous, siliceous duricrust; +/- minor quartz sand] or [bedrock] or [limestone: terrestrial; minor sand or clay] (from the 1:2,500,000 scale digital version of the surficial geology of Australia: BRS and AGSO 1991)

Many of these factors are highly intercorrelated, especially given the extraordinarily strong and simple relationship between climatic variation (especially rainfall) and latitude in the Northern Territory (e.g. Bowman 1996; Bowman and Connors 1996). Others (such as precipitation of driest period) are effectively invariant across the area considered. There are also estimation linkages between some variables, with the ANUCLIM climate surfaces being underpinned by the DEM. These links confound some analyses and interpretation. For example, while ironwood may functionally respond to annual rainfall, this response may be just as well predicted by latitude, and the initial inclusion of latitude in a model may mean that rainfall then provides no significant additional explanatory power.

Another source of interpretational problems is the coarse scale of the surficial geological coverage. The base layer for these coverages is Northcoteís 1:2,500,000 national soils map, with broad interpretation of various soil properties superimposed on each polygon of this coarse coverage. The imprecision of this coverage and coarseness of the categorisation will obscure possible real relationships between ironwood occurrence and soil and surficial geological features, and hence reduce the explanatory power of models.

Analysis

Known distribution

We initially map the location of all our sampled sites, marking those in which ironwood was reported.

Basal area frequency distribution

Summary statistics are presented for the occurrence of ironwood in samples, including the frequency distribution of basal area scores. Note that in many analyses (where indicated) we consider basal area of trees >20 cm DBH only, as this may best reflect merchantable timber resources.

Conversion of basal area data to biomass

Many of our samples include estimates of basal area, but none include direct assessment of biomass. There is no failsafe conversion factor, as the biomass of ironwood in any quadrat will depend not only on the total basal area of ironwood in that quadrat but also on the size distribution (e.g. a quadrat with many saplings totalling a basal area of 1m^2/ha will have a lower biomass than a quadrat where that same basal area is made up from only two large trees).

A subset of 66 of our samples (fire plots at Litchfield, Nitmiluk and Kakadu) included basal area measurements of every tree in the quadrat, from which we derived a total basal area measure (m^2/ha) per sample. For these sites. we also used the conversion equation from OíGrady *et al*. (2000) to estimate, from the measured basal area, the woody biomass for each tree in the quadrat, and thence the total woody biomass for ironwood in the quadrat. We then used the relationship between basal area per hectare and biomass per hectare from these sites to extrapolate more generally across all sites, albeit recognising that major variation in stand structure may add substantial noise to this relationship. We compared this derived relationship with a comparable one developed by A. OíGrady (*pers. comm*) from direct measurement of basal area and biomass at 30 plots in the Howard Springs region, but not published in the paper describing that study more generally (OíGrady *et al*. 2000).

Relationship with 1:1,000,000 vegetation map units

The locations of all of our sampled plots were intersected with the 1:1,000,000 Northern Territory vegetation map (Wilson *et al*. 1990). For those plots where complete floristic inventory was provided, we calculated the proportion of sites containing ironwood for each mapped vegetation type, with separate analyses for the Northern Territory as a whole, and that part of the Territory north of 20°S.

We similarly calculated mean basal area, and mean basal area for ironwood stems >20 cm DBH only, for every vegetation type, based only on those sampled sites in which basal area was suitably assessed. We also converted the basal area estimates to woody biomass estimates.

These estimates for each vegetation type were then mapped using the vegetation map as a template. A total biomass for ironwood in the Northern Territory (north of 20°S) was also calculated as the sum, over all vegetation types, of mean basal area per hectare in a particular vegetation type times the total extent of that vegetation type.

Note that in reporting results in relation to the vegetation types of Wilson *et al*. (1990), we use the botanical nomenclature given there, rather than recent changes which have recognised *Corymbia* as a genus distinct from *Eucalyptus*.

Quadrat-based environmental modeling

Only four environmental variables were evaluated at the time of sampling consistently in enough samples to warrant modelling. These were soil texture (as a 6-class factor: sand, sandy-loam, loam, clay-loam, clay, and heavy cracking clay), soil depth (as a 4-class factor: <5cm, 5-10cm, 10-40cm, and >40cm deep), rock cover (a continuous variable) and slope (in °).

For those sites where ironwood presence/absence was recorded, we used generalised linear modelling to relate incidence (proportion of sites in which ironwood occurred) to these four factors. A binomial distribution and logit link function were used. We derived a model including the best single term, and a minimum adequate model, based on backward stepwise selection of factors.

We similarly modeled basal area and basal area of trees >20 cm DBH, but for these continuous variables we assumed a Poisson distribution and used a log link function.

Models report the significance of each factor, and also the explanatory power of the model overall. This latter is measured as the percentage of deviance explained, a term analogous to r^2 in conventional multiple regression.

GIS-based modeling

We derived comparable models for ironwood proportion, basal area, and basal area of trees >20 cm DBH, but using the range of GIS-based climatic and locational variables described above. In the results below, we present only the minimum adequate model for these relationships.

Relationship to land tenure

We calculated the relative occurrence of ironwood biomass in lands of three tenure classes: conservation reserves, Aboriginal lands and pastoral lands.

Results

Characteristics of the data sets

We collated plant data from a total of 16,271 plots across the Northern Territory (Fig. 4.1), with most sites concentrated in the Top End (north of 20°S). Of these sites, 92 were simply vouchered specimen records of ironwood (from the NT Herbarium). Basal area information was available for 14,578 plots, of which a basal area >0 for ironwood was recorded in 1830 plots (i.e. 12.6% of plots in which basal area was measured). Presence/absence data were available for 13,328 plots, of which ironwood was recorded in 3282 plots (i.e. present in 24.1% of plots, excluding the 92 herbarium record sites).

Of all the plots at which basal area was recorded, the mean basal area for ironwood was 0.174 m^2/ha (s.e.=0.005). Of all the plots at which a basal area >0 for ironwood was recorded, the mean basal area was 1.383 m^2/ha (s.e.=0.032; median =1.00 m^2/ha). 41% of these latter plots had a basal area of ironwood >1.0 m^2/ha; 18.7% had basal area >2.0 m^2/ha; 9.0% had basal area >3 m^2/ha; 4.4% had basal area >4 m^2/ha; and 2.1% had basal area >5 m^2/ha (Fig. 4.2).

Biomass and basal area

There was a tight relationship between measured basal area and calculated woody biomass for the 66 sampled plots in which basal area of individual trees was measured (Fig. 4.3). The derived equation across these samples was reasonably similar to that determined by A. OíGrady (*pers. comm*) for his set of sites at Howard Springs:

$y=7.849\, x^{1.3922}$ (r^2=0.97) [this study]

$y=6.473\, x^{1.5263}$ (r^2=0.97) [OíGrady *pers. comm.*]

where y = woody biomass (t/ha) and x is basal area (m^2/ha) for ironwood.

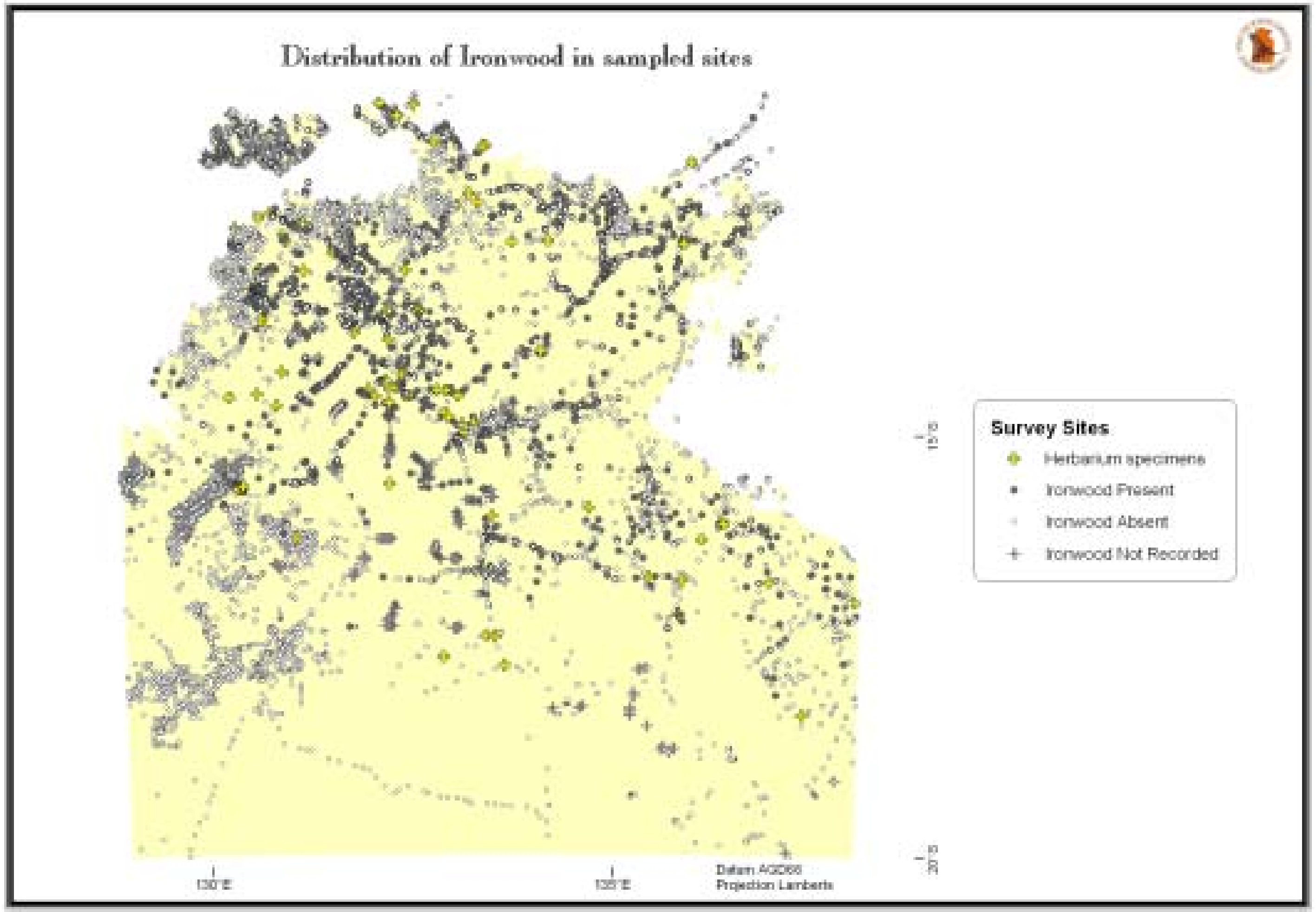


Fig. 4.1. Location of sample sites collated for this study. Vouchered herbarium specimens are indicated by yellow crosses. Records with field identifications of ironwood by filled circles. Sampled sites with no records of ironwood are differentiated according to whether full floristic lists were made (ironwood absent) or whether only dominant species or species with some basal area were recorded (ironwood not recorded).

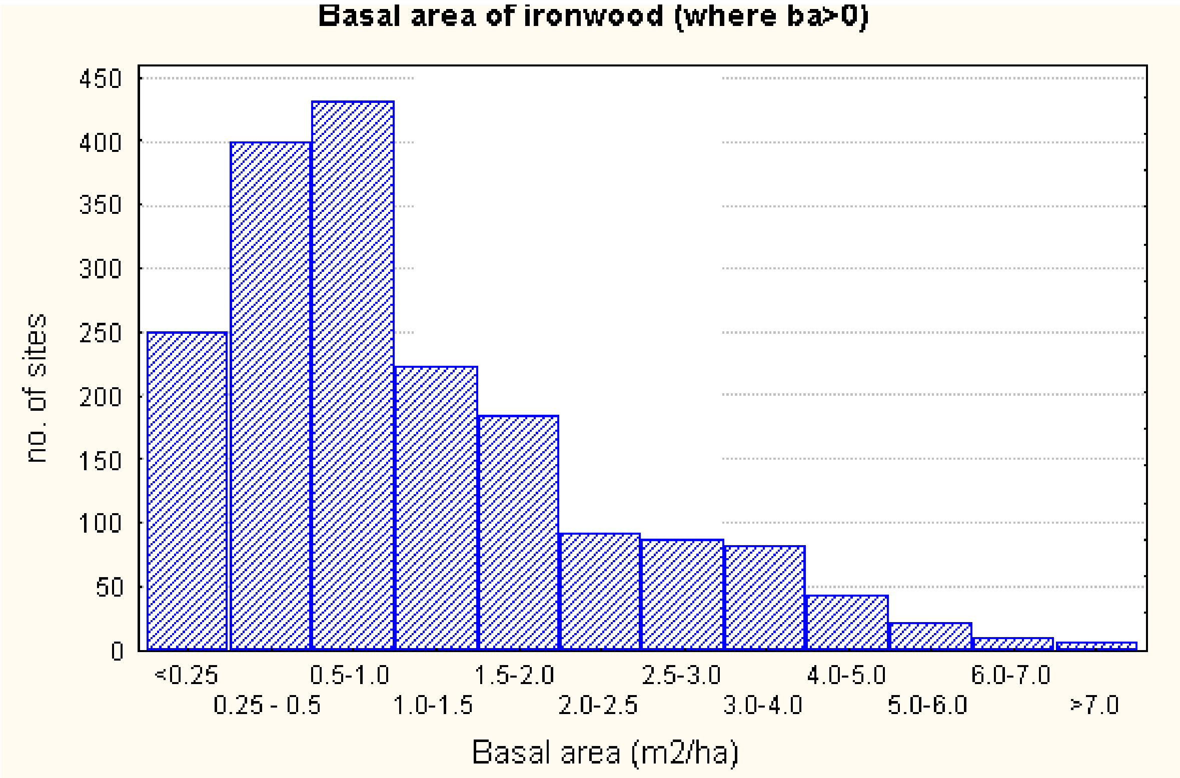


Fig. 4.2. Histogram showing the frequency distribution of basal area of ironwood across all sites in which basal area was recorded.

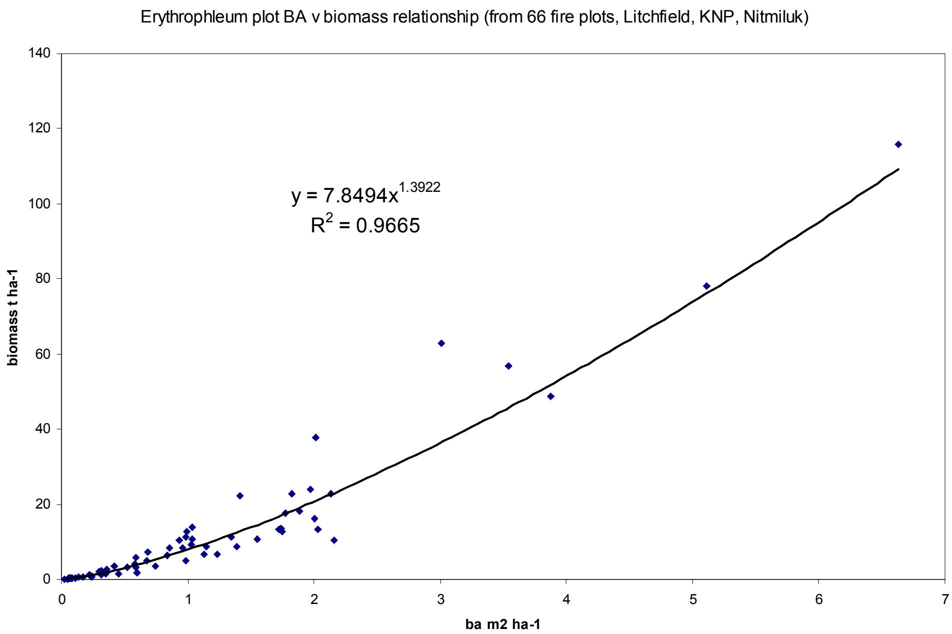


Fig. 4.3. Relationship between ironwood basal area (m²/ha) and biomass (t/ha), for the set of 66 plots at which DBH was measured for individual stems.

Relationship with vegetation types

Ironwood occurs in an extraordinarily broad range of environments in the Top End. Of 74 vegetation types mapped at 1:1,000,000 scale in the Northern Territory north of 20°S, our samples included ironwood within 49 types (Table 4.1). Of the 25 types in which we had no record of ironwood, 5 were not sampled (types 43, 52, 65, 91 and 100), and a further 13 were sampled with 10 or fewer quadrats. The well-sampled vegetation types in which ironwood was not represented comprised mainly treeless communities [types 106 (saline tidal flats); 96 and 97 (mitchell grass grasslands)], except for type 38 (*Eucalyptus brevifolia* low open woodland with hummock-grass understorey).

Ironwood was most likely to be present in sampled sites within vegetation type 3 (*Eucalyptus miniata - E. tetrodonta - E. nesophila* open forest), where 70% of sampled quadrats contained ironwood. There was also a high incidence (present in >20% of sampled sites) of ironwood in other vegetation types co-dominated by *E. miniata* and/or *E. tetrodonta* (e.g. types 4, 5, 7, 8, 9,10,11,12,13,14,17,31 and 32), in vegetation types dominated by *E. tectifica* and *E. latifolia* (type 15), *E. papuana* and *E. polycarpa* (type 18), *E. dichromophloia* (type 20), *E. tintinnans* (type 21), *E. pruinosa* (types 23 and 45), *E. microtheca* (type 25), *E. phoenicea* (type 29), *E. leucophloia* (type 35), *Acacia* spp. (types 47 and 55), *Melaleuca minutifolia* (type 50) and *M. viridiflora* (type 51).

Basal area data largely recapitulated that for presence/absence, except that some of the vegetation types in lower rainfall areas which had relatively high incidence of ironwood had relatively low ironwood basal areas (e.g. *E. papuana* and *E. polycarpa* (type 18), *E. dichromophloia* (type 20), *E. pruinosa* (types 23 and 45), *E. microtheca* (type 25), *E. phoenicea* (type 29), *E. leucophloia* (type 35), *Acacia* spp. (type 55), *Melaleuca minutifolia* (type 50) and *M. viridiflora* (type 51)).

Figures 4.4 - 4.7 show distribution maps of mean incidence, basal area and biomass of ironwood superimposed on vegetation map units. These distribution maps suggest that ironwood is extremely widespread in the Top End, but that it has highest incidence in the Katherine to Darwin region, Cobourg Peninsula and the Tiwi Islands, and, less so, in northern and eastern Arnhem Land. The maps of estimated basal area and biomass largely recapitulate those for incidence.

Total biomass

The biomass (t/ha) estimates for each vegetation type shown in Fig. 4.7 can be converted to total biomass across the Northern Territory by simply multiplying each estimate by the total area of that vegetation type. However, given that this total involves summing over 74 vegetation types, it is not possible to ascribe confidence limits to this sum.

The resulting estimate for the Northern Territory north of 20°S is 94.99×10^6 tonnes (woody biomass) of ironwood.

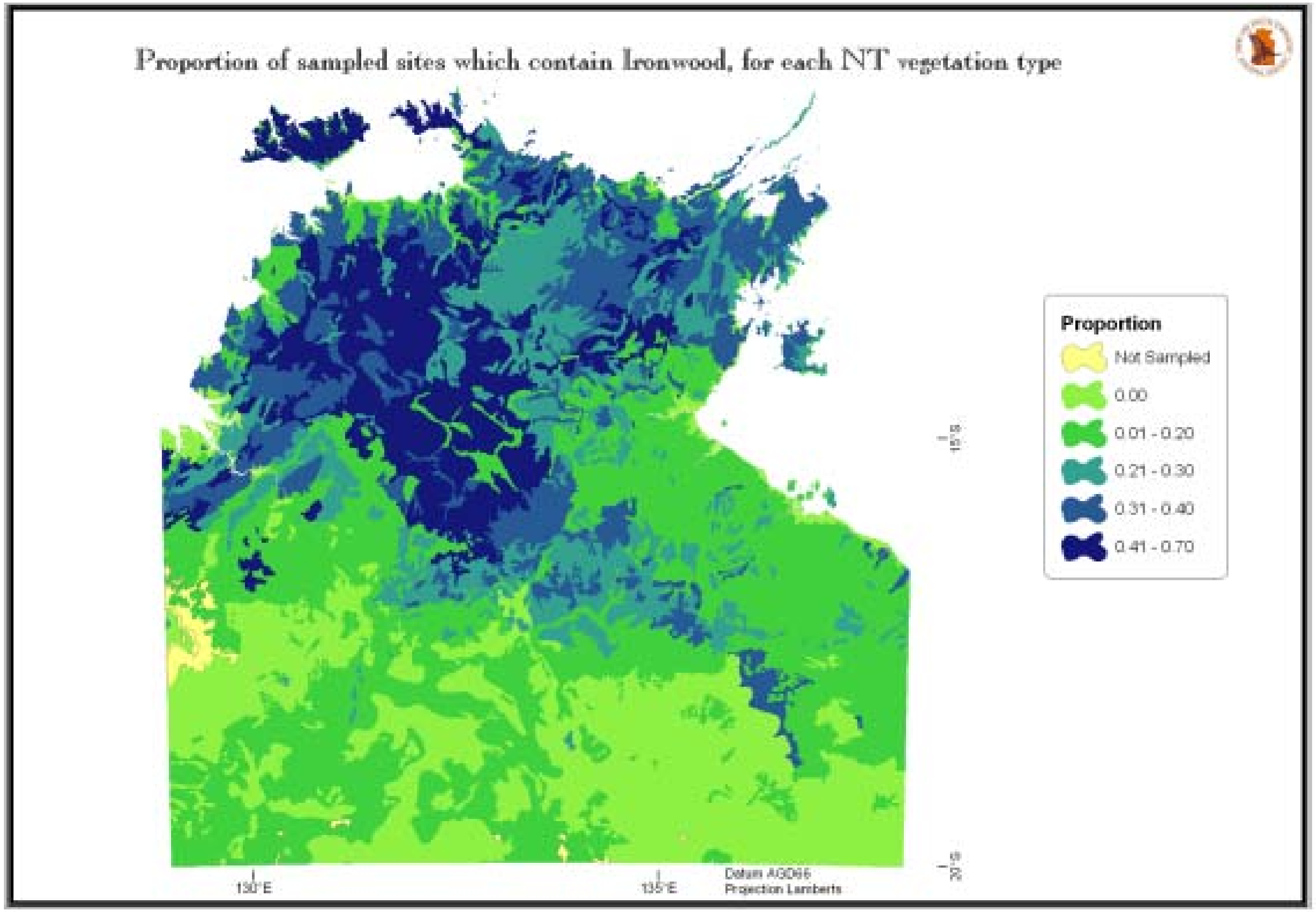


Fig. 4.4. Distribution of the incidence of ironwood, as estimated from mean occurrence in mapped vegetation types.

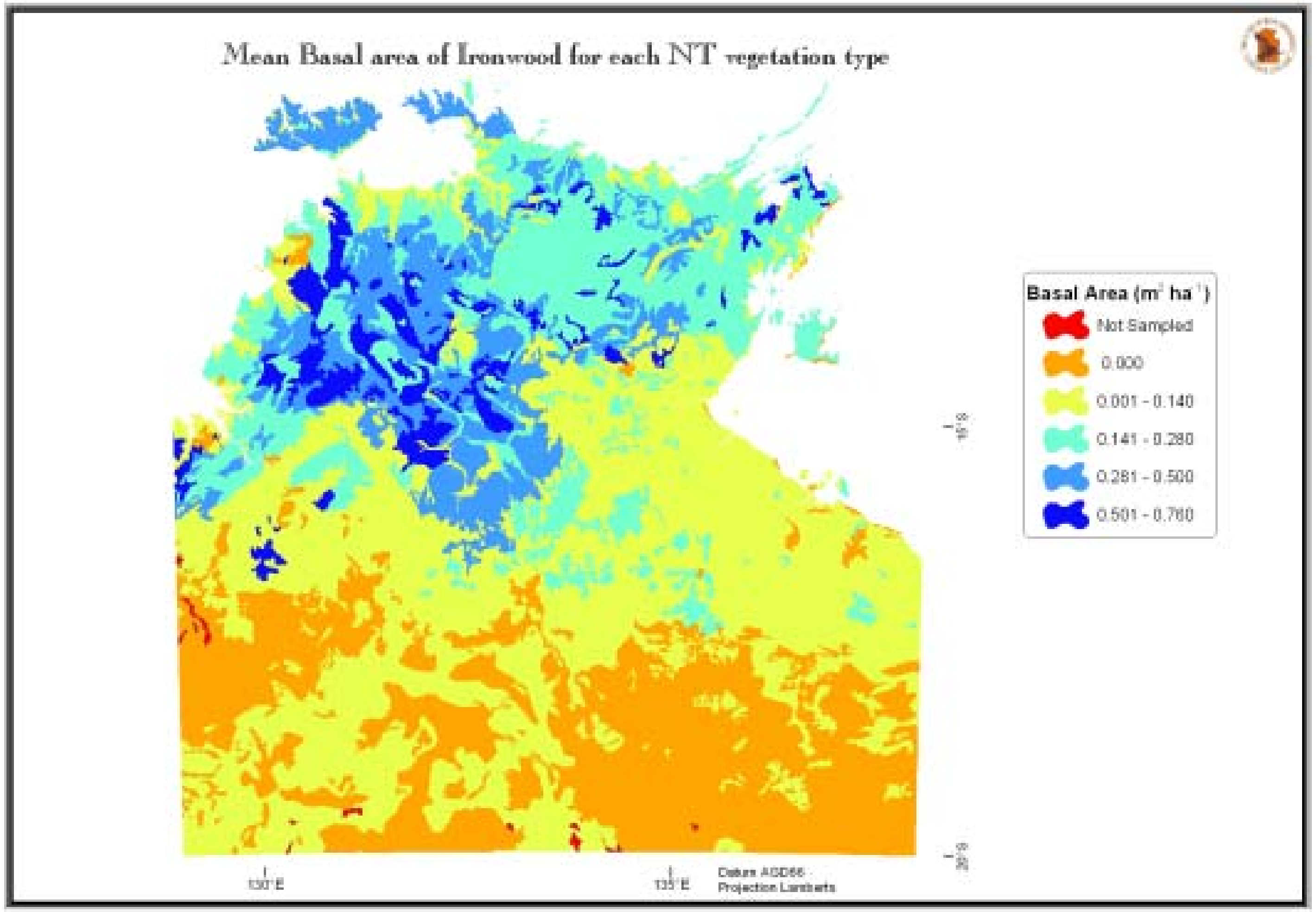


Fig. 4.5. Distribution of basal area of ironwood, as estimated from mean occurrence in mapped vegetation types.

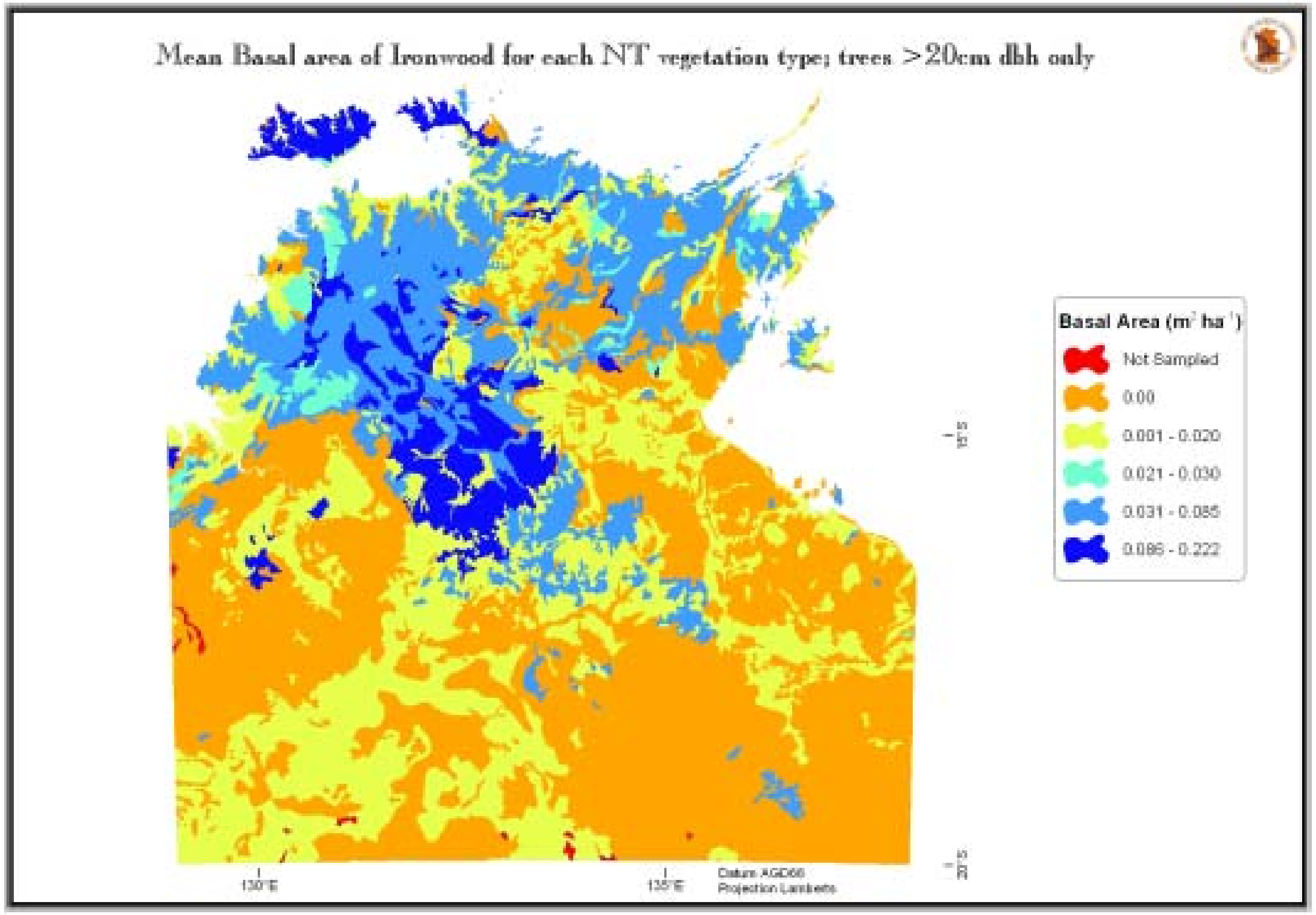


Fig. 4.6. Distribution of basal area of big ironwood trees (>20 cm DBH only), as estimated from mean occurrence in mapped vegetation types.

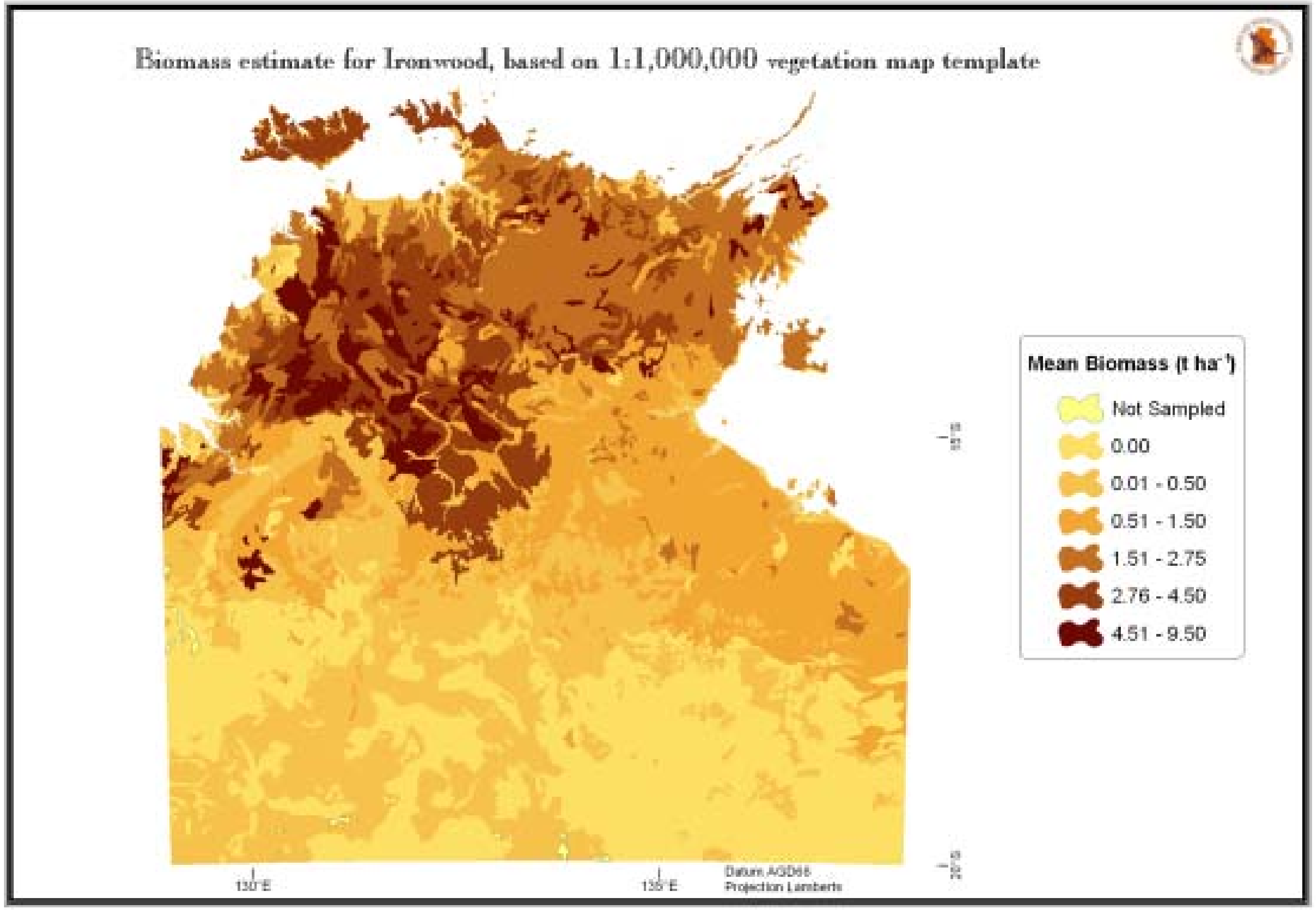


Fig. 4.7. Distribution of woody biomass of ironwood, as estimated from mean occurrence in mapped vegetation types.

Table 4.1. Occurrence, basal area and biomass of ironwood in vegetation types described for the NT at 1:1,000,000 scale (Wilson *et al*. 1990). Values in body of table are means, with number of sampled points in brackets.

Unit	Description	Proportion of Ironwood		Mean Basal Area		Big Tree Basal Area		Mean Biomass	
		all NT	N 20∫	all NT	N 20∫	all NT	N20∫	all NT	N 20∫
1	Mixed species closed-forest (Monsoon vine-thicket).	0.04(25)	0.04(25)	0.03(30)	0.03(30)	0(29)	0(29)	0.26(30)	0.26(30)
2	Allosyncarpia ternata closed-forest.	0.04(47)	0.04(47)	0.05(58)	0.05(58)	0(56)	0(56)	0.5(58)	0.5(58)
3	E. miniata (Darwin Woolly Butt), E. tetrodonta (Stringybark), E. nesophila (Melville Island Bloodwood) open-forest with Sorghum grassland understorey.	0.7(738)	0.7(738)	0.33(1678)	0.33(1678)	0.15(1638)	0.15(1638)	3.31(1678)	3.31(1678)
4	E. miniata (Darwin Woolly Butt), E. tetrodonta (Stringybark) open-forest with Sorghum grassland understorey.	0.32(1103)	0.32(1103)	0.24(1551)	0.24(1551)	0.07(1319)	0.07(1319)	2.7(1551)	2.7(1551)
5	E. miniata (Darwin Woolly Butt), E. nesophila (Melville Island Bloodwood), Callitris intratropica (Cypress Pine) open-forest with open-shrubland understorey.	0.24(62)	0.24(62)	0.34(65)	0.34(65)	0(50)	0(50)	4.3(65)	4.3(65)
6	E. tetrodonta (Stringybark), Callitris intratropica (Cypress Pine) woodland with Plectrachne pungens (Curly Spinifex) open-grassland understorey.	0.18(11)	0.18(11)	0(11)	0(11)	0(9)	0(9)	0(11)	0(11)
7	E. tetrodonta (Stringybark), Callitris intratropica (Cypress Pine) woodland with grassland understorey.	0.29(49)	0.29(49)	0.07(108)	0.07(108)	0.02(100)	0.02(100)	0.57(108)	0.57(108)
8	E. tetrodonta (Stringybark), E. miniata (Darwin Woolly Butt), E. ferruginea (Rusty Bloodwood) woodland with Sorghum grassland understorey.	0.29(223)	0.29(223)	0.18(296)	0.18(296)	0(238)	0(238)	1.73(296)	1.73(296)
9	E. tetrodonta (Stringybark), E. miniata (Darwin Woolly Butt), E. bleeseri (Smooth-stemmed Bloodwood) woodland with Sorghum grassland understorey.	0.4(314)	0.4(314)	0.52(516)	0.52(516)	0.02(407)	0.02(407)	6.44(516)	6.44(516)
10	E. tetrodonta (Stringybark) woodland with Plectrachne pungens (Curly Spinifex) open-grassland understorey.	0.2(155)	0.2(155)	0.1(199)	0.1(199)	0(168)	0(168)	0.86(199)	0.86(199)
11	E. miniata (Darwin Woolly Butt) woodland with grassland understorey.	0.46(56)	0.46(56)	0.27(83)	0.27(83)	0.03(66)	0.03(66)	2.74(83)	2.74(83)
12	E. miniata (Darwin Woolly Butt), E. tetrodonta (Stringybark) woodland with Plectrachne pungens (Curly Spinifex) grassland understorey.	0.28(64)	0.28(64)	0.1(66)	0.1(66)	0(43)	0(43)	0.69(66)	0.69(66)
13	E. tetrodonta (Stringybark), E. miniata (Darwin Woolly Butt), E. dichromophloia (Variable-barked Bloodwood) woodland with Plectrachne pungens (Curly Spinifex), Chrysopogon fallax (Golden Beard Grass) grassland understorey.	0.54(79)	0.54(79)	0.59(105)	0.59(105)	0.22(81)	0.22(81)	6.76(105)	6.76(105)
14	E. tetrodonta (Stringybark), E. tectifica, (Northern Box) woodland with Sorghum grassland understorey.	0.37(41)	0.37(41)	0.19(41)	0.19(41)	0(26)	0(26)	1.74(41)	1.74(41)
15	E. tectifica (Northern Box), E. latifolia (Round-leaved Bloodwood) woodland with Sorghum grassland understorey.	0.51(843)	0.51(843)	0.39(1103)	0.39(1103)	0.06(839)	0.06(839)	4.37(1103)	4.37(1103)
16	E. tectifica (Northern Box), E. terminalis (Bloodwood) woodland with Sehima nervosum (White Grass), Chrysopogon fallax (Golden Beard Grass) grassland understorey.	0.15(383)	0.15(383)	0.07(452)	0.07(452)	0(399)	0(399)	0.59(452)	0.59(452)
17	E. dichromophloia (Variable-barked Bloodwood), E. tetrodonta (Stringybark) woodland with grassland understorey.	0.66(101)	0.66(101)	0.42(154)	0.42(154)	0.09(105)	0.09(105)	4.03(154)	4.03(154)
18	E. papuana, (Ghost Gum), E. polycarpa (Long-fruited Bloodwood) woodland with grassland understorey.	0.29(86)	0.29(86)	0.19(145)	0.19(145)	0.03(132)	0.03(132)	2.09(145)	2.09(145)
19	E. terminalis (Bloodwood), E. patellaris (Weeping Box) woodland with grassland understorey.	0.17(18)	0.17(18)	0.15(26)	0.15(26)	0.03(24)	0.03(24)	1.3(26)	1.3(26)
20	E. dichromophloia (Variable-barked Bloodwood) low woodland with Chrysopogon fallax (Golden Beard Grass), Plectrachne pungens (Curly Spinifex) grassland understorey.	0.36(88)	0.36(88)	0.15(158)	0.15(158)	0.05(137)	0.05(137)	1.42(158)	1.42(158)

Table 4.1. continued

Unit	Description	Proportion of Ironwood all NT	Proportion of Ironwood N 20∫	Mean Basal Area all NT	Mean Basal Area N 20∫	Big Tree Basal Area all NT	Big Tree Basal Area N20∫	Mean Biomass all NT	Mean Biomass N 20∫
21	E. tintinnans (Salmon Gum) low woodland with Sorghum grassland understorey.	0.56(279)	0.56(279)	0.76(257)	0.76(257)	0.09(143)	0.09(143)	9.37(257)	9.37(257)
22	E. terminalis (Bloodwood), E. chlorophylla (Box) low woodland with Sehima nervosum (White Grass), Chrysopogon fallax (Golden Beard Grass) grassland understorey.	0.03(252)	0.03(252)	0.01(267)	0.01(267)	0(261)	0(261)	0.12(267)	0.12(267)
23	E. pruinosa (Silver Box) low woodland with Eulalia aurea (Silky Browntop), Sehima nervosum (White Grass) grassland understorey.	0.26(193)	0.26(193)	0.11(275)	0.11(275)	0(227)	0(227)	0.97(275)	0.97(275)
24	E. microtheca (Coolibah), Excoecaria parvifolia (Gutta-percha)low woodland with Chrysopogon fallax (Golden Beard Grass), Dichanthium (Bluegrass) grassland understorey.	0.08(13)	0.08(13)	0.01(113)	0.01(113)	0(112)	0(112)	0.12(113)	0.12(113)
25	E. microtheca (Coolibah) low open-woodland with Eulalia aurea (Silky Browntop), Dichanthium (Bluegrass) grassland understorey.	0.31(49)	0.31(49)	0.05(96)	0.05(96)	0.01(89)	0.01(89)	0.29(96)	0.29(96)
26	E. microtheca (Coolibah) low-open woodland with Eulalia aurea (Silky Browntop), Astrebla (Mitchell Grass) grassland understorey.	0.03(37)	0.03(37)	0.02(49)	0.02(49)	0.08(49)	0.08(49)	0.13(49)	0.13(49)
27	E. microtheca (Coolibah) low open-woodland with open-grassland understorey.	0(12)	0(2)	0(12)	0(2)	0(12)	0(2)	0(12)	0(2)
28	E. microtheca (Coolibah) low open-woodland with Chenopodium auricomum (Bluebush) sparse-shrubland understorey.	0(6)	0(6)	0(13)	0(13)	0(13)	0(13)	0(13)	0(13)
29	E. phoenicea (Scarlet Gum) low woodland with Plectrachne pungens (Curly Spinifex) hummock grassland understorey.	0.33(79)	0.33(79)	0.16(92)	0.16(92)	0(70)	0(70)	1.5(92)	1.5(92)
30	E. gongylocarpa (Marble Gum) open-woodland with open-hummock grassland understorey.	0(2)	0(0)	0(2)	0(0)	0(2)	0(0)	0(2)	0(0)
31	E. dichromophloia (Variable-barked Bloodwood), E. tetrodonta (Stringybark) low open-woodland with Plectrachne pungens (Curly Spinifex) open-hummock grassland understorey.	0.2(147)	0.2(147)	0.09(179)	0.09(179)	0(150)	0(150)	0.82(179)	0.82(179)
32	E. dichromophloia (Variable-barked Bloodwood), E. miniata (Darwin Woolly Butt) low open-woodland with Plectrachne pungens (Curly Spinifex) open-hummock grassland understorey.	0.24(431)	0.24(431)	0.16(569)	0.16(569)	0(468)	0(468)	1.84(569)	1.84(569)
33	E. dichromophloia (Variable-barked Bloodwood) low open-woodland with Plectrachne pungens (Curly Spinifex) open-hummock grassland understorey.	0.13(112)	0.13(112)	0.07(137)	0.07(137)	0.01(125)	0.01(125)	0.86(137)	0.86(137)
34	E. dichromophloia (Variable-barked Bloodwood) low open-woodland with Triodia pungens (Soft Spinifex) hummock grassland understorey.	0(1)	0(1)	0(1)	0(1)	0(1)	0(1)	0(1)	0(1)
35	E. leucophloia (Snappy Gum) low open-woodland with Plectrachne pungens (Curly Spinifex) hummock grassland understorey.	0.23(40)	0.23(40)	0.14(40)	0.14(40)	0(31)	0(31)	1.26(40)	1.26(40)
36	E. leucophloia (Snappy Gum) low open-woodland with Triodia pungens (Soft Spinifex), Plectrachne pungens (Curly Spinifex) open-hummock grassland understorey.	0.04(46)	0.04(46)	0(48)	0(48)	0(46)	0(46)	0(48)	0(48)
37	E. brevifolia (Snappy Gum) low open-woodland with Plectrachne pungens (Curly Spinifex) hummock grassland understorey.	0.06(102)	0.06(102)	0.01(152)	0.01(152)	0(146)	0(146)	0.07(152)	0.07(152)
38	E. brevifolia (Snappy Gum) low open-woodland with Triodia pungens (Soft Spinifex) hummock grassland understorey.	0(513)	0(513)	0(534)	0(534)	0(534)	0(534)	0(534)	0(534)
39	E. pruinosa (Silver Box), Lysiphyllum cunninghamii (Bauhinia) low open-woodland with hummock/tussock grassland understorey.	0.13(8)	0.13(8)	0.01(17)	0.01(17)	0(17)	0(17)	0.03(17)	0.03(17)
40	E. ferruginea (Rusty Bloodwood) low open-woodland or Jacksonia odontocarpa open-shrubland with Plectrachne pungens (Curly Spinifex) open-hummock grassland understorey.	0(10)	0(10)	0(10)	0(10)	0(10)	0(10)	0(10)	0(10)
41	E. opaca (Bloodwood) low open-woodland with Plectrachne pungens (Curly Spinifex) hummock grassland understorey.	0(5)	0(5)	0(5)	0(5)	0(5)	0(5)	0(5)	0(5)
42	E. opaca (Bloodwood) low open-woodland with Triodia pungens (Soft Spinifex) hummock grassland understorey.	0(19)	0(11)	0(19)	0(11)	0(19)	0(11)	0(19)	0(11)

Table 4.1. continued

Unit	Description	Proportion of Ironwood		Mean Basal Area		Big Tree Basal Area		Mean Biomass	
		all NT	N 20∫	all NT	N 20∫	all NT	N20∫	all NT	N 20∫
43	Eucalyptus low open-woodland and/or Acacia sparse-shrubland with Triodia spicata (Spike Flower Spinifex), Triodia pungens (Soft Spinifex) hummock grassland understorey.	0(8)	0(0)	0(8)	0(0)	0(8)	0(0)	0(8)	0(0)
44	Terminalia arostrata (Nutwood) low open-woodland with Chrysopogon fallax (Golden Beard Grass), Dichanthium (Bluegrass) grassland understorey.	0.04(27)	0.04(27)	0.02(33)	0.02(33)	0(32)	0(32)	0.09(33)	0.09(33)
45	Lysiphyllum cunninghamii (Bauhinia), E. pruinosa (Silver Box) low open-woodland with Eulalia aurea (Silky Browntop), Sehima nervosum (White Grass) grassland understorey.	0.2(15)	0.2(15)	0.02(19)	0.02(19)	0(16)	0(16)	0.08(19)	0.08(19)
46	Lysiphyllum cunninghamii (Bauhinia), mixed species low open-woodland with Sehima nervosum (White Grass), Chrysopogon fallax (Golden Beard Grass) open-grassland understorey.	0(21)	0(21)	0(21)	0(21)	0(21)	0(21)	0(21)	0(21)
47	Acacia open-shrubland with Sorghum grassland understorey.	0.57(7)	0.57(7)	0.23(24)	0.23(24)	0.14(24)	0.14(24)	2.27(24)	2.27(24)
48	Livistona humilis (Fan Palm) tall open-shrubland with Sorghum grassland understorey.	0.03(40)	0.03(40)	0(55)	0(55)	0(54)	0(54)	0(55)	0(55)
49	Melaleuca citrolens (Paperbark) low woodland with Chrysopogon fallax (Golden Beard Grass) open-grassland understorey.	0.14(35)	0.14(35)	0.1(49)	0.1(49)	0(44)	0(44)	1.06(49)	1.06(49)
50	Melaleuca minutifolia (Paperbark) low woodland with Sorghum grassland understorey.	0.23(35)	0.23(35)	0.01(189)	0.01(189)	0(184)	0(184)	0.11(189)	0.11(189)
51	Melaleuca viridiflora (Broad Leaved Paperbark), Eucalyptus low open-woodland with Chrysopogon fallax (Goldern Beard Grass) grassland understorey.	0.24(183)	0.24(183)	0.17(273)	0.17(273)	0.05(260)	0.05(260)	2.07(273)	2.07(273)
52	Melaleuca glomerata (Inland Teatree) open-shrubland.	0(4)	0(0)	0(4)	0(0)	0(4)	0(0)	0(4)	0(0)
53	Melaleuca forest (Paperbark Swamp).	0.03(146)	0.03(146)	0.01(228)	0.01(228)	0(224)	0(224)	0.06(228)	0.06(228)
54	Mixed closed-grassland/sedgeland (Seasonal Floodplain).	0.01(698)	0.01(698)	0(815)	0(815)	0(813)	0(813)	0.04(815)	0.04(815)
55	A. shirleyi (Lancewood) open-forest with open-grassland understorey.	0.24(136)	0.24(136)	0.04(275)	0.04(275)	0(254)	0(254)	0.27(275)	0.27(275)
56	Complex of A. shirleyi (Lancewood) low-woodland mixed with Eucalyptus low open-woodland.	0.18(50)	0.18(50)	0.08(81)	0.08(81)	0(72)	0(72)	0.65(81)	0.65(81)
57	Macropteranthes kekwickii (Bullwaddy) tall shrubland with open-grassland understorey.	0(3)	0(3)	0(5)	0(5)	0(5)	0(5)	0(5)	0(5)
58	A. aneura (Mulga)/mixed species low open-woodland with open-grassland understorey.	0(14)	0(0)	0(14)	0(0)	0(14)	0(0)	0(14)	0(0)
59	A. estrophiolata (Ironwood), Atalaya hemiglauca (Whitewood) low open-woodland with open-grassland understorey.	0(19)	0(0)	0(19)	0(0)	0(19)	0(0)	0(19)	0(0)
60	A. aneura (Mulga), Hakea (Needlewood) low open-woodland with herb/grassland understorey.	0(6)	0(0)	0(6)	0(0)	0(6)	0(0)	0(6)	0(0)
61	Complex of mixed species low open-woodland between dunes with Zygochloa paradoxa (Sandhill Cane Grass) open-hummock grassland on dune crests.	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)
62	A. georginae (Giddier) low open-woodland with Astrebla pectinata (Bull Mitchell Grass) open-grassland understorey.	0(18)	0(0)	0(18)	0(0)	0(18)	0(0)	0(18)	0(0)
63	A. georginae (Gidyea) low open-woodland with open-grassland understorey.	0(11)	0(0)	0(11)	0(0)	0(11)	0(0)	0(11)	0(0)
64	A. georginae (Gidyea) low open-woodland with herbland understorey.	0(3)	0(0)	0(3)	0(0)	0(3)	0(0)	0(3)	0(0)
65	A. aneura (Mulga) tall open-shrubland with Eragrostis eriopoda (Woolybutt) open-grassland understorey.	0(41)	0(0)	0(41)	0(0)	0(41)	0(0)	0(41)	0(0)
66	A. aneura (Mulga) tall open-shrubland with Cassia, Eremophila (Fuchsia) open-shrubland understorey.	0(9)	0(0)	0(9)	0(0)	0(9)	0(0)	0(9)	0(0)
67	A. ammobia tall open-shrubland with sparse-grassland understorey.	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)
68	A. kempeana (Witchetty Bush) Acacia tall open-shrubland with Cassia, Eremophila (Fuchsia) open-shrubland understorey.	0(2)	0(0)	0(2)	0(0)	0(2)	0(0)	0(2)	0(0)
69	A. aneura (Mulga) tall sparse-shrubland with Aristida contorta (Bunched Kerosene Grass) or Triodia open-tussock/hummock grassland understorey.	0(4)	0(1)	0(4)	0(1)	0(4)	0(1)	0(4)	0(1)
70	A. aneura (Mulga) tall sparse-shrubland with Cassia, Eremophila (Fuchsia) low sparse-shrubland understorey.	0(3)	0(0)	0(3)	0(0)	0(3)	0(0)	0(3)	0(0)

Table 4.1. continued

Unit	Description	Proportion of Ironwood		Mean Basal Area		Big Tree Basal Area		Mean Biomass	
		all NT	N 20∫	all NT	N 20∫	all NT	N20∫	all NT	N 20∫
71	A. aneura (Mulga) tall sparse-shrubland with grassland understorey.	0(22)	0(0)	0(22)	0(0)	0(22)	0(0)	0(22)	0(0)
72	A. kempeana (Witchetty Bush) sparse-shrubland to tall sparse-shrubland with grassland understorey.	0(6)	0(0)	0(6)	0(0)	0(6)	0(0)	0(6)	0(0)
73	A. tetragonophylla (Dead Finish), A. kempeana (Witchetty Bush) sparse-shrubland with herb/grassland understorey.	0(12)	0(0)	0(12)	0(0)	0(12)	0(0)	0(12)	0(0)
74	A. stowardii (Bastard Mulga), Cassia, Eremophila (Fuchsia) sparse-shrubland.	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)
75	Triodia pungens (Soft Spinifex) hummock grassland understorey with A. lysiphloia (Turpentine) tall open-shrubland overstorey.	0(1)	0(1)	0(1)	0(1)	0(1)	0(1)	0(1)	0(1)
76	Triodia pungens (Soft Spinifex), Plectrachne schinzii (Curly Spinifex) hummock grassland with Acacia tall sparse-shrubland overstorey.	0.05(129)	0.06(96)	0.01(150)	0.02(117)	0(148)	0.01(115)	0.07(150)	0.09(117)
77	Triodia pungens (Soft Spinifex), Plectrachne schinzii (Curly Spinifex), hummock grassland with Acacia tall sparse-shrubland overstorey between dunes.	0(9)	0(9)	0(9)	0(9)	0(9)	0(9)	0(9)	0(9)
78	Triodia spicata (Spike Flowered Spinifex) hummock grassland with Grevillea wickhamii (Holly Grevillea), Acacia sparse-shrubland overstorey.	0(3)	0(0)	0(3)	0(0)	0(3)	0(0)	0(3)	0(0)
79	Plectrachne melvillei (Spinifex) hummock grassland with A. aneura (Mulga), A. kempeana (Witchetty Bush) tall open-shrubland overstorey.	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)
80	Triodia longiceps (Grey Spinifex) hummock grassland with Acacia tall open-shrubland overstorey.	0(2)	0(0)	0(2)	0(0)	0(2)	0(0)	0(2)	0(0)
81	Triodia basedowii (Hard Spinifex) hummock grassland with Acacia tall sparse-shrubland overstorey.	0(16)	0(0)	0(16)	0(0)	0(16)	0(0)	0(16)	0(0)
82	Triodia basedowii hummock grassland with A. aneura (Mulga) tall sparse-shrubland overstorey between dunes.	0(7)	0(0)	0(7)	0(0)	0(7)	0(0)	0(7)	0(0)
83	Triodia basedowii (Hard Spinifex) or Triodia pungens (Soft Spinifex) hummock grassland with E. gamophylla (Blue Mallee), Acacia tall sparse-shrubland overstorey.	0(18)	0(0)	0(18)	0(0)	0(18)	0(0)	0(18)	0(0)
84	Triodia basedowii (Hard Spinifex) hummock grassland with E. gamophylla (Blue Mallee) tall sparse-shrubland overstorey.	0(10)	0(0)	0(10)	0(0)	0(10)	0(0)	0(10)	0(0)
85	Triodia basedowii (Hard Spinifex) hummock grassland with Acacia tall sparse shrubland. overstorey between dunes and Zygochloa paradoxa (Sandhill Cane Grass) open-hummock grassland on dune crests	0(1)	0(0)	0(1)	0(0)	0(1)	0(0)	0(1)	0(0)
86	Triodia pungens (Soft Spinifex) or Triodia basedowii (Hard Spinifex) hummock grassland with Acacia tall sparse-shrubland overstorey between dunes	0(10)	0(0)	0(10)	0(0)	0(10)	0(0)	0(10)	0(0)
87	Triodia (Spinifex) open-hummock grassland with A. aneura tall sparse-shrubland overstorey.	0(6)	0(0)	0(6)	0(0)	0(6)	0(0)	0(6)	0(0)
88	Triodia (Spinifex) hummock grassland.	0(10)	0(0)	0(10)	0(10)	0(10)	0(10)	0(10)	0(10)
89	Triodia pungens (Soft Spinifex) open-hummock grassland with scattered shrubs.	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)
90	Triodia irritans (Porcupine Grass) open-hummock grassland.	0(1)	0(0)	0(1)	0(0)	0(1)	0(0)	0(1)	0(0)
91	Triodia wiseana (Limestone Spinifex) hummock grassland with Terminalia arostrata (Nutwood) low open-woodland overstorey.	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)
92	Triodia clelandii (Weeping Spinifex) hummock grassland with mixed species low open-woodland overstorey.	0(21)	0(0)	0(21)	0(0)	0(21)	0(0)	0(21)	0(0)
93	Triodia basedowii (Hard Spinifex) hummock grassland with Allocasuarina decaisneana (Desert Oak) open-woodland overstorey between dunes.	0(43)	0(0)	0(43)	0(0)	0(43)	0(0)	0(43)	0(0)

Table 4.1. continued

Unit	Description	Proportion of Ironwood		Mean Basal Area		Big Tree Basal Area		Mean Biomass	
		all NT	N 20∫	all NT	N 20∫	all NT	N20∫	all NT	N 20∫
94	Triodia basedowii (Hard Spinifex) hummock grassland with Allocasuarina decaisneana (Desert Oak) low open-woodland or Acacia tall sparse-shrubland overstorey.	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)
95	Mixed species sparse-grassland or herbland.	0(1)	0(0)	0(1)	0(0)	0(1)	0(0)	0(1)	0(0)
96	Astrebla pectinata (Barley Mitchell grass) grassland.	0(428)	0(390)	0(438)	0(400)	0(438)	0(400)	0(438)	0(400)
97	Astrebla (Mitchell Grass), mixed species grassland with scattered trees and shrubs.	0(284)	0(284)	0(291)	0(291)	0(291)	0(291)	0(291)	0(291)
98	Chrysopogon fallax (Golden Beard Grass), Dichanthium fecundum (Bluegrass) grassland.	0.02(198)	0.02(198)	0(316)	0(316)	0(314)	0(314)	0.02(316)	0.02(316)
99	Enneapogon purpurascens (Nine Awn Grass) grassland.	0(2)	0(2)	0(2)	0(2)	0(2)	0(2)	0(2)	0(2)
100	Eragrostis xerophila (Neverfail) open-grassland with scattered trees and shrubs.	0(2)	0(0)	0(2)	0(0)	0(2)	0(0)	0(2)	0(0)
101	Seasonal grassland with Muehlenbeckia cunninghamii (Lignum) low sparse-shrubland overstorey.	0(1)	0(1)	0(1)	0(1)	0(1)	0(1)	0(1)	0(1)
102	Coastal dune complex.	0.02(50)	0.02(50)	0(51)	0(51)	0(50)	0(50)	0(51)	0(51)
103	Vetiveria elongata grassland.	0(3)	0(3)	0(3)	0(3)	0(3)	0(3)	0(3)	0(3)
104	Xerochloa (Rice Grass) grassland.	0(9)	0(9)	0(23)	0(23)	0(23)	0(23)	0(23)	0(23)
105	Mangal low closed-forest (Mangroves).	0.06(16)	0.06(16)	0.01(32)	0.01(32)	0.01(32)	0.01(32)	0.04(32)	0.04(32)
106	Saline tidal flats with scattered chenopod low shrubland (Samphire).	0.05(86)	0(86)	0.03(137)	0.03(137)	0.02(136)	0.02(136)	0.25(137)	0.25(137)
107	Chenopodium auricomum (Bluebush) low open-shrubland with ephemeral grassland understorey.	0(29)	0(27)	0(35)	0(32)	0(35)	0(32)	0(35)	0(32)
108	Maireana astrotricha (Southern Bluebush) low open-shrubland with ephemeral open-herb/grassland.	0(16)	0(0)	0(16)	0(0)	0(16)	0(0)	0(16)	0(0)
109	Chenopod open-herbland with ephemeral open-herb/grassland.	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)
110	Atriplex vesicaria (Bladder Saltbush) low sparse-shrubland with ephemeral open-herb/grassland.	0(2)	0(0)	0(2)	0(0)	0(2)	0(0)	0(2)	0(0)
111	Halosarcia (Samphire) low open-shrubland fringing bare salt pans.	0(3)	0(1)	0(3)	0(1)	0(3)	0(1)	0(3)	0(1)
112	Bare salt pan.	0(2)	0(0)	0(2)	0(0)	0(2)	0(0)	0(2)	0(0)

Of this biomass,

- 40.44 x 10^6 tonnes (42.6%) is in Aboriginal lands;
- 34.39 x 10^6 tonnes (36.2%) is in pastoral leasehold;
- 10.59 x 10^6 tonnes (11.2%) is in conservation reserves; and
- 9.52 x 10^6 tonnes (10.0%) is in other land tenures.

Quadrat-based environmental models

1716 sites had data for all four of the variables considered (soil texture, soil depth, rock cover and slope), of which 1109 sites also had real absence/presence data, 1715 had an assessment of ironwood basal area and 1546 had an assessment of basal area for trees >20 cm DBH.

Univariate responses to the four environmental variables assessed consistently across sufficient quadrats are presented in Fig. 4.8. Note that there are some substantial variations in the pattern of relationships with environmental variables between incidence, basal area and basal area of trees>20 cm DBH only. For example, while incidence and basal area of ironwood is greatest in rockiest sites, the least rock sites supported the highest basal area of larger trees. Likewise, while ironwood occurred almost equally across soil depth classes, larger trees were particularly well represented in sites with the deepest soils.

Presence/absence

Of the four terms considered (soil texture, soil depth, slope and rock cover), soil texture was by far the best predictor of ironwood presence (Table 4.2a), but the explanatory power was not high (15.5%). Slope and rock cover were also significantly (at $p<0.01$) associated with presence, but the addition of these terms to the model resulted in little increase in explanatory power (Table 4.2b). Soil depth did not contribute significantly to the model. The most critical component of the presence/absence models was sandy-loam soils, which were closely linked with high probability of ironwood occurrence. The composite model included a weak negative relationship with rock cover and weak positive relationship with slope.

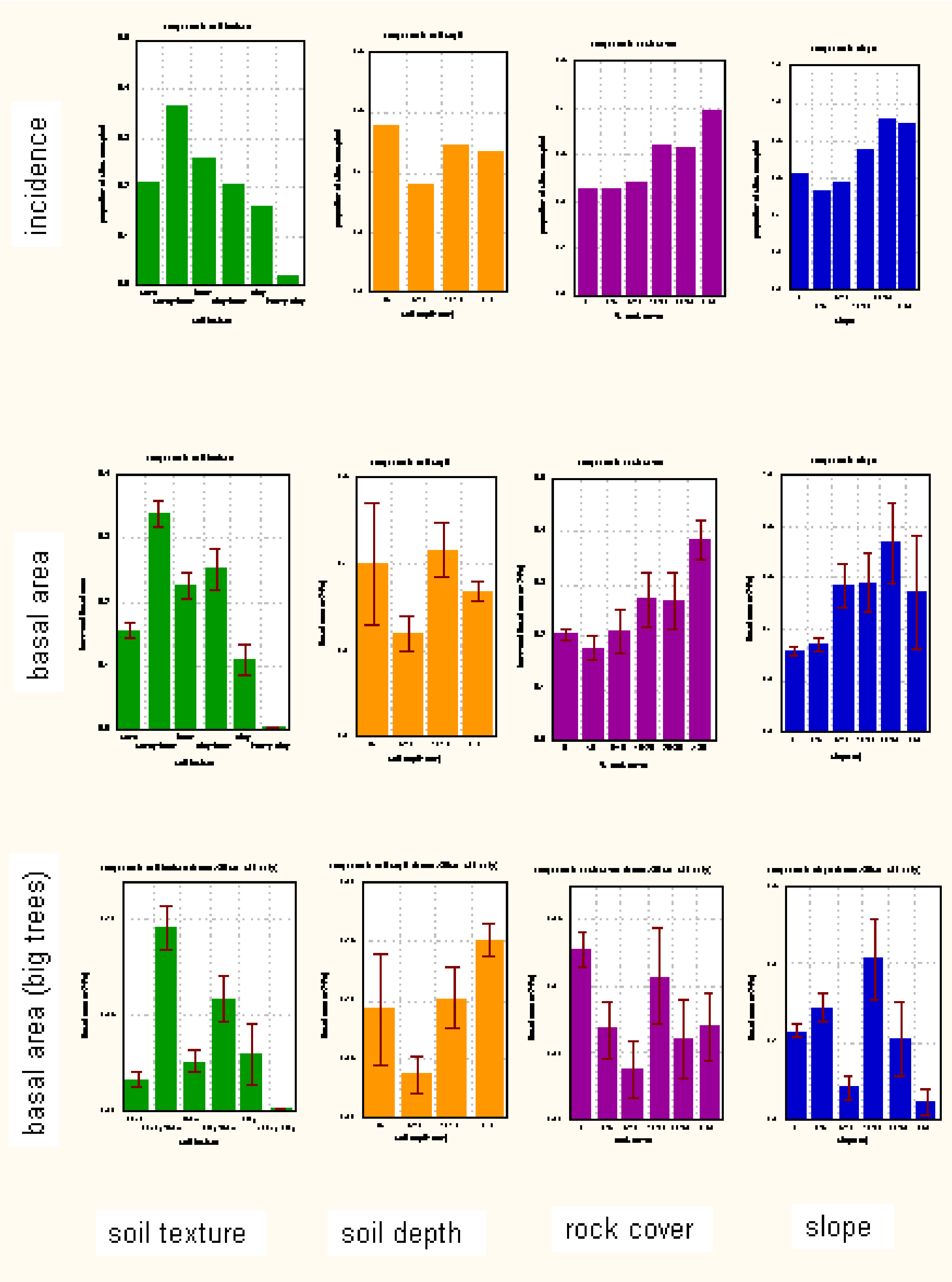


Fig. 4.8. Univariate relationships between incidence and basal area of ironwood and four environmental factors assessed at sites during sampling. Columns represent means, and whiskers (for basal area) signify standard errors.

Table 4.2a. Summary of model for incidence of ironwood and environmental variables (measured at the sample site): best single factor model.

MODEL: **presence/absence - best single-term model**
N= 1109 *total deviance*=1527.1 *residual deviance*=1289.8 *explained deviance*=15.5%

Term	df	Wald statistic	p	Category	Estimate	s.e.	p
Intercept	1	40.8	<.000001		-.787	.123	
Soil texture	5	179.5	<.000001	sand	-.215	.160	.179
(*heavy clay* aliased)				sandy-loam	1.659	.153	<.000001
				loam	.300	.183	.1008
				clay loam	1.133	.200	<.000001
				clay	-.513	.293	.080

Table 4.2b. Summary of model for incidence of ironwood and environmental variables (measured at the sample site): minimum adequate model.

MODEL: **presence/absence - minimum adequate model**
N=1109 *total deviance*= 1527.1 *residual deviance*= 1277.7 *explained deviance*=16.3%

Term	df	Wald statistic	p	Category	Estimate	s.e.	p
Intercept	1	37.7	<.000001		-.783	.128	
Rock cover	1	9.0	.0028		-.0121	.00405	
Slope	1	7.2	.0074		.0454	.0169	
Soil texture	5	169.7	<.000001	sand	-.206	.162	.205
(*heavy clay* aliased)				sandy-loam	1.625	.154	<.000001
				loam	.349	.184	.084
				clay loam	-.0121	.0041	.0028
				clay	.0454	.0169	.0074

Basal area

The best single-term model for basal area also involved soil texture, and this explained 11.8% of the deviance (Table 4.3a). In the multiple term model, (Table 4.3b) slope and soil depth were also significant, although their contribution added only a further 0.9% to the deviance explained by the single factor model.

The model for basal area of trees >20 cm DBH alone largely recapitulated that for total basal area, with soil texture being the best single term (significant at p<0.000001 but explaining only 10.8% of the deviance: Table 4.4a), and two of the three other terms also significant but together explaining only another 1.5% of deviance (Table 4.4b).

Table 4.3a. Summary of model for ironwood basal area and environmental variables (measured at the sample site): best single factor model.

MODEL: **basal area - best single term model**
N= 1715 *total deviance*=2244.5 *residual deviance*=1979.4 *explained deviance*=11.8%

Term	df	Wald statistic	p	Category	Estimate	s.e.	p
Intercept	1	82.1	<.000001		-1.980	.219	
Soil texture	5	130.8	<.000001	sand	.558	.235	.0174
(*heavy clay* aliased)				sandy-loam	1.522	.222	<.000001
				loam	.746	.243	.0021
				clay loam	1.069	.234	.000005
				clay	-.2766	.330	.402

Table 4.3b. Summary of model for ironwood basal area and environmental variables (measured at the sample site): minimum adequate model.

MODEL: **basal area - minimum adequate model**
N=1715 *total deviance*= 2244.5 *residual deviance*= 1960.4 *explained deviance*=12.7%

Term	df	Wald statistic	p	Category	Estimate	s.e.	p
Intercept	1	78.8	<.000001		-2.123	.239	
Soil depth	3	11.0	.012	<5cm	.247	.244	.312
(*soil depth >40cm* aliased)				5-10cm	-.560	.181	.00194
				10-40cm	.194	.120	.104
Slope	1	8.8	.0030		.0201	.0068	
Soil texture	5	121.2	<.000001	sand	.569	.235	.016
(*heavy clay* aliased)				sandy-loam	1.494	.223	<.000001
				loam	.754	.243	.0019
				clay loam	1.063	.234	.000006
				clay	-.275	.330	.406

GIS-based models

A total of 13,628 samples were included in GIS-based distributional modeling. Note that for the surficial geology, only seven samples fell within one class (limestone: terrestrial; minor sand and clay), and because of this low representation these samples were discarded.

Univariate responses of basal area of ironwood to a range of variables are illustrated in Fig. 4.9.

Table 4.4a. Summary of model for basal area of big ironwood trees (>20 cm DBH only) and environmental variables (measured at the sample site): best single factor model.

MODEL: **basal area of trees >20cm DBH - best single term model**
N= 1564 *total deviance*=1171.1 *residual deviance*=1045.2 *explained deviance*=10.8%

Term	df	Wald statistic	p	Category	Estimate	s.e.	p
Intercept	1	93.1	<.000001		-2.74	.283	
Soil texture	5	66.0	<.000001	sand	.309	.322	.337
(*heavy clay* aliased)				sandy-loam	1.485	.291	<.000001
				loam	.166	.360	.645
				clay loam	1.214	.307	.000076
				clay	.194	.406	.632

Table 4.4b. Summary of model for basal area of big ironwood trees (>20 cm DBH only) and environmental variables (measured at sample site): minimum adequate model.

MODEL: **basal area of trees >20 cm DBH - minimum adequate model**
N=1564 *total deviance*= 1171.1 *residual deviance*= 1027.3 *explained deviance*=12.3%

Term	df	Wald statistic	p	Category	Estimate	s.e.	p
Intercept	1	88.7	<.000001		-2.68	.285	
Rock cover	1	12.8	.00035		-.027	.0077	
Sope	1	4.7	.030		.0295	.0136	
Soil texture	5	59.7	<.000001	sand	.388	.322	.230
(*heavy clay* aliased)				sandy-loam	1.468	.291	<.000001
				loam	.236	.361	.512
				clay loam	1.183	.307	.00012
				clay	.134	.406	.742

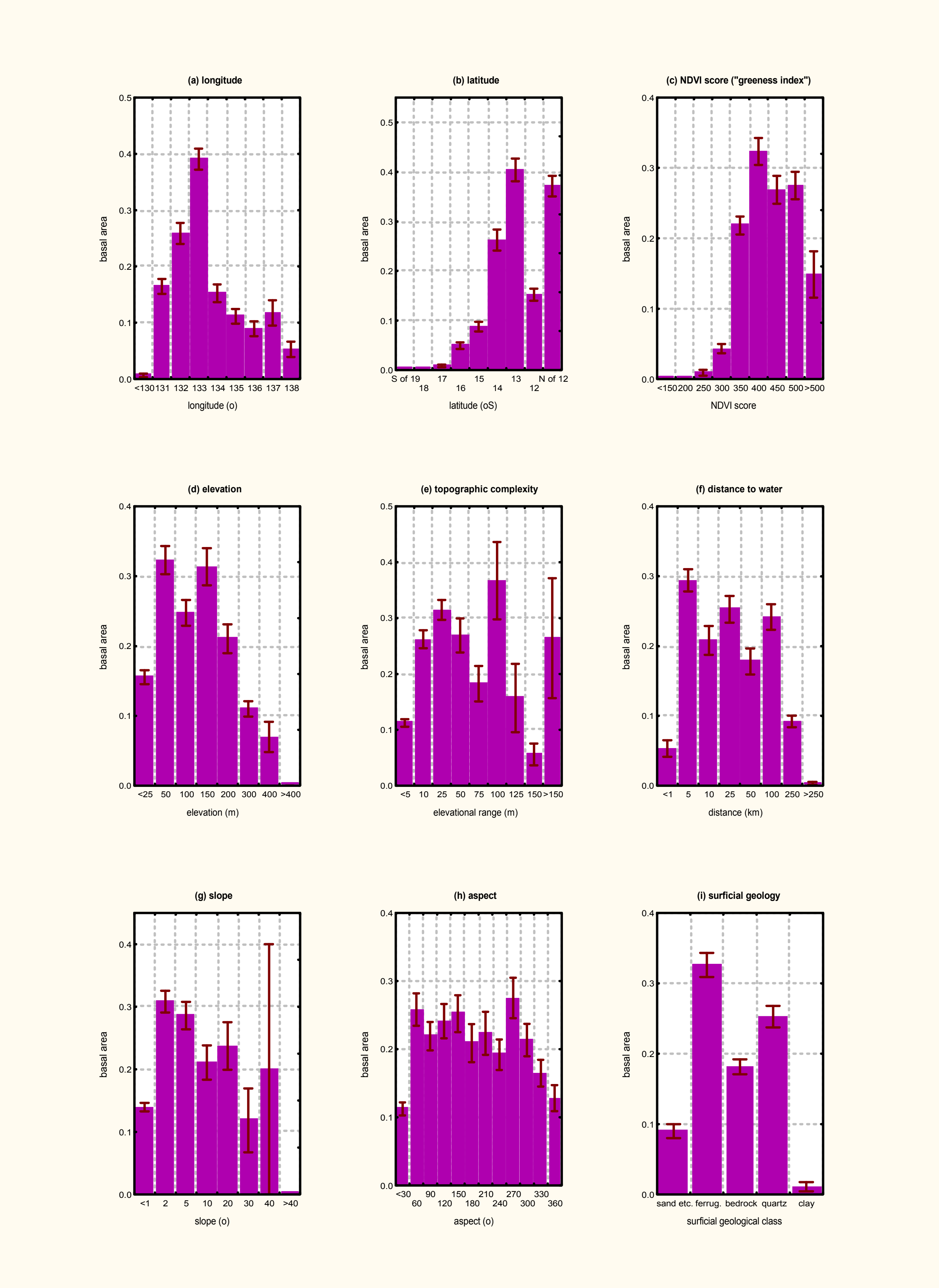


Fig. 4.9. Univariate relationships between incidence and basal area of ironwood and a set of climatic, locational, edaphic and other factors interpolated from GIS layers. Columns represent means, and whiskers (for basal area) signify standard error.

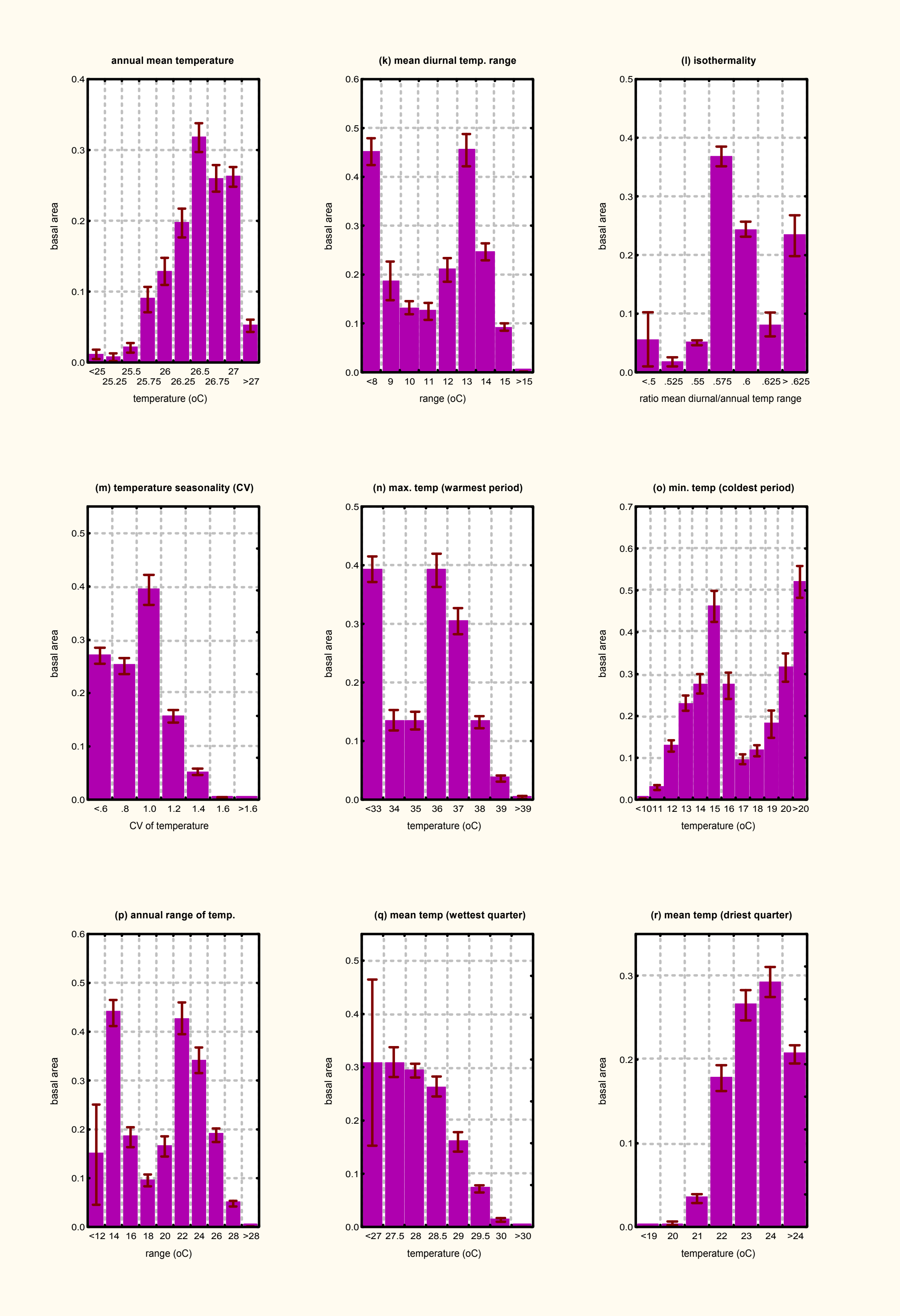


Fig. 4.9. continued

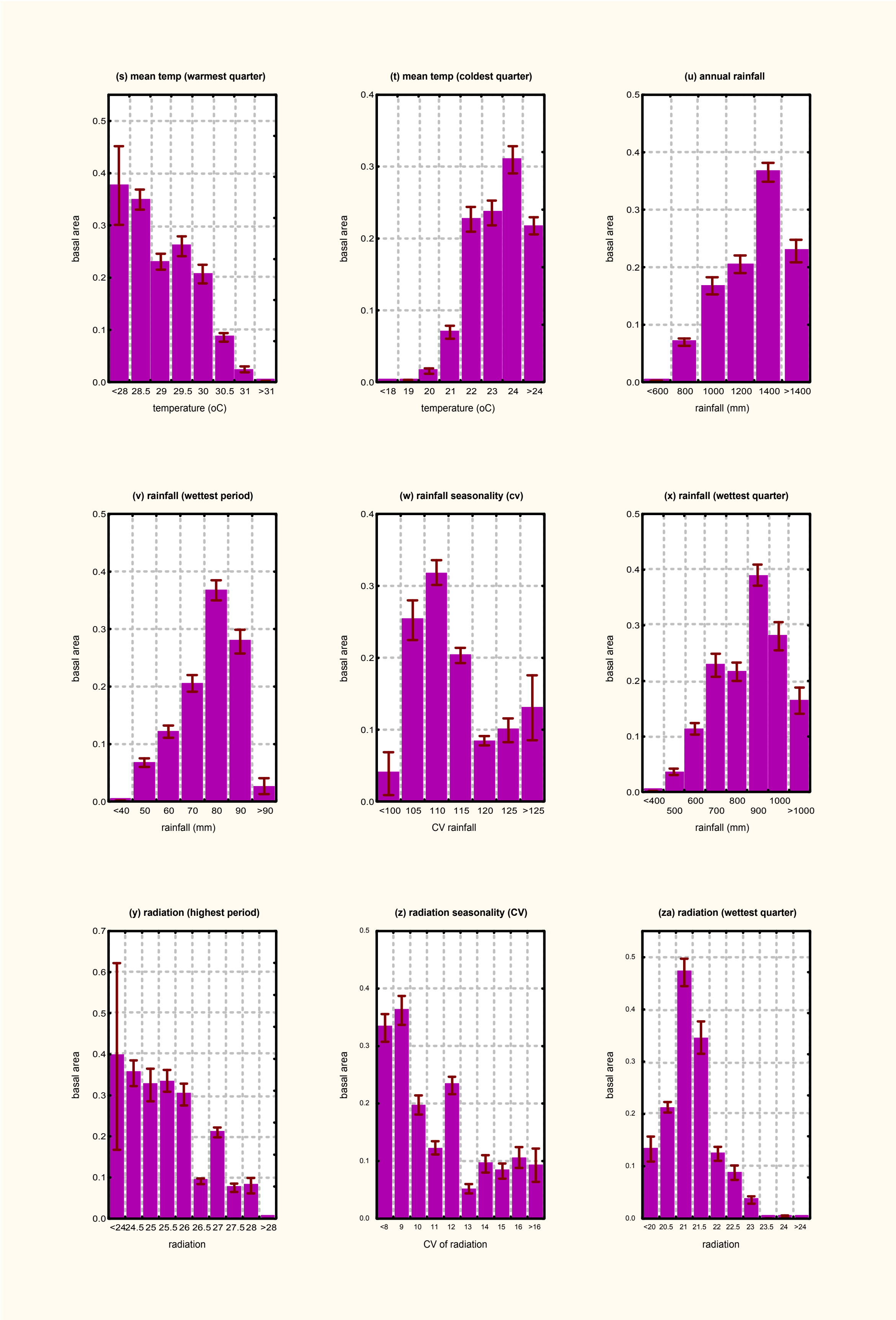


Fig. 4.9. continued

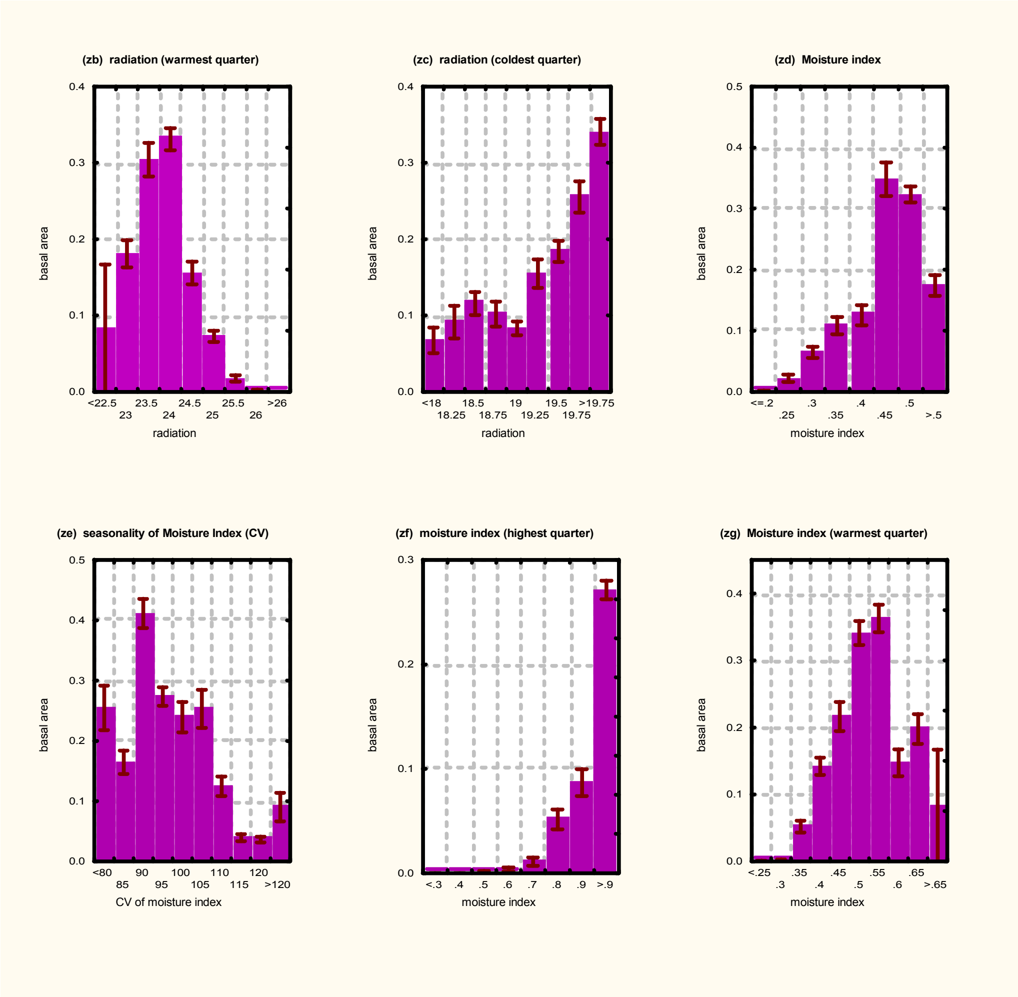


Fig. 4.9. continued

There is a strong geographic response, with ironwood being especially prevalent in a narrow latitudinal strip between 130 and 134°E (the Katherine-Darwin belt) and also generally increasing in prevalence further northward (with the notable exception of the 12-13°S latitude, where our data set included a relatively high proportion of samples from the treeless floodplains between Darwin and Jabiru). Ironwood was associated with relatively high NDVI values, although this response was humped, with a decrease in the wettest areas. Basal area of ironwood was highest at altitudes between 25 and 200m, and was virtually absent at altitudes above 400m: to some extent this reflects the conjunction of geographic, topographic and climatic variables, with altitude generally rising towards the driest southern edge of the study area. There was no apparent relationship with topographical complexity, slope nor distance to water, with no suggestion that flatter areas close to water are favoured. There was a weak tendency for ironwood to have least basal area on north-facing slopes. Ironwood was strongly associated with surficial geology, even at the coarse scale here considered, with marked preference for ferruginous and quartz substrates, and avoidance of clay. Basal area was highest at sites with moderately high annual mean temperature, especially in the coldest and driest quarter; but at sites with relatively low temperatures in the warmest and wettest quarter, and hence relatively low temperature seasonality. Association with rainfall and with the moisture index was analogous with that of annual mean temperature, with highest basal area in sites with moderately high (but not highest) rainfall and moisture indices. Basal area peaked at sites with relatively low values for radiation, except that basal area was greatest at sites with highest radiation scores in the coldest quarter.

Notwithstanding these apparently clear relationships between ironwood and many of the climatic, locational and other variables considered, the minimum adequate model for ironwood presence was weak, with only 17% of the deviance explained (Table 4.5).

The most significant terms in this model are mean moisture index of the highest quarter (positively associated with ironwood incidence) and tree height (positively associated).

The distribution map based upon this model is shown in Fig. 4.10. This map suggests that ironwood is most common in the north east portion of the Top End, particularly in a strip of country stretching from the source of the Moyle River through to central Arnhem Land and including may coastal areas and larger islands.

The minimum adequate model for basal area of ironwood is summarised in Table 4.6. The six factors of this model explained almost 20% of the deviance, with especially strong relationships for latitude, moisture index (highest quarter), radiation (highest period) and minimum temperature (coldest quarter). Note that there are high intercorrelations among many of these included variables, which explains, for example, why the estimate for rainfall is negative. Soil texture, even at the coarse scale here measured, was also highly significant, with basal area especially high in ìferruginousî soils and low in ìsandî.

Table 4.5. Summary of model for incidence of ironwood and environmental variables (derived from GIS): minimum adequate model.

MODEL: **incidence - minimum adequate model**
N=12512 *total deviance*= 13504 *residual deviance*= 11174 *explained deviance*= 17.3%

Term	df	Wald statistic	p	Category	Estimate	s.e.	p
Intercept	1	12.1	<.001		5.00	1.43	
NDVI	1	91.47	<.000001		-0.004	0.0004	
Tree height	1	194.57	<.000001		0.083	0.005	
Annual mean temperature	1	165.3	<.000001		-0.737	0.057	
Radiation - lowest period	1	132.14	<.000001		0.377	0.032	
Moisture index - highest qrter	1	582.78	<.000001		7.868	0.553	
Surficial geology	4	89.94	<.001	sand, etc.	-0.45	0.08	<.001
(*clay, silt etc*. aliased)				ferruginous, etc.	0.602	0.08	<.001
				bedrock	0.111	0.07	0.135
				quartz, sand	0.1	0.07	0.194

Table 4.6. Summary of model for basal area of ironwood and environmental variables (derived from GIS): minimum adequate model.

MODEL: **basal area - minimum adequate model**
N=12512 *total deviance*= 11352 *residual deviance*= 9148 *explained deviance*=19.4%

Term	df	Wald statistic	p	Category	Estimate	s.e.	p
Intercept	1	147.3	<.000001		36.931	3.043	
Latitude	1	171.5	<.000001		0.893	0.068	
Mean temp - coldest qrter	1	171.4	<.000001		-0.621	0.047	
Annual rainfall	1	78.9	<.000001		-0.00284	0.00032	
Radiation - highest period	1	159.3	<.000001		-0.633	0.050	
Moisture index - highest qrter	1	197.9	<.000001		7.784	0.553	
Surficial geology	4	308.0	<.000001	sand, etc.	-0.809	0.098	<.000001
(*clay, silt etc*. aliased)				ferruginous, etc.	0.541	0.092	<.000001
				bedrock	0.070	0.089	.433
				quartz, sand	0.180	0.090	.045

Table 4.7. Summary of model for basal area of big ironwood trees (>20 cm DBH only) and environmental variables (derived from GIS): minimum adequate model.

MODEL: **basal area (trees >20 cm DBH only) - minimum adequate model**
N=11128 *total deviance*=3249 *residual deviance*= 2286 *explained deviance*=29.6%

Term	df	Wald statistic	p	Category	Estimate	s.e.	p
Intercept	1	47.0	<.000001		-46.22	6.74	
Latitude	1	172.3	<.000001		2.218	0.169	
Min temp - coldest qrter	1	187.4	<.000001		-1.149	0.084	
Radiation - coldest quarter	1	111.1	<.000001		2.940	0.279	
Radiation - 1 highest period	124.2	<.000001		1.262	0.113		
Surficial geology (*clay, silt etc*. aliased)	4	153.6	<.000001	sand, etc.	-0.421	0.236	.075
				ferruginous, etc	1.130	0.223	<.000001
				bedrock	-0.693	0.245	.0046
				quartz, sand	0.0822	0.230	.721

The distribution of ironwood basal area based on this model is shown in Figure 4.11. This map attributes the highest density of ironwood to the plateau country north of the Fitzmaurice River, a small area to the East of Litchfield National Park as well as the uplands lying between the Adelaide and Mary River floodplains.

The minimum adequate model for basal area of ironwood trees >20 cm DBH only is summarised in Table 4.7. The five factors of this model explained almost 30% of the deviance, again with especially strong relationships for latitude, radiation (highest period) and minimum temperature (coldest quarter). Soil texture, even at the coarse scale here measured, was also highly significant, with basal area especially high in ìferruginousî soils and low in ìbedrockî.

The distribution of basal area of big ironwood trees (>20 cm DBH only) based on this model is shown in Fig. 4.12. This maps suggests that the highest density of large Ironwood trees is to be found in an area stretching west from Katherine through to the plateau country at the source of the Moyle River.

Discussion

This review and analysis of a large data set shows clearly that ironwood is an extremely widespread species across the Top End of the Northern Territory, occurring in most environments other than grasslands on cracking clay soils.

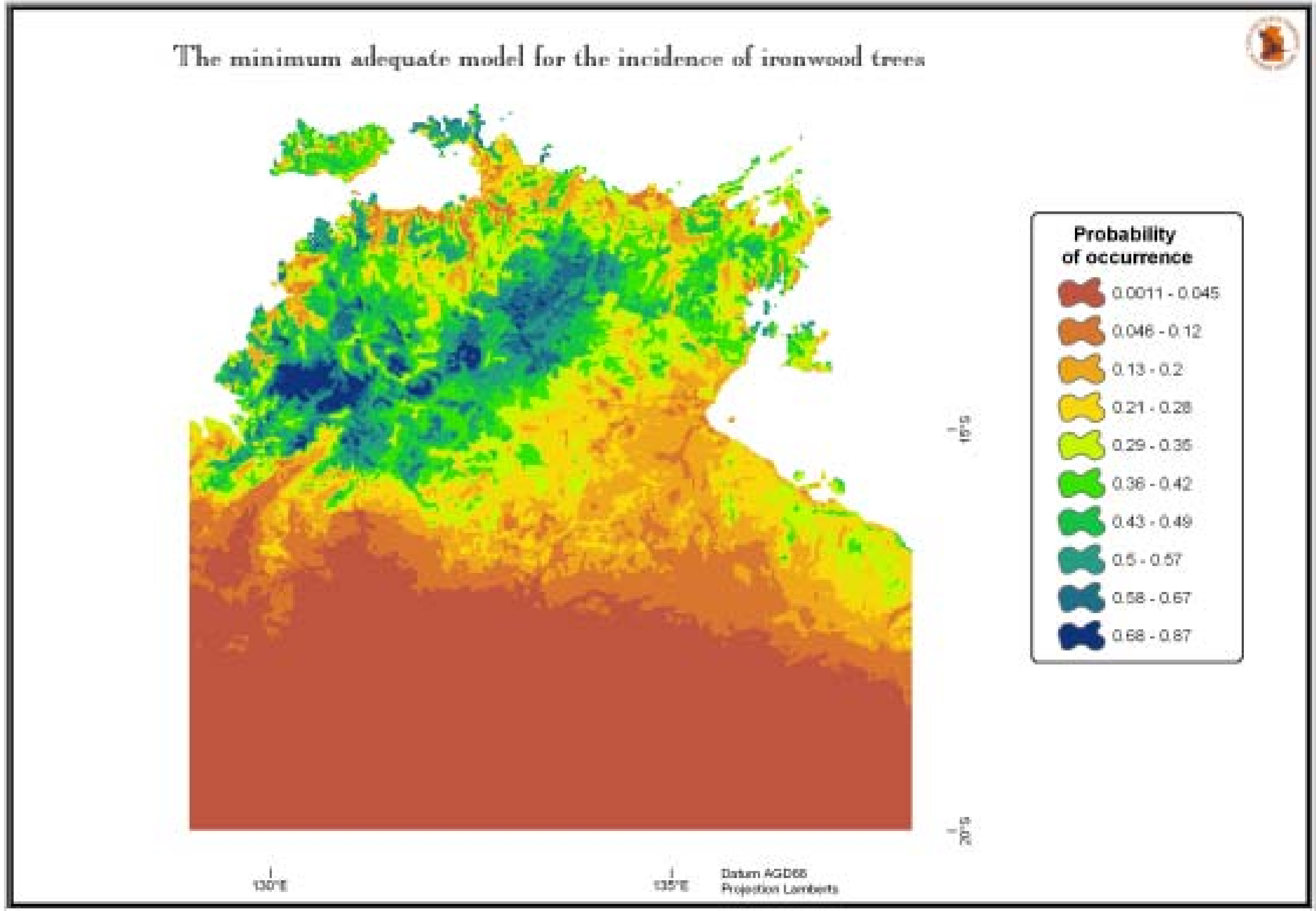


Figure 4.10. The probability of occurrence of ironwood.

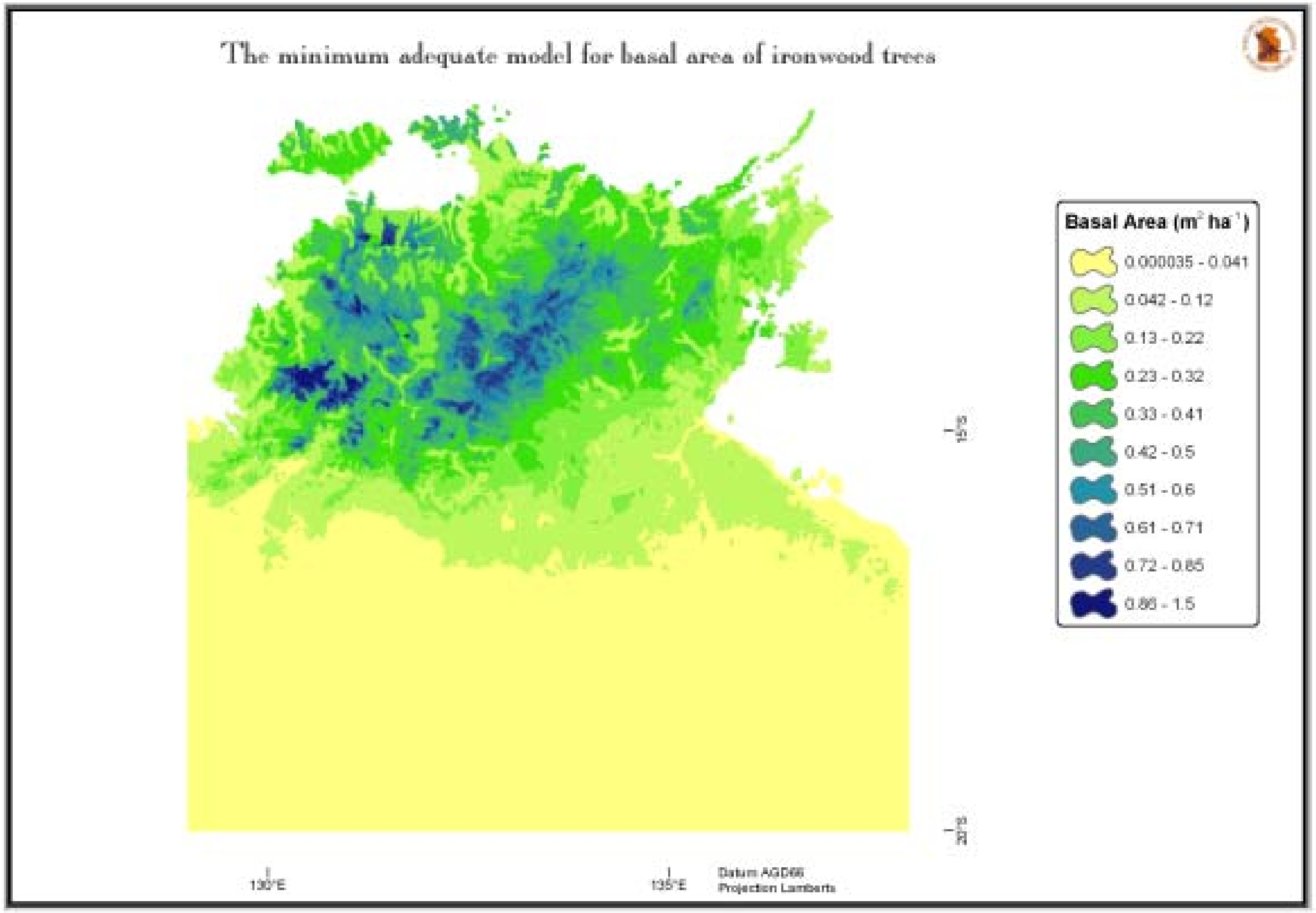


Figure 4.11. The distribution of basal area of ironwood.

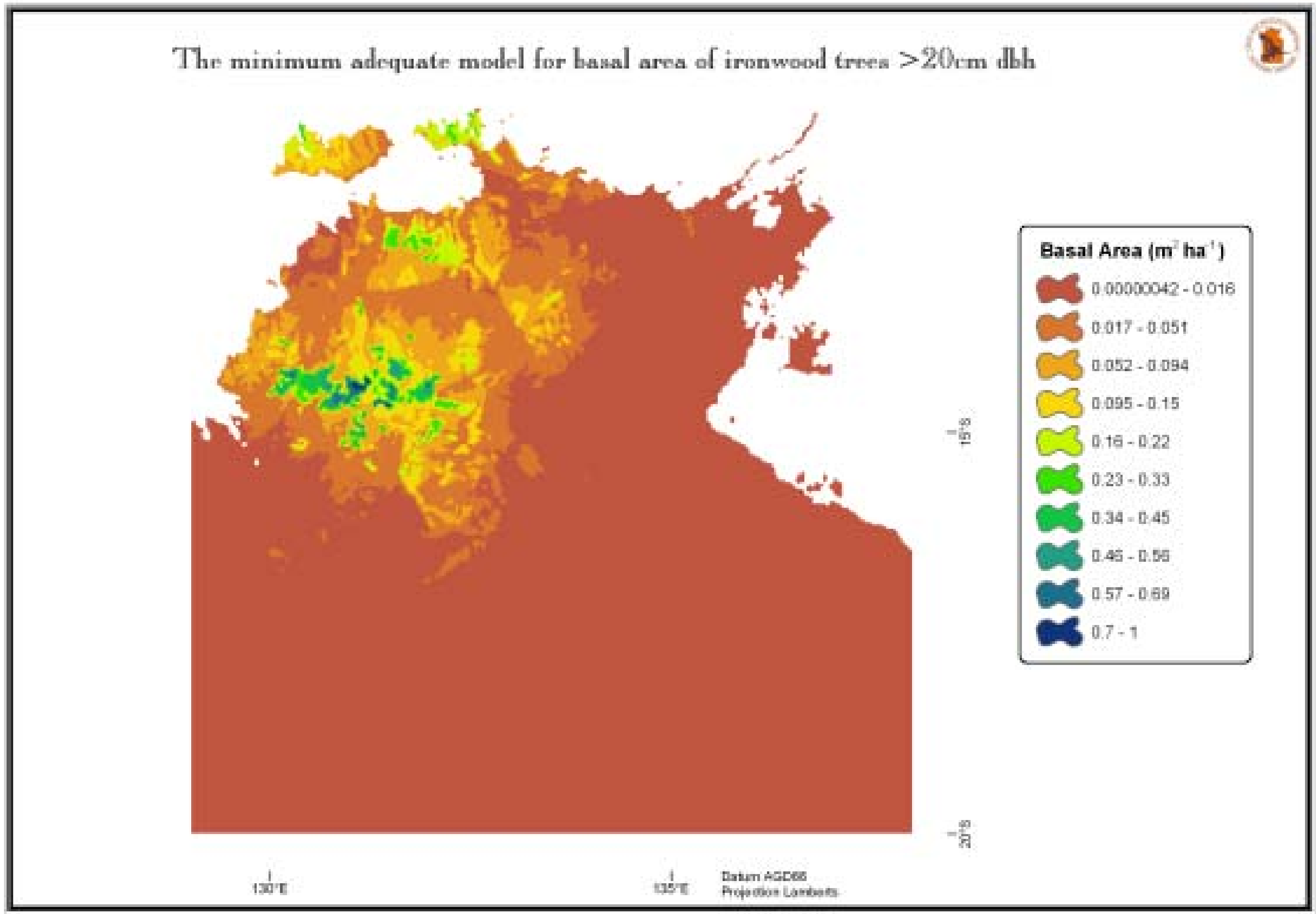


Fig. 4.12. The distribution of basal area of big ironwood (>20 cm DBH).

Within this broad range, it is possible to identify factors which are associated with variation in basal area and incidence. However, the precision of this modeling is hampered by four factors:

- the very breadth of its ecological tolerance within this region;
- the coarseness of the only available coverages for some environmental factors (most notably surficial geology and soil features);
- the likelihood of large difference between potential and realised basal area at many sites, because of the influence of fire history;
- the broad network of intercorrelated climatic and locational variables in the Top End generally, which simplifies distributional modeling but hampers the identification of particular causal factors; and
- some inconsistencies in sampling procedures and locational precision among our data sets.

Our judicious scrutiny of quirks in the data sets minimised the influence of the last factor as much as possible, but this involved a balancing of data set size and quality.

The highly interwoven network of climatic and geographic factors in the Top End has been previously and widely noted (e.g. Whitehead 1992; Bowman 1996; Bowman and Connors 1996). The intercorrelations are so strong that it is almost impossible to disentangle causative factors from a host of other linked factors. This is not a major problem for predicting distribution within the region, but it is a problem when the factors are packaged differently. Thus, the strength of intercorrelation hampers any extrapolation from this region to others where the matrix of climatic, altitudinal and other factors is different, the prediction of response to climate change, and the interpretation of functionality among the observed correlations.

Notwithstanding these problems, the modeling provides significant insight into the patterning of occurrence and abundance of ironwood. Modeling based on the few environmental variables measured at sample sites demonstrated that soil texture was a major determinant of the incidence and basal area of ironwood, with this relationship somewhat modified by rock cover, slope and soil depth. Although occurring across all soil textures, ironwood had highest incidence and largest basal area on sandy-loam soils and least on cracking clay soils. This association is consistent with the set of published studies which have (generally incidentally) also reported avoidance of heavy clays and preference for medium-textured soils.

Given the lack of fine-scale soil/substrate mapping available for this region, our GIS-based models would always lose much explanatory power. Nonetheless, they provided a good complement to the modeling based on quadrat-based variables, with highly significant associations between ironwood basal area and a small array of locational and climatic factors. Ironwood appears to be sensitive to cold (e.g. is best developed in areas where the mean temperatures in the coldest quarter is relatively high (generally >21^{o}C)), and prefers areas with moderately high rainfall and moisture indices (but with a decrease in areas where annual rainfall >1400mm).

Ironwood is also shown to be concentrated in a broad lowland band between Katherine and Darwin, on the Tiwi Islands and on Cobourg Peninsula. To a large extent this coincides with previous identification of the most highly productive lands in the Northern Territory. The Daly Basin and Katherine-Darwin region has long been recognised as environmentally distinct from other areas of the Top End, and as the prime area for agricultural development, not least because of its deep sandy-loam soils and high water availability (Christian and Stewart 1953), in part the factors shown here to be best associated with ironwood development. Likewise, plantation forestry is considered to be most likely to develop on the Tiwi Islands, again because of the extent of deep sandy-loam soils and high rainfall (ForSci 1999). This conjunction of development potential with areas of best development of ironwood suggests that there may be some resource conflicts liable to develop.

We consider it likely that a major source of noise in our models is the substantial influence of fire regimes on the variation between potential basal area at any given site and the actual value. Ironwood is one of the most fire-sensitive tree species in the savanna woodlands and open forests of northern Australia. Indeed, given its remarkable tolerance to edaphic and climatic factors, it may well be that it would be the dominant species across most of these environments were it not for the prevailing fire regime. Thus at any one site, ironwood may have a high basal area of trees and shrubs when fire is infrequent or excluded, or it may have a very low basal area of trees and a dense suppressed ground (sucker) layer if exposed to frequent fire. The importance of prevailing fire regime renders distributional modeling based on static features somewhat compromised. It also means that any attempt at sustainable use of ironwood resources must focus substantially on fire management.

References

Bowman, D.M.J.S. (1986). Stand characteristics, understorey associates and environmental correlates of *Eucalyptus tetrodonta* F. Muell. forests on Gunn Point, northern Australia. *Vegetatio* **65**, 105-113.

Bowman, D.M.J.S. (1988). Stability amid turmoil?: towards and ecology of north Australian eucalypt forests. *Proceedings of the Ecological Society of Australia* **15**, 149-158.

Bowman, D.M.J.S. (1991). Environmental determinants of *Allosyncarpia ternata* forests that are endemic to western Arnhem Land, northern Australia. *Australian Journal of Botany* **39**, 575-589.

Bowman, D.M.J.S. (1994). Preliminary observations on the mortality of *Allosyncarpia ternata* stems on the Arnhem Land Plateau, northern Australia. *Australian Forestry* **57**, 62-64.

Bowman, D.M.J.S. (1996). Diversity patterns of woody species on a latitudinal transect from the monsoon tropics to desert in the Northern Territory, Australia. *Australian Journal of Botany* **44**, 571-580.

Bowman, D.M.J.S. and Connors, G.T. (1996). Does low temperature cause the dominance of *Acacia* on the central Australian mountains?: evidence from latitudinal gradient from 11° to 26° South in the Northern Territory, Australia. *Journal of Biogeography* **23**, 245-256.

Bowman, D.M.J.S. and Dunlop, C.R. (1986). Vegetation pattern and environmental correlates in coastal forests of the Australian monsoon tropics. *Vegetatio* **65**, 99-104.

Bowman, D.M.J.S. and McDonough, L. (1991). Tree species distribution across a seasonally flooded elevation gradient in the Australian monsoon tropics. *Journal of Biogeography* **18**, 203-212.

Bowman, D.M.J.S. and Minchin, P.R. (1987). Environmental relationships of woody vegetation patterns in the Australian monsoon tropics. *Australian Journal of Botany* **35**, 151-169.

Bowman, D.M.J.S. and Panton, W.J. (1993). Decline of *Callitris intratropica* R.T. Baker & H.G. Smith in the Northern Territory: implications for pre- and post-European colonization fire regimes. *Journal of Biogeography* **20**, 373-381.

Bowman, D.M.J.S. and Panton, W.J. (1995). Munmarlary revisited: response of a north Australian *Eucalyptus tetrodonta* savanna protected from fire for 20 years. *Australian Journal of Ecology* **20**, 526-531.

Bowman, D.M.J.S. and Wightman, G.M. (1985). Small scale vegetation pattern associated with a deeply incised gully, Gunn Point, northern Australia. *Proceedings of the Royal Society of Queensland* **96**, 63-73.

Bowman, D.M.J.S., Wilson, B.A. and Hooper, R.J. (1988*a*). Response of *Eucalyptus* forest and woodland to four fire regimes at Munmarlary, Northern Territory, Australia. *Journal of Ecology* **76**, 215-232.

Bowman, D.M.J.S., Wilson, B.A. and Dunlop, C.R. (1988*b*). Preliminary biogeographic analysis of the Northern Territory vascular flora. *Australian Journal of Botany* **36**, 503-517.

Bowman, D.M.J.S., Wilson, B.A. and Wilson, P.L. (1988*c*). Floristic reconnaissance of the northern portion of the Gregory National Park, Northern Territory, Australia. *Journal of the Royal Society of Western Australia* **70**, 57-67.

Bowman, D.M.J.S., Wilson, B.A., and Fensham, R.J. (1990). Sandstone vegetation pattern in the Jim Jim Falls region, Northern Territory, Australia. *Australian Journal of Ecology* **15**, 163-174.

Bowman, D.M.J.S., Wilson, B.A. and Woinarski, J.C.Z. (1991). Floristic and phenological variation in a northern Australian rocky *Eucalyptus* savanna. *Proceedings of the Royal Society of Queensland* **101**, 79-90.

Bowman, D.M.J.S., Woinarski, J.C.Z. and Menkhorst, K.A. (1993). Environmental correlates of tree species diversity in Stage III of Kakadu National Park, northern Australia. *Australian Journal of Botany* **41**, 649-660.

Bureau of Rural Sciences after Australian Geological Survey Organisation (1991). *Digital Version of the 1976 Edition of Geology of Australia, 1:2 500 000 Scale* (ARC/INFO[Æ] vector format). [Online] Available HTML: http://www.brs.gov.au/data/datasets

Burgman, M.A. and Thompson, E.J. (1982). Cluster analysis, ordination and dominance-structural classification applied to diverse tropical vegetation at Jabiluka, Northern Territory. *Australian Journal of Ecology* **7**, 375-387.

Christian, C.S. and Stewart, G.A. (1953). General report on survey of Katherine-Darwin region, 1946. *CSIRO Land Research Series no. 1*. (CSIRO: Canberra.)

Eamus, D., Berryman, C.A. and Duff, G.A. (1995a). Photosynthetic responses to temperature, light flux density, CO_2 concentration and vapour pressure deficit in *Eucalyptus tetrodonta* grown under CO_2 enrichment. *Environmental Pollution* **90**, 41-49.

Eamus, D., Berryman, C.A. and Duff, G.A. (1995b). The impact of CO_2 enhancement on water relations of *Maranthes corymbosa* and *Eucalyptus tetrodonta. Australian Journal of Botany* **43**, 273-282.

Fensham, R.J. (1990). Interactive effects of fire frequency and site factors in tropical *Eucalyptus* forest near Darwin, northern Australia. *Australian Journal of Ecology* **15**, 255-266.

Fensham, R.J. (1993). The environmental relations of vegetation pattern on chenier beach ridges on Bathurst Island, Northern Territory. *Australian Journal of Botany* **41**, 275-291.

Fensham, R.J. and Bowman, D.M.J.S. (1992). Stand structure and the influence of overwood on regeneration in tropical eucalypt forest on Melville Island. *Australian Journal of Botany* **40**, 335-352.

Fordyce, I.R., Duff, G.A. and Eamus, D. (1995). The ecophysiology of *Allosyncarpia ternata* (Myrtaceae) in northern Australia: tree physiognomy, leaf characteristics and assimilation at contrasting sites. *Australian Journal of Botany* **43**, 367-377.

Fordyce, I.R., Eamus, D., Duff, G.A.,and Williams, R.J. (1997a). The role of seedling age and size in the recovery of *Allosyncarpia ternata* following fire. *Australian Journal of Ecology* **22**, 262-269.

Fordyce, I.R., Duff, G.A. and Eamus, D. (1997b). The water relations of *Allosyncarpia ternata* (Myrtaceae) at contrasting sites in the monsoonal tropics of northern Australia. *Australian Journal of Botany* **45**, 259-274.

ForSci Pty Ltd (1999). *Environmental impact assessment of establishment of fast grown plantations on the Tiwi Islands*. (ForSci: Sydney.)

Hatton, T., Taylor, P. and McEwan, K. (1998). Does leaf water efficiency vary among eucalypts in water-limited environments? *Tree Physiology* **18**, 529-536.

Kirkpatrick, J.B., Bowman, D.M.J.S., Wilson, B.A. and Dickinson, K.J.M. (1987). A transect study of the *Eucalyptus* forests and woodlands of a dissected sandstone and laterite plateau near Darwin, Northern Territory. *Australian Journal of Ecology* **12**, 339-359.

Kirkpatrick, J.B., Fensham, R.J., Nunez, M. and Bowman, D.M.J.S. (1988). Vegetation-radiation relationships in the wet-dry tropics: granite hills in northern Australia. *Vegetatio* **76**, 103-112.

Langkamp, P.J., Ashton, D.H. and Dalling, M.J. (1981). Ecological gradients in forest communities on Groote Eylandt, Northern Territory, Australia. *Vegetatio* **48**, 27-46.

Mueller-Dombois, D. and Ellenberg, H. (1974). *Aims and Methods of Vegetation Ecology*. (Wiley: New York.)

Myers, B.A., Duff, G.A., Eamus, D., Fordyce, I.R., OíGrady, A. and Williams, R.J. (1997). Seasonal variation in water relations of trees of differing leaf phenology in a wet-dry tropical savanna near Darwin, Northern Territory. *Australian Journal of Botany* **45**, 225-240.

Price, O. and Bowman, D.M.J.S. (1994). Fire-stick forestry: a matrix model in support of skilful fire management of *Callitris intratropica* R.T. Baker by north Australian Aborigines. *Journal of Biogeography* **21**, 573-580.

Prior, L.D. and Eamus, D. (1999). Seasonal changes in leaf water characteristics of *Eucalyptus tetrodonta* and *Terminalia ferdinandiana* saplings in a north Australian savanna. *Australian Journal of Botany* **47**, 587-599.

Prior, L.D., Eamus, D. and Duff, G.A. (1997). Seasonal and diurnal patterns of carbon assimilation, stomatal conductance and leaf water potential in *Eucalyptus tetrodonta* saplings in a wet-dry savanna in northern Australia. *Australian Journal of Botany* **45**, 241-258.

Russell-Smith, J., Lucas, D.E., Brock, J. and Bowman, D.M.J.S. (1993). *Allosyncarpia*-dominated rain forest in monsoonal northern Australia. *Journal of Vegetation Science* **4**, 67-82.

Werner, P.A. and Murphy, P.G. (2001). Size-specific biomass allocation and water content of above- and below- ground components of three *Eucalyptus* species in a northern Australian savanna. *Australian Journal of Botany* **49**, 155-167.

Whitehead, P.J. (1992). Biogeographic patterns, environmental correlates and conservation of avifauna in the Northern Territory, Australia. *Journal of Biogeography* **19**, 151-161.

Williams, R.J. and Douglas, M. (1995). Windthrow in a tropical savanna in Kakadu National Park, northern Australia. *Journal of Tropical Ecology* **11**, 547-558.

Williams, R.J., Myers, B.A., Muller, W.J., Duff, G.A. and Eamus, D. (1997). Leaf phenology of woody species in a north Australian tropical savanna. *Ecology* **78**, 2542-2558.

Williams, R.J., Myers, B.A., Eamus, D. and Duff, G.A. (1999a). Reproductive phenology of woody species in a north Australian tropical savanna. *Biotropica* **31**, 626-636.

Williams, R.J., Cook, G.D., Gill, A.M. and Moore, P.H.R. (1999b). Fire regime, fire intensity and tree survival in a tropical savanna in northern Australia. *Australian Journal of Ecology* **24**, 50-59.

Wilson, B.A. and Bowman, D.M.J.S. (1994). Factors influencing tree growth in tropical savanna: studies of an abrupt *Eucalyptus* boundary at Yapilika, Melville Island, northern Australia. *Journal of Tropical Ecology* **10**, 103-120.

Wilson, B.A., Brocklehurst, P.S., Clark, M.J. and Dickinson, K.J.M. (1990). *Vegetation Survey of the Northern Territory, Australia*. Technical report no. 49. (Conservation Commission of the Northern Territory: Darwin.)

Woinarski, J.C.Z., Franklin, D. and Connors, G. (2000). Thinking honeyeater: nectar maps for the Northern Territory, Australia, showing spatial and temporal variation in nectar availability. Pacific Conservation Biology **6,** 61-80.

Appendix 4A. Vegetation data sources compiled for this study.

Data set	*Custodian*	*no. sites*	*Record type* (*e.g. presence-absence, basal area*)	*Environmental variables measured*
Arafura Swamp fauna survey	BAU (Kym Brennan)	88	basal area (4 size classes)	BAU (Appendix 3B)
Auvergne	DLPE	226	basal area; pres-abs	Appendix C
Bradshaw FTA99	BAU	78	basal area (4 size classes), cover, freq	BAU (Appendix 3B)
Bluebush fauna survey	BAU (Chris Brock)	45	basal area (4 size classes)	BAU (Appendix 3B)
Bradshaw fireplots	BFC (Cameron Yates)	22	basal area (DBH every tree)	Soil texture and depth, rock cover
Bullita ranger training camp	BAU	16	basal area	BAU (Appendix 3B)
Bungle Bungle survey (WA)	BAU	150	basal area, cover	related to BAU (Appendix B)
ClayNHT	BAU	132	basal area (4 size classes)	BAU (Appendix 3B)
Cobourg ranger training camp and rabbit rat surveys	BAU (Alaric Fisher)	1084 (points in 4 trapping grids)	basal area (4 size classes)	none
CRCVRD	BAU	46	basal area	BAU (Appendix 3B)
CSIRO 30 Kakadu Stage I and II sites	CSIRO	30	pres-abs	none
Daly River fauna survey	BAU (Owen Price)	136	basal area (4 size classes)	BAU (Appendix 3B)
Drysdale fauna survey (WA)	BAU	11	basal area	BAU (Appendix 3B)
Dyer fauna survey	BAU	32	basal area	BAU (Appendix 3B)
Fragments fauna survey	BAU (Owen Price; Brooke Rankmore)	91	basal area (4 size classes)	BAU (Appendix 3B)
Gregory NP fireplots	BFC (Cameron Yates)	50	pres-abs	none
Herbarium flora survey plots	Herbarium	2894	pres-abs	none
Herbarium specimens	Herbarium	92 (ironwood records only)	presence	None
Kakadu NP fireplots	BFC (Andrew Edwards)	134	basal area (DBH every tree)	Soil texture and depth, rock cover
Kakadu NP stage 3 fauna survey	BAU	380	basal area	Subset of BAU (Appendix 3B)
Kalumburu fauna survey (WA)	BAU	10	basal area	BAU (Appendix 3B)
Lancewood	BAU	270	basal area, cover, dominant cover	mostly BAU (Appendix 3B)
Limmen Gate fauna survey	BAU	45	basal area	BAU (Appendix 3B)

Data set	*Custodian*	*no. sites*	*Record type* *(e.g. presence-absence, basal area)*	*Environmental variables measured*
Litchfield NP fauna survey	BAU	116	basal area, cover	BAU (Appendix 3B)
Litchfield NP fireplots	BFC (Andrew Edwards)	41	basal area (DBH every tree)	Soil texture and depth, rock cover
Mary River fauna survey	BAU (Martin Armstrong)	151	basal area (4 size classes)	BAU (Appendix 3B)
Mary River land unit mapping	DLPE (Di Napier)	385	presence, dominant cover	Soil texture and depth
Mary River lower catchment vegetation monitoring	DLPE (Christine Bach)	31	pres-abs, basal area (DBH every tree)	Calibrated to BAU (Appendix 3B)
Mary River pasture fauna survey	BAU (Kerry Beggs)	36	basal area (4 size classes)	BAU (Appendix 3B)
Mitchell grasslands survey	BAU (Alaric Fisher)	225	presence	BAU (Appendix 3B)
NATT fauna survey	BAU	30	basal area	BAU (Appendix 3B)
Nitmiluk NP fireplots	BFC (Andrew Edwards)	46	basal area (DBH every tree)	Soil texture and depth, rock cover
Spirit Hills survey	BAU	18	basal area	BAU (Appendix 3B)
Sturt Plateau fauna survey	BAU (Alaric Fisher)	164	basal area (4 size classes)	BAU (Appendix 3B)
Tiwi Islands fauna survey	BAU	319	basal area (4 size classes)	BAU (Appendix 3B)
Tiwi islands (AMRAD)	PWCNT Herbarium	169	presence	None
Tiwi islands (BW Plains)	QEPA (Bruce Wilson)	123	presence	None
Tiwi Islands Eucs and weeds	QEPA (Rod Fensham)	243	presence	None
Tiwi Islands herbarium plots	Herbarium	84	pres-abs	None
Vegetation map NT	DLPE (Peter Brocklehurst)	7396	pres-abs, basal area, cover, dominant cover	Appendix 3C
VRD fireplots	BFC (Cameron Yates)	106	pres-abs	None
VRD ñ Judy Egan	Judy Egan	74	pres-abs	Some soil, rock cover
VRD99 fauna survey	BAU	45	basal area (4 size classes)	BAU (Appendix 3B)
Wessel Islands fauna survey	BAU	226	basal area (4 size classes)	BAU (Appendix 3B)

Appendix 4B. Description of the assessment of environmental variables for the bioregional survey data sets used in this study. The habitat and vegetation structure proforma is designed to collect standardised, ecologically meaningful data about the sample sites

Plot identification and location variables

quad unique label for each quadrat eg. TIPP1
survey bioregional survey eg, Daly Basin
quad size *size of the quadrat*
region/station usually park name, station name or sample region
observer the person deciding what data values go onto the sheet (not necessarily the scribe)
location explicit details about the site location ñ in relation to roads, tracks, creeks, landscape features etc ñsufficient for someone else to relocate it
lat/long precise location from GPS. Use averaged readings from large Magellans if possible
x/y AMG easting and northings ñ alternative reading from GPS

Environmental variables

landscape position brief description of landscape setting of site. Use the format of the ìYellow Bookî eg: narrow valley in sandstone plateau; midslope on low hills
landunit where available, from land unit mapping
run on/off run off sites shed rainfall (eg hill crests, upper slopes); run-on sites receive run-off eg. swamps, base of hills; plains are extensive flat areas
slope measured in degrees using a clinometer ñ estimate a mean slope for heterogeneous quadrats
aspect the direction the slope faces ñ leave blank for zero slope
altitude from topo map
perm water estimated distance to nearest permanent water (including artificial sources)
curr water distance to nearest water at time of survey
rock cover the total cover of rocks within the quadrat is estimated using cover classes for different size classes of rocks (see the ìYellow Bookî for examples). Rock sizes refer to the longest dimension on the rock.
** includes rock cover underneath vegetation or litter**
rock type broad classifications of the principal rock types ñ add others if you can determine them
lithology an optional field for the underlying lithology from a geological map
soil texture broad texture classes relating to the amount of clay in the soil ñ see Yellow Book
soil depth *four categories i.e. 0, <10, 10-40, >40*
soil colour
termite mounds estimate the total number in the quadrat, the maximum height and whether they are tall and thin, squat and wide or magnetic mounds

Vegetation structure

canopy height mode height of canopy trees (not the tallest), using a clinometer
canopy cover estimation of projective foliage cover of canopy. Best done objectively, using a device which we will try out shortly

veg profile estimate the cover of vegetation (using cover classes) in different height zones. The same plant could contribute cover to more than one zone

structural formation classification of the upper storey (in the quadrat and the surrounding vegetation it represents) as closed forest, open forest, woodland, open woodland, scattered trees or none. Canopy cover and crown separation are given as guides. A crown separation of 0.25 means the mean distance between the crowns of adjacent trees is one-quarter of the mean crown width

Bitterlich sweeps (basal area measure) Basal area is estimated using sweeps with a Bitterlich measure. The number of sweeps is ideally four, from the 4 corners of the quadrat ñ fewer sweeps could be used in very open homogeneous vegetation. Unless the tree layer is very dense or trees are very large, use the smallest slot (multiplier = 0.25).

** record the number of sweeps and the slot size (multiplier) used **

For each individual tree scored, visually estimated the DBH class it falls into. All tree species registering a hit are scored separately. The total is the number of hits for each species over all the sweeps

Dominant species Record the species with at least 5% cover in the three strata of the vegetation in decreasing order of cover. Only enter a max. of 5 species per strata. If there is a tall shrub layer and no tree layer, regard this as the mid layer.

** except in monsoon forests, very few species have >5% cover in a 50m quadrat **

ground cover ** these variables are quantified by stretching out a 100m tape through the quadrat (use a V-shape). Walk along the tape, looking vertically down and at each 1m score which feature is directly below the mark. The measures should add to 100%, so a piece of grass above litter or rocks would be scored only as grass.

<u>hummock grass</u> is spinifex (Triodia or Plectrachne)
<u>annual grasses</u> can easily be pulled out and have very short root systems;
<u>perennial grasses</u> are more firmly rooted in the ground and mostly form distinct tussocks
<u>other forbs</u> are herbs, ferns and small shrubs

** only score vegetation in the ground layer ie: below c. 50cm tall

Floristic data

The aim is that all quadrats used in bioregional surveys will also have a full floristic inventory done. This will usually be done by a botanist, concurrently with the fauna survey or on a separate trip. The botanist should record the following:

- all plant species present in the 50x50m quadrat
- for each species, an estimate of cover (projective foliage cover) as <1%, 1%, 2%, 5%, 10% or to the nearest 10%. It is recommended that a point-intercept or wheel-point measure is used for the ground layer species

If the floristic inventory is to be done separately, the quadrat must be marked in such a way that the botanist can find both the location and at least approximately the boundaries

Edge variables

The following edge variables are relevant where deliberately sampling ecotones or fragmented landscapes:

edge indicate if sampling an ecotone (quadrat on the boundary) or the distance to nearest boundary

adj unit the veg type or land unit adjacent to habitat being sampled *patch size* contiguous area of sampled habitat type. Most relevant for restricted habitats eg: rainforest, lancewood, rock outcrop

Disturbances

Various disturbance are scored on a scale of zero to 5, for major impact affecting all of quadrat. This will be somewhat subjective. 1 should mean that the disturbance is present but has had virtually no effect, 3 that there is a low level of disturbance throughout the quadrat, or a moderate effect concentrated in patches.

fire impact

last fire estimate form fire scars and regeneration whether the site was burnt during the current year; the previous year; fire scars present but apparently old; or no sign of fire or its effects

pig damage

cow/horse/donkey damage

weeds

Appendix 4C. Description of assessment of environmental variables for the Northern Territory vegetation map data sets used in this study. The plot size is 20x20 metres.

Variable		**Description**
1	Survey name	Whatever name is applicable (i.e. Tennant Creek fauna survey No.l)
2	Site number	Discrete site number
3	Described by	The person/s filling out proforma
4	Date	Day-month-year
5	Site photo	Film roll number
6	Site photo	Frame number
7	Sheet number	The name and/or number of the topographic sheet on which plot site is marked. For the vegetation map we-marked each site on topographic map as we did it in the field. The hard copy maps were kept
8	Easting	The easting for the site as a five digit number taken from the map or GPS
9	Northing	The northing of the site as a six digit number taken off to topographic map or GPS
10	Latitude/longitude	Referencing of site in degrees and minutes.
11	Landsat	Referencing of landsat used (if used) that covers the region where site was located and that contained the mapping boundaries for our vegetation sites.
12	Veg. Structure	Structural formations code, either Camahan (see Technical report 49, page 15) or Walter & Hopkins depending on which classification scheme adopted. This can be filled out after plot has been done by referring to variables 25,26,27 or filled out in the office after the survey.
13	Mapping unit	This was a code or name for the mapping unit delineated from our mapping boundaries to which site hopefully represented.

14 Landform pattern The type of landform (within a 300 metre radius of plot) of which the site is part (i.e. rises). Landform patterns are outlined in Walker & Hopkins. It is probable best to write the full name on the plot-sheet. Codes can be determined in the office when the information goes into the computer. Similarly you may wish to include landform element (within 40 metres of site-see attachment 2). See Walker & Hopkins pages 8-43.

1. Alluvial fan
2. Alhivial plain
3. Dastomotic plam
4. Badlands
5. Bar plain
6. Beach ridge plain
7. Caldera
8. Chenier plain
9. Coral reef
10. Covered plain
11. Delia
12. Dunefield
13. Escarpement
14. Flood plain
15. Hills
16. Karst
17. Lava plain
18. Low bills .
19. Made land
20. Meander plain
21. Meteor crater :
22. Mountains
23. Pediment
24. Pediplain
25. Peniplain
26. Plain
27. Platean
28. Playa plain
29. Rises
30. Sand plain
31. Slieet-floodfan
32. Stagnant alluvial plain
33. Tenace (alluvial)
34. Tidal flat
35. Volcano

15 Slope Slope measured in degrees.

16 Aspect Direction of slope as per the following. If no slope aspect=0

1. North
2. North-east
3. East
4. South-east
5. South
6. South-west
7. West

17 Geology Underlying geology taken from geology maps. However the surface soil may not reflect underlying geology.

18 % rock outcrop Particulate matter greater than approximately 10 cm diameter up to sheet rock (i.e. sandstone ranges) measured as a straight -percentage for the amount of rock cover in the plot. (generally determined from I metre square sub-plots scattered through main plot and extrapolated for whole plot).

19 % gravel — Straight percentage cover of plot by gravels defined as anything greater than sands but less than 10 cm diameter.

20 % bare ground — Straight percentage figure of area of bare earth in the plot (not rock)

21 Surface Soil text — As per following (fairly crude)

1. The Sands-sand; loamy sand; cleavey sand.
2. The Sandy Loams-sandy laom; fine sandy loam; light clay loam.
3. The Loams-loam; silt loam; sandy clay loam.
4. The clay loams-clay loam; silty clay loam; fine sandy clay loam.
5. Light Clays-sandy clay; silty clay; light clay; light medium clay.
6. The Medium Heavy Clays-medium clay; heavy clay.

22 Burnt <1year — If plot has been recently burnt code=I. If pie not recently burnt code=0. This measure is more suitable to the humid tropics.

23 %crown cover/%cover by life-form

For each life-form present (see Technical report for definition of life-form page 14) at the site a %cover is estimated. For lifeforms above the general ground cover, it is a, % crown cover-**that is the percentage of the sample site within the vertical projection of the periphery of the tree or shrub**. You may be using a Bitterlich gauge to measure this as there will be very few trees. A CSR ratio technique can also be used on upper and mid stratum trees and shrubs.(see Walker & Hopkins page 52-54). For the ground layer, the straight percentage cover of the particular lifeform covering the plot is determined

24 Average height — The average height of each life-form that ispresent in metres, measured with a sunto direct reading clinometer.

25 Dominant lifeform in each stratum — The dominant life-form in each stratum. The life-form codes are taken from the lifeform table near variable 23. Therefore life-form I is trees> 8 metres moving down to a life-form of 15 for vines.

26 %cover — This is the **total** vegetative cover in the sample site that occurs in each stratum. For the upper and mid stratum it is generally a **% crown cover** while for the ground layer it is generally a straight **% cover**. This box (with heights) is a ësummaryí of the structure of the vegetation

at any site. (Variables 23 and 24 are an expansion on this table)

27 Average height The average height of each stratum in metres

28-30 Upper stratum

28 Species A list of species occurring in the upper stratum. In some instances relatively common trees may fall out of the plot confines or the basal count. These should be written in the comment section (i.e. trees outside). These are generally recorded as a code with the first three(or four) letters of the genus, and species of the plant.

29 Ecopak This is a number, based on the herbarium checklist, which is used when entering the data on computer. This is done in the office after the survey and depends on the type of database used to store the information.

30 Basal This is the number of trees (or shrubs) which are larger than the aperture of the basal wedge back to the old story of trying to pick representative sites versus the number of sites which can be sampled. However in your instance the dominant vegetative layer will probably be the ground stratum in most cases (ring me if this sounds unclear)

31-33 Mid-stratum

31 Species A species list in triplet code as defined for variable 28

32 Ecopak As for variable 29.

33 % cover The %crown cover. of species in the mid-stratum is recorded as per definition of variable 23.

34-36 Ground-stratum

34 Species A species list in triplet code as defined for variable 28

35 Ecopak As for variable 29.

36 % cover The %cover of species in the mid-stratum is recorded as per definition of variable 23.

5. Local distribution patterns

Robert Taylor, Craig Hempel and Leigh Granger

Introduction

The previous chapter discussed the results of modelling the distribution of ironwood across the whole of its distribution in the Northern Territory. Some important variables likely to be influencing distribution at a more local level (within catchment) were not able to be included in this exercise. This chapter focuses on the distribution of ironwood at a catchment scale, using the Mary River catchment as a case study. Information at a finer scale was available for lithology for the Mary River region and the influence of drainage could be examined in more detail. A bioregional survey had recently been completed in the catchment (Armstrong *et al.* 2001) and thus survey data was available at a reasonable sampling intensity. This catchment contains most of the areas used to harvest ironwood in the past five years and the Territory-wide modelling (chapter 4) indicated that the area supported a reasonable density of ironwood trees. It was hoped that examination of data at a finer scale would produce a model with a greater explanatory power that could be used to examine the influence of regulation on the resource availability of ironwood for the timber industry. Because the primary interest in this exercise related to the occurrence of larger ironwood that could be utilised as timber, modelling was limited to the largest size class recorded during the bioregional survey (ie > 20 cm DBH). Sampling of the distribution of ironwood in relation to drainage lines was also undertaken within the catchment to quantify this relationship and to aid interpretation of the results of the modelling.

Study area

The Mary River catchment comprises an area of 8062 km^2 in the northern Top End between Darwin and Kakadu. The catchment originates in the western Arnhem Land plateau in rugged escarpment country and then flows through dissected foothills into gently undulating country in the lower catchment. A tributary from the west, the McKinlay River, drains an extensive 1,300 km^2 system of grassland and savanna-dominated blacksoil plains. The lower catchment encompases a 60 km long system of mainly freshwater wetlands. The locations of sample sites where measurements of the presence and density of ironwood *Erythrophleum chlorostachys* were undertaken by Armstrong *et al.* (2001) are shown in Fig. 5.1. The largest size class of ironwood differentiated in field surveys by Armstrong *et al.* (2001) was >20 cm DBH.

Mary River East Station is located about 40 km north east of Pine Creek. It experiences the pronounced wet and dry seasons typical of monsoon regions. Mary River East is approximately 1356 km≤ and is generally inaccessible during the Wet season with limited access in the dry season due to washouts and other enduring flood damage. Mary River East is characterised by a sequence of rocky strike ridges flanked by narrow pediments separated from one another by alluvial flats of variable width (Woodroffe and Mulrennan 1993). Soils in the area typically consist of rocky, skeletal soils on the ridges and hills with deep silty loams associated with the alluvial flats of the major creeklines. Tropical eucalypt savanna dominates. A number of *Eucalyptus* and *Corymbia* species occur within the study area; *Corymbia foelsheana* and *Eucalyptus tectifica* are common on the skeletal soils of the ridges, while *Corymbia bella*, *Corymbia polycarpa* and *Corymbia grandifolia* are more common on the deep alluvial soils of the creek flats where they often obtain good growth form.

Logging events have probably occurred in the Mary River area for over 100 years. Recent harvesting of ironwood and some *Eucalypt / Corymbia* species in the study area has occurred in the past decade. These recent harvest events are diffuse and are restricted to creekflats (see chapter 7).

Methods

In order to map the occurrence of ironwood in the Mary River Catchment from models a set of spatial layers that can be intersected with field data are required. These layers represent various features of the landscape that, in combination, provide a means of mapping areas most suitable to the species of interest.

Spatial layers

Satellite Data. Landsat imagery provides layers representing surface reflectance in different spectral wavelengths, highlighting differences in the landscape. The presence of fire scars on such imagery is common in Northern Australia and can often confound interpretations of such data. For this reason a median image was computed from a series of Landsat data (Path/Row 105/69) provided by the Natural Resources Division of the Department of Infrastructure, Planning and Environment. Acquisition dates for these passes was as follows: 29/04/1990 (Late Wet), 27/04/1995 (Late Wet), 25/08/1998 (Late Dry), 24/05/1999 (Early Dry), 29/09/1999 (Late Dry). All image dates were rectified, resampled and co-registered by the Natural Resources Division to ensure between image spatial continuity. Image calibration, based on robust regression of pixel values from invariant targets (Campbell *et al.* 1994), was also undertaken on all images by the Natural Resources Division to reduce atmospheric and seasonal variation between dates.

Elevation Model. Digital Terrain Elevation Data (DTED), provided by the Department of Defence, was clipped to the extent of the Mary River Catchment and was also used to compute a topographic ruggedness layer, evaluated as the difference between the lowest and highest point within a 100 x 100 m moving window.

Surficial Geology. Four digital geology map sheets (1: 250,000 scale) provided by Geoscience Australia were merged and edited to provide a complete geological coverage of the Mary River Catchment. A complete list of the lithological units for each polygon within this coverage was then used to output a simplified surficial geology layer consisting of six broad classes: Granitic; Sand/Gravel; Sandstone/ Volcanics; Siltstone/Quartz; and Laterite and Alluvium (Fig 5.1).

Drainage and Hydrography. A complete drainage coverage of the catchment was created from Ausligís Version 1 Geodata series (Fig 5.2). The extent of the floodplain was taken from the Mary River Floodplain Vegetation map (Lynch *et al.* 1996).

Modelling

To effectively model and thence map the occurrence of ironwood within the catchment, a standard mapping environment needed to be established within which all spatial analysis would be performed. This environment must provide an optimal scale that best represents all input GIS layers. Analysis of this type is most often performed in a raster data environment, its simple structure allowing for complex spatial analyses (Farina 1998). A raster calculator was used to combine the model estimates and their associated grids in a conditional statement. The resultant output grid was then transformed into ërealí numbers using the same calculatorís logarithmic functions and mapped using the spatial analyst extension in ArcviewÆ. In this analysis the resolution and extent of the Landsat Imagery was chosen as the base raster that all other GIS layers would be converted to. The Lamberts Conformal Conic projection, based upon the 1966 Australian Geodetic Datum, was chosen as the most appropriate projection to work within due to its shape preservation properties. Datasets used as inputs to the modelling process were as follows:

Data set	**Landscape Representation**
Landsat TM Band 1	Differentiation of soil and water, soil moisture content
Landsat TM Band 2	Vegetation vigour
Landsat TM Band 3	Discrimination of vegetation type
Landsat TM Band 4	Biomass content
Landsat TM Band 5	Moisture content of vegetation and soil
Landsat TM Band 7	Discrimination of rock types, clay mapping
Normalised Difference Veg Index (NDVI)	Indicative of vegetation biomass
Global Environment Monitoring Index (GEMI) (Pinty and Verstraete1992)	Indicative of the presence and status of green vegetation
Albedo (Saunders 1990)	Indicative of the brightness of the land surface
Elevation	Elevation above sea level (meters)
Topographic Ruggedness	Range in elevation
Surficial Lithology	Broad soil type
Euclidean distance from mapped drainage	Distance from water

A total of 134 samples were used to model both the incidence and basal area of ironwood >20 cm DBH within the Mary River Catchment. The geographic

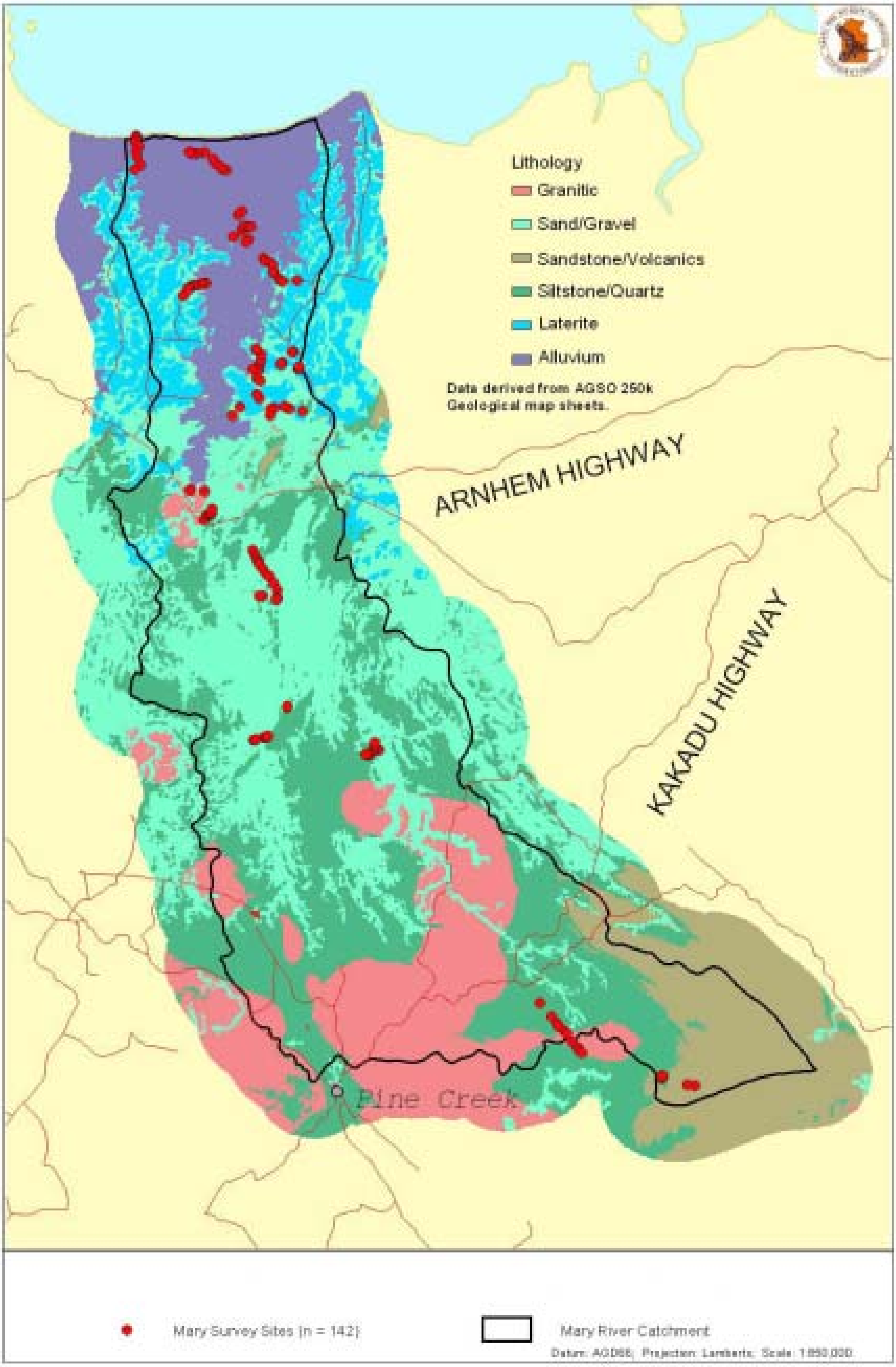


Fig. 5.1. Location of vegetation sampling sites and the distribution of lithology units in the Mary River catchment.

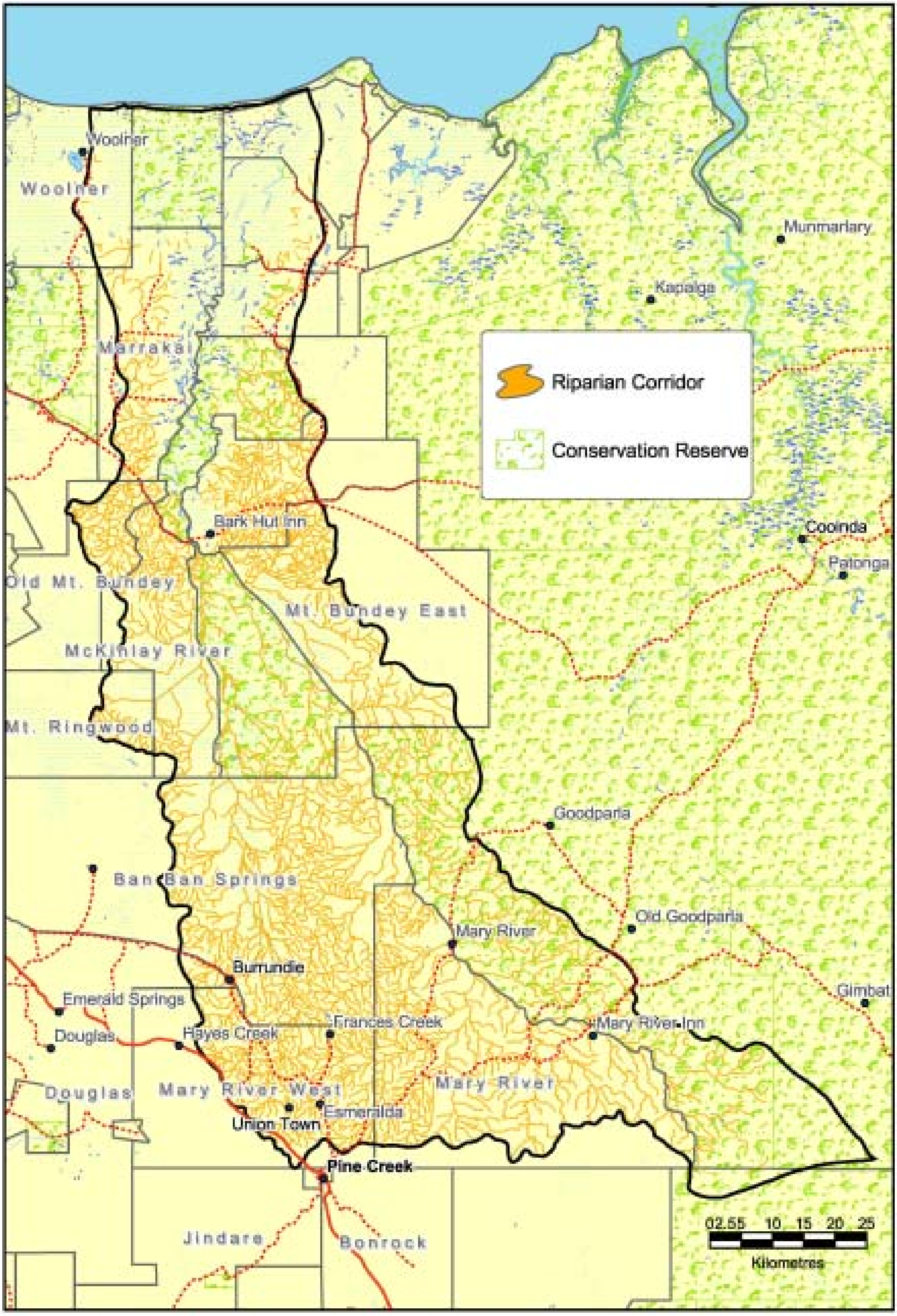


Fig. 5.2. Drainage lines used in the modelling of ironwood distribution in the Mary river catchment.

locations of these samples were used to attribute each one with the variables listed in the methods. Areas of lower floodplain habitats were not included as the seasonal inudation experienced in these areas made them unsuitable for ironwood.

Backward stepwise Generalised Linear Modeling (GLM) was used to derive minimum adequate models using the above variables. We assumed a poisson distribution for variables and used a logit link function.

Sampling of distribution across topographic gradients

Transects were established in locations in Mary River East station with suitable topographic gradients. Generally this consisted of an area where a creekflat was curtailed on one side by the presence of a hill or slope where rocky skeletal soil emerged. Two transects were placed in each of two different areas: the OíNeil Creek system and the Eureka Creek system. Transects ran perpendicular to the creekline for a length of 100 m on each side of the creek with a widths of 50 m. All ironwood within the transects were assessed for DBH, height and distance from the creekline. Slope and soil type were recorded throughout the transect every 10 metres.

The size classes and commercial suitability of trees were also assessed in circular plots placed in riparian and non riparian areas. 11 plots were located in riparian areas; six of these had been logged in 1996-97. For the logged plots four had a radius of 50 m, one had a radius of 56 m and the other a radius of 70 m. For the other riparian plots their radius was 25 m. Six of the non-riparian plots had a radius of 25 m and the other had a radius of 50m. All trees within the plots were identified and DBH (diameter at breast height), bole height and overall height were recorded. Trees were classified as acceptable or unacceptable for commercial use based on the following criteria:

- Dbh >35 cm;
- Bole height >2.2 m;
- No hollows or major irregularities.

These criteria were established from discussions with people involved in the industry (David Clarke pers. comm.). The 2.2 m bole height is a safety requirement of the Red Ebony Sawmill that processed logs harvested from Mary River East. Other mobile sawmills can process logs not less than 1.2 m, although longer ones are preferred (David Clark pers. comm.) Where wood is being used in the furniture industry, trees less than 40 cm dbh will only provide low yields of useable timber (David Clark pers. comm.).

Data was transformed using log and square root where necessary to achieve normality. Where data achieved a normal distribution Anova were used to analyse the data. In most cases the data did not display a normal distribution and non parametric tests were used: Mann Whitney U test and Kruskal Wallis Anova by ranks. Chi-square tests were used to compare frequencies in different categories.

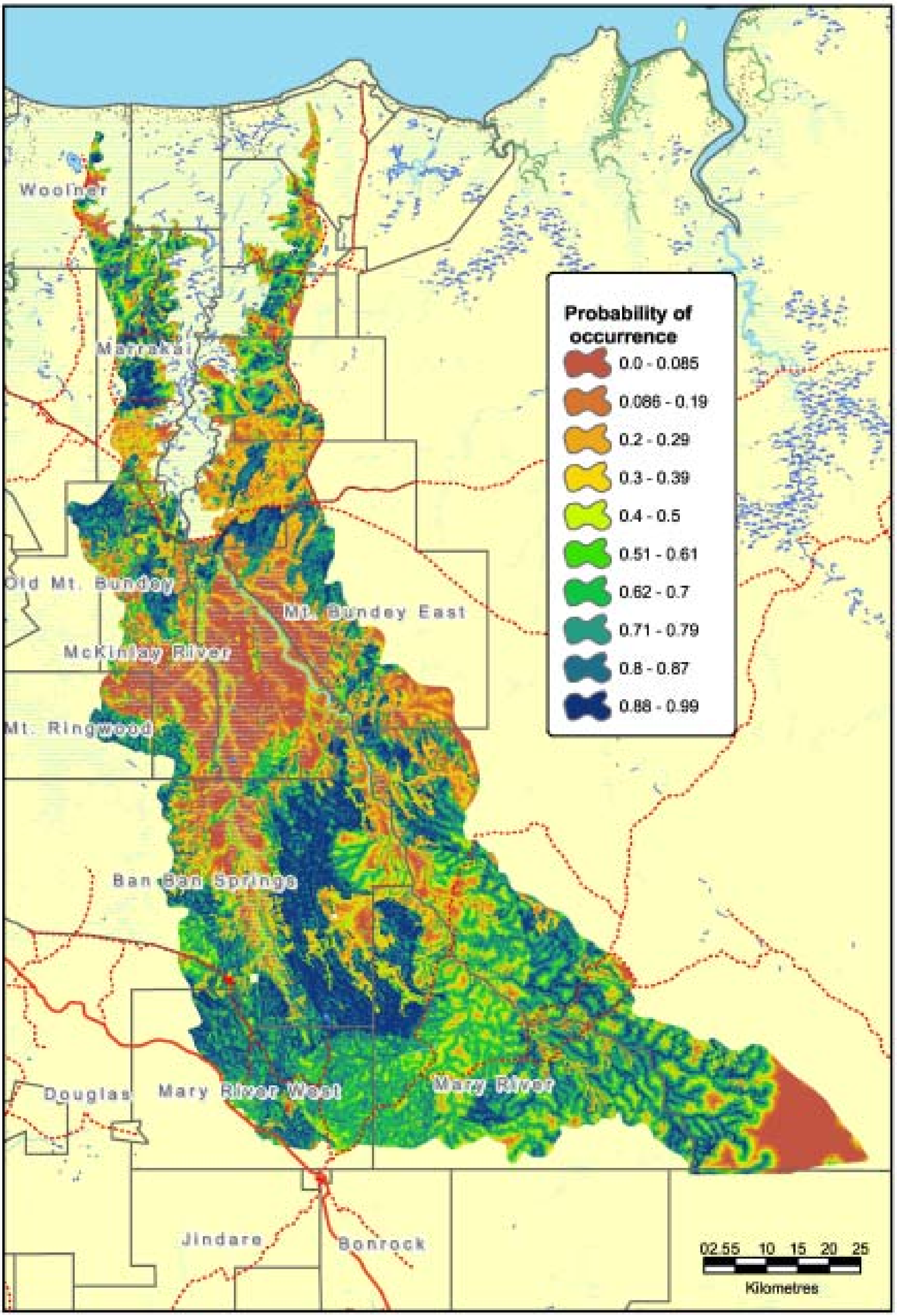


Fig 5.3. The probability of occurrence of ironwood >20 cm DBH.

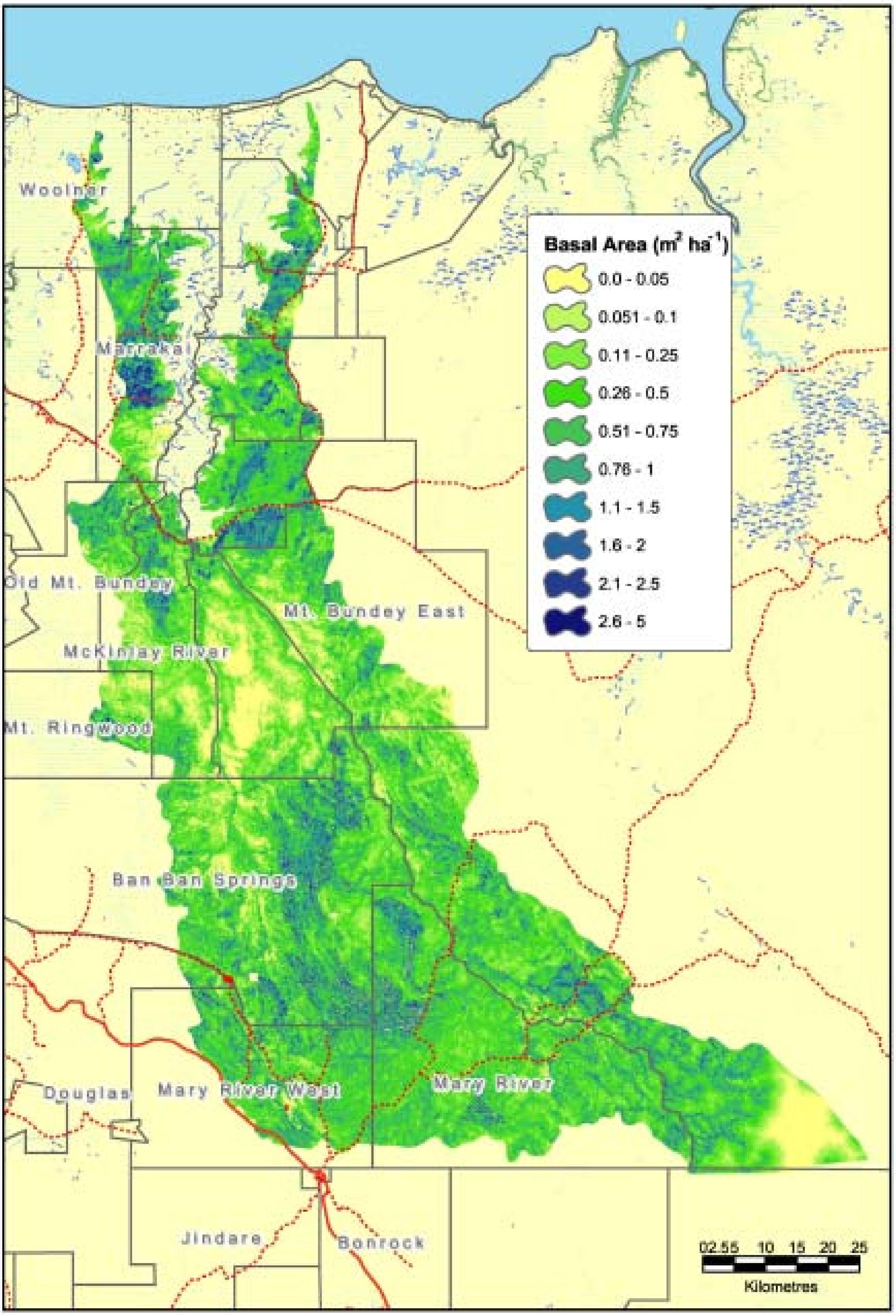


Fig. 5.4. The distribution of basal area of ironwood >20 cm DBH.

Fig. 5.5. Slope (non-riparian) habitat (top photo) and a flat area nearby creekline (riparian habitat) (bottom photo). Note the ironwood stumps resulting from logging in the bottom photo.

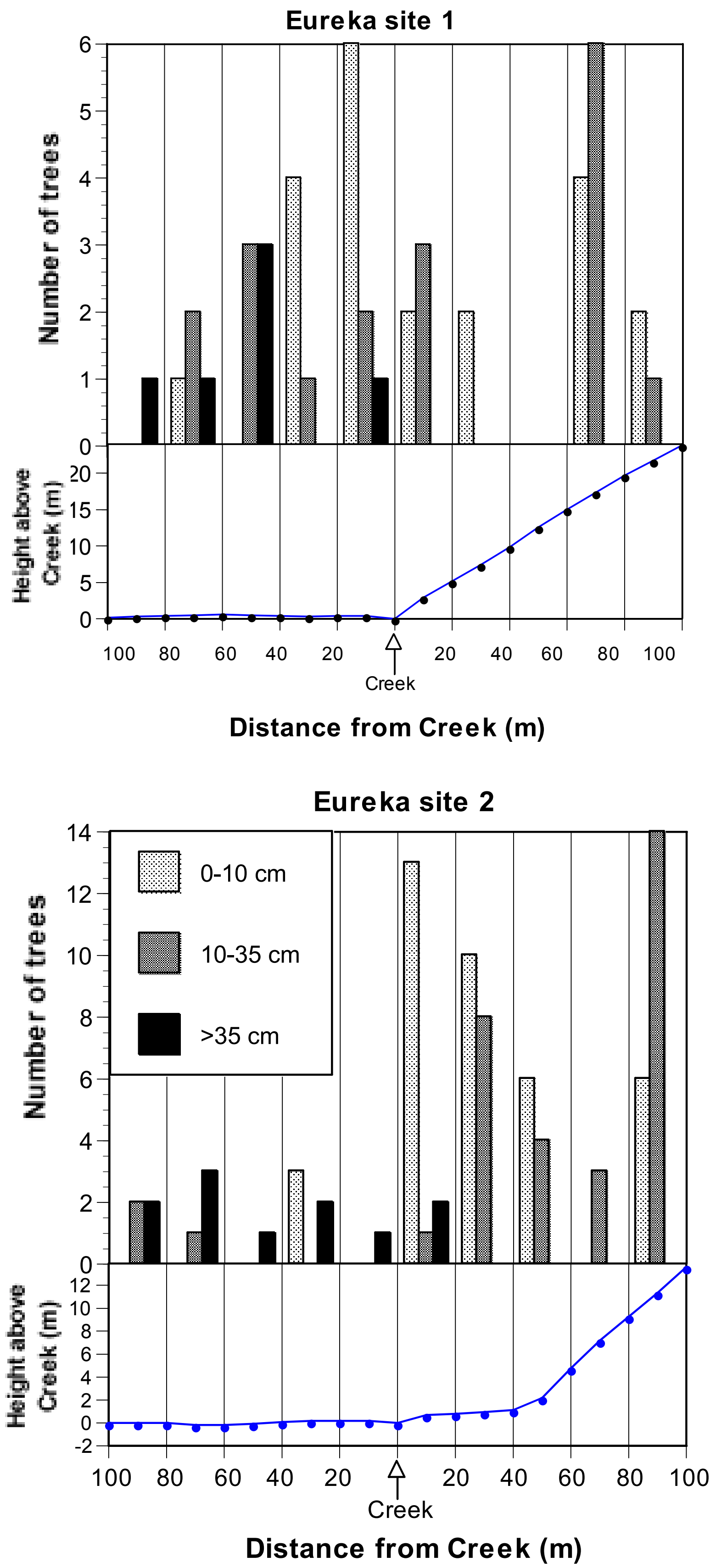
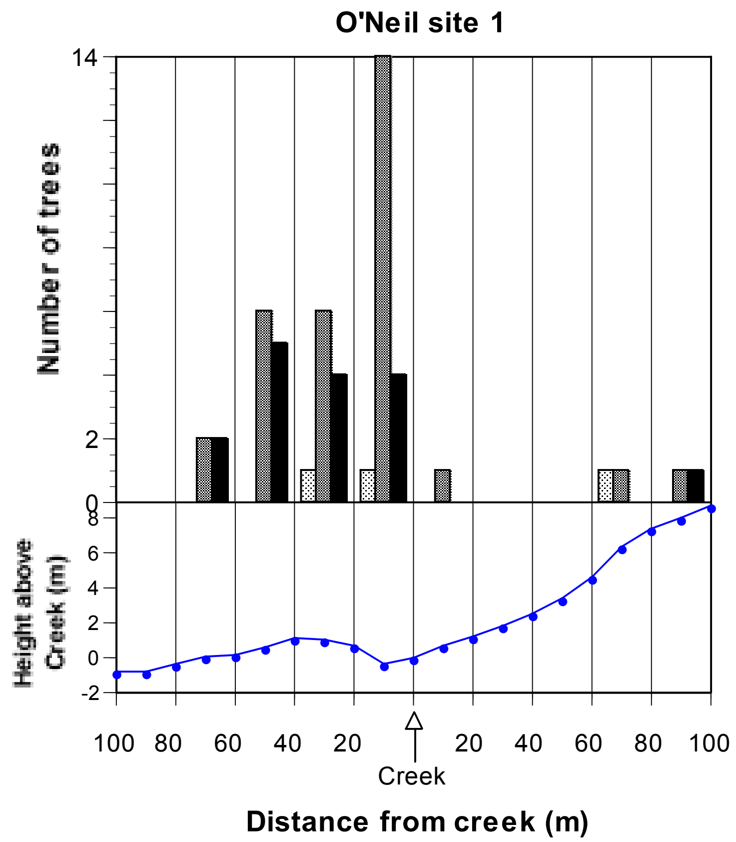


Fig. 5.6. Relationship between DBH of ironwood and distance from creeks and slope at two locations at Eureka Creek, Mary River East.



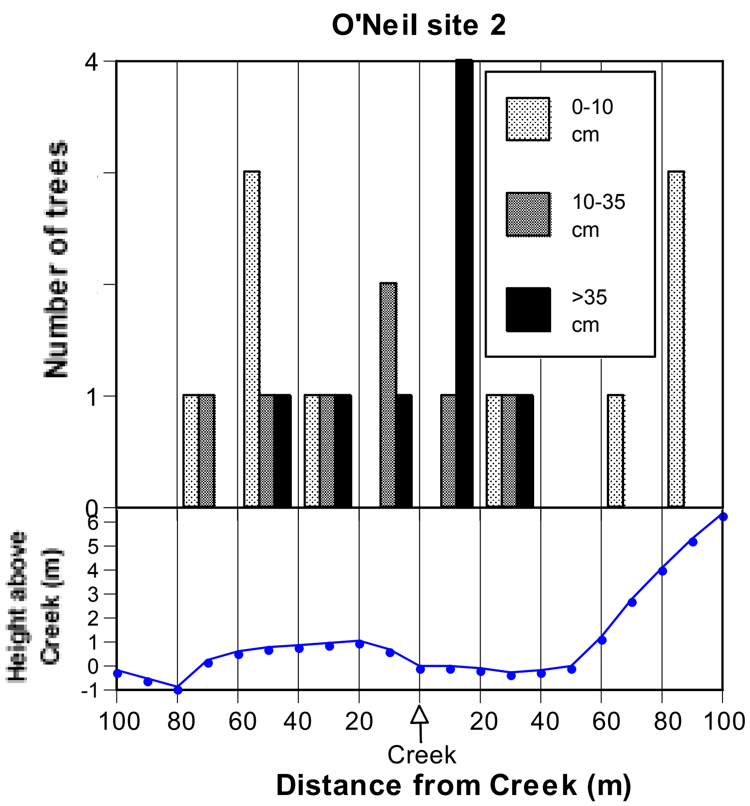


Fig. 5.7. Relationship between DBH of ironwood and distance from creeks and slope at two locations at OíNeil Creek, Mary River East.

Table 5.1. Summary of minimum adequate model for the incidence of large ironwood and environmental variables (derived from GIS).

Term	df	Estimate	s.e.	p
Intercept	1	-1.963	1.018	0.054
Distance from water	1	-0.002	0.001	0.004
GEMI	1	0.025	0.007	<0.001
Surficial geology				
Sand/gravel	1	-1.856	0.348	<0.001
Siltstone/quartz	1	0.739	0.394	0.060

Table 5.2. Summary of minimum adequate model for basal area of ironwood >20 cm DBH and environmental variables (derived from GIS).

Term	df	Estimate	s.e.	p
Intercept	1	-2.416	1.508	0.109
Landsat TM 3	1	0.567	0.271	0.036
Albedo	1	-0.654	0.309	0.034
GEMI	1	0.073	0.030	0.015
Landsat TM 7	1	-0.129	0.044	0.003
Landsat TM 5	1	0.075	0.025	0.002
Distance from water	1	-0.0009	0.001	0.012
Surficial geology				
Sand/gravel	1	-0.680	0.191	<0.001
Siltstone/quartz	1	0.131	0.225	0.561

Table 5.3. Comparison of size of ironwood trees in riparian and non riparian areas of transects from the OíNeil and Eurek Creek sites. Values are means ± standard error with sample size in brackets.

	Riparian	Non-riparian
DBH (cm)	24.5 ± 1.3 (141)	12.2 ± 1.1 (61)
Total height (m)	11.2 ± 0.5 (134)	6.8 ± 0.3 (61)

Results

Modeling Ironwood Occurrence and Biomass

For the minimum adequate model for the incidence (presence/absence) of ironwood trees >20 cm DBH only three factors were required to explain 31% of the deviance of 185 (Table 5.1, Fig. 5.3), with surficial geology providing the strongest relationship. The minimum adequate model for basal area of ironwood trees >20 cm DBH contained seven factors that explained 41% of the total deviance of 202

Table 5.4. Comparison of characteristics of Ironwood and *Eucalyptus* / *Corymbia* species in riparian and non riparian plots. Values are means ± standard error with sample size in brackets.

	Ironwood		*Eucalyptus/Corymbia*	
	Riparian	Non-riparian	Riparian	Non-riparian
Total height	12.35 ± 0.35 (129)	7.81 ± 0.49 (38)	13.62 ± 0.27 (192)	10.42 ± 0.32 (76)
Bole height	4.01 ± 0.20 (114)	2.87 ± 0.15 (24)	4.45 ± 0.15 (177)	3.75 ± 0.19 (59)
No. of trees/ha	19.3 ± 2.8 (11)	23.6 ± 11.6 (7)	34.3 ± 6.7 (11)	44.9 ± 11.7 (7)
Basal area (m^2/ha)	1.72 ± 0.41 (11)	0.78 ± 0.43 (7)	2.18 ± 0.37 (11)	2.48 ± 0.40 (7)
% of trees of commercial value	26%	0%	16%	3%
Volume of commercial timber (m^3/ha)	3.52 ± 1.10 (11)	0 (7)	6.58 ± 3.21 (11)	1.86 ± 1.24 (7)

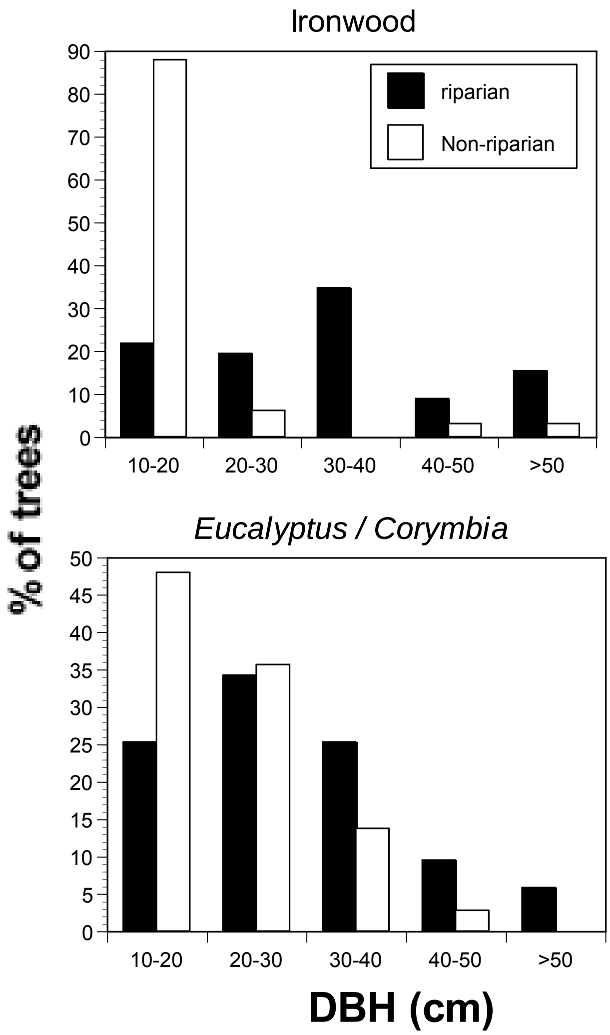


Fig. 5.8. Size distributions of DBH of Ironwood and *Eucalyptus / Corymbia* trees in plots from riparian and non-riparian areas.

(Table 5.2, Fig. 5.4). Surficial geology and Landsat TM band 5 (indicative of the moisture content of the vegetation and soil) provided the strongest relationships.

Distribution in relation to topography

There is a clear trend for larger ironwood trees (>35 cm DBH) to occur in the creek flats compared with slopes (Fig. 5.5) along transects at both the OíNeil and Eureka Creek sites (Figs. 5.6 and 5.7). Trees were on average significantly taller ($p<0.001$) and had a larger DBH ($p<0.001$) in creek flats than those on slopes (Table 5.3). Tree density was not significantly different between slope and creek flat for either site. The DBH of trees was also significantly different between soil types ($p<0.01$) with larger trees on the silty, clay loam compared with the rocky, shallow soil).

DBH of both ironwood and *Eucalyptus* and *Corymbia* species was significantly greater in riparian plots compared with the non-riparian plots ($p<0.001$ and $p<0.05$ respectively, Fig. 5.8). Total tree heights and bole heights were also significantly greater in the riparian sites for both ironwood and *Eucalyptus* / *Corymbia* ($p<0.05$, Table 5.4). However density and basal area/ha of both ironwoods and *Eucalyptus* / *Corymbia* was not significantly different between riparian and non riparian sites Table 5.4). The proportion of trees that was of commercial value was higher in riparian sites for both ironwood ($\chi^2=12.5$, df=1, $p<0.001$) and the *Eucalypt / Corymbia* group ($\chi^2=9.2$, df=1, $p<0.01$, Table 5.4). The volume of commercial trees (m^3/ha) was significantly higher for ironwoods in riparian areas ($p<0.05$) but not for the *Eucalypt / Corymbia* group.

Discussion

Ironwood and *Eucalypt / Corymbia* trees in riparian areas were taller, had higher bole heights and larger DBH compared with those in non-riparian sites. Similar trends have been found in riverflat communities in north central Arnhem Land: basal area of woody stems decreasing as rock cover and surface slope increased (Yibarbuk *et al.* 2001). The larger size of trees in riparian areas is probably related to greater soil depth, higher soil nutrients and greater water availability, all of which change with slope and distance from creeklines. The soils of the creek flats are deep alluvial soils while the surrounding slopes and hills display a rocky skeletal soil type. Higher soil moisture and nutrients in the creek flats would allow trees a faster growth rate (Wilson and Bowman 1987). The moist and low-lying creekflats may also be less fireprone than riparian areas (Wilson and Bowman 1987). However, a high fuel load was evident along some creeklines in the Mary River East area at the time of the study. In particular an area adjacent to the OíNeil Creek harvest site had dense stands of tall tussock grasses that may indicate the lack of an annual fire but also suggests a potential for higher intensity fires.

The modelling of ironwood at the catchment scale also highlighted soil, moisture and distance from water as important predictive variables for the distribution of large ironwood trees. The amount of variance explained by the catchment model was greater than for the Territory-wide modelling (for abundance 41% compared with 12% with on-site variables and 30% with GIS variables). This is probably attributable to a more accurate geology layer and the inclusion of a variable related to distance from water. Unfortunately the drainage layer used to derive the distance from water variable only included drainage lines that carried water during the dry season. Most of the major drainage lines that dry out over the dry season also support larger sized trees and hence inclusion of these in the GIS layer would probably have increased the explanatory power of the model greatly.

Data from Mary River East indicates that commercially acceptable ironwood appear to be restricted to creekflats. Riparian sites carried a volume of 3.5 m^3/ha of commercially acceptable ironwood. This is an underestimate as most of the riparian areas, excluding a buffer zone of 20 m, had been subject to logging. However, modelling results (see chapter 3) indicate a very low basal area of ironwood in the Northern Territory in comparison with many other timber species.

The finding of a greater abundance of ironwood in riparian areas is in accord with general descriptions of the occurrence of ironwood. For example, Boland *et al.* (1984) state that ìIt grows on rocky hillsides but probably reaches its best development on creek and river flatsî. However, other studies have not always found ironwood to have its greatest abundance associated with riparian areas. Bowman *et al.* (1991) reported ironwood to have maximum basal area on ridge lines in a landscape of rolling hills with skeletal sandy loam soils 40 km north of Katherine. Bowman *et al.* (1993) found Ironwood in Stage III of Kakadu National Park had its greatest basal area in sites with high rockiness on slopes, low water availability and soils with a high clay content. It may be that soil type has the most important influence on ironwood and can override the negative effects of slope and rockiness. Thus for the modelling of ironwood with on-site variables on a Territory wide basis (section 4), soil texture explained the highest deviance with slope and rock cover being significant but adding little increase in the modelís explanatory power. It is also possible that site history, particularly fire regimes, could mask the influence of slope and water availability in some situations. Although the studies quoted above found ironwood not to be most abundant in riparian areas it is still possible that riparian areas in these sites could have supported the most commercially acceptable trees. Such an example is provided in Table 5.4 for *Eucalyptus/Corymbia* where basal area is greater in non-riparian areas but the size of trees is greater and the % that are of commercial value is greater in riparian areas. On Mary River East the form of trees was poor on rocky hillsides with trees more often showing a crooked bole compared with riparian areas.

References

Armstrong, M., Woinarski, J., Hemple, C., Connors, G. and Beggs, K. (2001). *A plan for the conservation of biodiversity in the Mary River catchment, Northern Territory.* Report to the Natural heritage Trust. (Parks and Wildlife Commission of the Northern Territory, Palmerston).

Bowman, D.M.J.S. and Wilson, B.A. (1991) Floristic and phenological variation in a northern Australian rocky *Eucalyptus* savanna. *Proceedings of the Royal Society of Queensland* **101,** 79-90.

Bowman, D.M.J.S., Woinarski, J.C.Z. and Menkhorst, K.A. (1993) Environmental correlates of tree species diversity in Stage III of Kakadu National Park, Northern Australia. *Australian Journal of Botany* **41,** 649-660.

Campbell, N., Furby. S. and Fergusson, B. (1994). *Callibrating images from different dates.* Report to Land and Water Resources Research and Development Corporation. (CSRIO Division of Mathematics and Statistics, Perth).

Farina, A.. (1998). *Principles and Methods in Landscape Ecology.* (Chapman and Hall: London).

Lynch, D. (1996). *Mary River floodplain vegetation survey*. (Department of Lands, Planning and Environment: Darwin).

Pinty, B. and Verstraete, M., (1992). GEMI: a non-linear index to monitor global vegetation from satellites. *Vegetatio* **101**, 15-20.

Saunders, R.W. (1990). The determination of broad band surface albedo from AVHRR visible and near-infrared radiances. *International Journal of Remote Sensing* **11**, 59-67.

Wilson, B.A. and Bowman, D.M.J.S. (1987). Fire, storm, flood, and drought: The vegetation ecology of Howards Peninsula, Northern Territory, Australia. *Australian Journal of Ecology* **12,** 165-174.

Woodroffe and Mulrennan, M.E. Geomorphology of the lower Mary River plains, Northern Territory. (North Australia Research Unit, Australian National University, Darwin).

Yibarbuk, D., Whitehead, P.J., Russell-Smith, J., Jackson, D., Godjuwa, C., Fisher, A., Cooke, P., Choquenot, D. and Bowman, D.M.J.S. (2001). Fire ecology and Aboriginal land management in central Arnhem Land, northern Australia: a tradition of ecosystem management. *Journal of Biogeography.* **28,** 325-343.

Appendix 5.1. Mean and standard deviation of basal area and numbers of trees (per 0.25ha) in riparian and non-riparian plots on Mary River East.

Riparian Plots

Site	Logged or unlogged	Plot number	Species	Mean Basal Area (m≤)	S.D. of BA (m^2)	No. of Trees /0.25 ha
Eureka	unlogged	38-3	*Corymbia grandifolia*	0.136		1.27
			Corymbia polycarpa	0.283	0.009	2.55
			Erythrophleum chlorostachys	0.124	0.104	7.64
			Eucalyptus patellaris	0.357		1.27
			Ficus coronulata	0.205		1.27
			Ficus opposita	0.024		1.27
			Lophostemon grandiflorus	0.114		1.27
			Pandanus spiralis	-		1.27
Eureka	logged	36A	*Corymbia bella*	0.023	0.008	1.25
			Corymbia grandifolia	0.012	0.006	1.75
			Corymbia polycarpa	0.025	0.028	1.50
			Erythrophleum chlorostachys	0.008	0.010	2.00
			Eucalyptus bigalerita	0.032	0.017	1.00
Eureka	logged	36B	*Acacia* sp.	0.009		0.32
			Corymbia grandifolia	0.009	0.004	2.55
			Corymbia polycarpa	0.018	0.012	1.91
			Erythrophleum chlorostachys	0.051	0.041	7.96
			Eucalyptus bigalerita	0.040	0.053	0.95
			Eucalyptus patellaris	0.019	0.002	0.64
Eureka	logged	36C	*Canarium* sp.	0.005		0.32
			Corymbia bella	0.042	0.025	1.27
			Corymbia grandifolia	0.018	0.003	0.95
			Corymbia latifolia	0.005		0.32
			Corymbia polycarpa	0.031	0.019	2.23
			Erythrophleum chlorostachys	0.036	0.027	6.37
			Eucalyptus bigalerita	0.036	0.027	6.37
			Eucalyptus tectifica	0.022		0.32
OíNeil	unlogged	29-3	*Corymbia bella*	0.347		1.27
			Corymbia confertiflora	0.065	0.040	3.82
			Corymbia latifolia	0.057		1.27
			Corymbia polycarpa	0.247		2.55
			Erythrophleum chlorostachys	0.105	0.121	3.82
			Eucalyptus bigalerita	0.075		1.27
			Ficus coronulata	0.044	0.034	3.82
			Lophostemon grandiflorus	0.045	0.029	2.55
OíNeil	unlogged	40-5	*Acacia* sp.	0.056	0.011	2.55
			Corymbia bella	0.172	0.113	3.82
			Erythrophleum chlorostachys	0.067	0.073	2.55
			Eucalyptus patellaris	0.042	0.043	2.55
			Lophostemon grandiflorus	0.110	0.106	2.55
			Terminalia platyphylla	0.057	0.056	3.82
OíNeil	unlogged	40-6	*Corymbia bella*	0.137	0.098	2.55
			Erythrophleum chlorostachys	-		1.27
			Hakea arborescens	-		1.27
OíNeil	logged	40A	*Brachychiton* sp.	0.013		0.16
			Corymbia bella	0.010	0.004	2.44
			Corymbia polycarpa	0.018	0.001	0.32
			Erythrophleum chlorostachys	0.016	0.011	3.41
			Eucalyptus bigalerita	0.011	0.008	1.46
			Eucalyptus patellaris	0.007	0.005	2.44
			Ficus opposita	0.001		0.16
			Terminalia sp.	0.005	0.003	0.49
OíNeil	logged	40B	*Buchanania obovata*	0.020		0.32
			Corymbia bella	0.036	0.022	4.14
			Corymbia polycarpa	0.051		0.32
			Erythrophleum chlorostachys	0.029	0.013	7.32

			Eucalyptus patellaris	0.019		0.32
			Ficus opposita	0.013		0.32
OíNeil	logged	40C	*Corymbia bella*	0.023	0.010	2.23
			Corymbia grandifolia	0.007	0.002	0.95
			Corymbia polycarpa	0.073	0.044	1.27
			Erythrophleum chlorostachys	0.029	0.019	4.46
			Eucalyptus bigalerita	0.024	0.015	5.09
			Eucalyptus patellaris	0.016	0.009	1.27
			Terminalia sp.	0.015		0.32

Non-Riparian Plots

Site	Plot number	Species	MeanBA (m≤)	S.D. of BA (m^2)	No. of Trees /0.25 ha
Eureka	36-1	*Brachychiton* sp.	0.012		1.27
		Corymbia confertiflora	0.051	0.041	5.09
		Corymbia foelscheana	0.048	0.034	3.82
		Erythrophleum chlorostachys	0.010	0.001	2.55
		Eucalyptus tectifica	0.025	0.013	12.73
Eureka	36-2	*Eucalyptus bigalerita*	0.012		1.27
		Eucalyptus patellaris	0.149		1.27
Eureka	36-3	*Corymbia foelscheana*	0.073	0.047	3.82
		Corymbia grandifolia	0.077	0.046	2.55
		Erythrophleum chlorostachys	0.035	0.042	3.82
		Eucalyptus bigalerita	0.011	0.000	2.55
		Eucalyptus patellaris	0.086	0.051	10.19
Eureka	38-5	*Corymbia grandifolia*	0.018		1.27
		Erythrophleum chlorostachys	0.016	0.009	5.09
		Eucalyptus tectifica	0.050	0.024	22.92
		Lophostemon grandiflorus	0.048		1.27
OíNeil	29-4	*Corymbia confertiflora*	0.023	0.014	5.09
		Corymbia foelscheana	0.075	0.033	3.82
		Erythrophleum chlorostachys	0.043	0.026	6.37
		Terminalia sp.	0.043	0.026	6.37
Eureka	38-6	*Corymbia confertiflora*	0.012		0.32
		Corymbia foelscheana	0.028	0.010	0.64
		Corymbia latifolia	0.010	0.005	1.91
		Erythrophleum chlorostachys	0.006	0.003	3.50
		Eucalyptus tectifica	0.006	0.003	3.18
OíNeil	41-3	*Corymbia confertiflora*	0.046	0.011	3.82
		Corymbia foelscheana	0.035	0.020	5.09
		Erythrophleum chlorostachys	0.017	0.004	22.92
		Eucalyptus tectifica	0.095	0.015	5.09
OíNeil	41-5	*Buchanania obovata*	0.090		1.27
		Corymbia bella	0.095		1.27
		Corymbia confertiflora	0.043		1.27
		Erythrophleum chlorostachys	0.226	0.226	3.82
		Eucalyptus patellaris	0.042	0.025	10.19

6. The occurrence of hollows in eucalypts and ironwoods

Robert Taylor

Introduction

In southern Australia arboreal mammals and birds have been shown to be influenced by the distribution and abundance of hollows (Lindenmayer*, et al.* 1990a,1991; Milledge *et al.* 1991; Smith and Lindenmayer 1988) and the large scale forestry operations that occur there have been shown to have a dramatic influence on the hollow resource (Recher *et al.* 1980; Lindenmayer*, et al.* 1990b; Loyn 1993; Ball *et al.* 1999; Gibbons *et al.* 2000). These studies have been used to develop prescriptions for the retention of a proportion of habitat trees (ie trees with hollows suitable for fauna) with all of the States involved in logging of native forest requiring their retention through logged areas (Gibbons and Lindenmayer 1997).

Knowledge of the hollow resource and its use by fauna in the Northern Territory is extremely limited. However it is likely that hollows are as important in the Northern Territory as in southern States. Thus, for the Top End of the Northern Territory, 41% of 71 mammal species, 16% of 267 bird species, 21% of 150 reptile species and 13% of 32 frog species use hollows (Taylor *et al.* 2002). Very few studies of

Fig. 6.1. *E. miniata* on sandy flats with a rocky hill in the background.

hollow use or the occurrence of hollows have been undertaken in Northern Australia. Tidemann *et al.* (1992) examined hollow use by two species of finches, Braithwaite *et al.* (1985) examined the incidence of hollows in trees in five different habitat types in Kakadu National Park and Kurucz (2000) has looked at the use of hollows by Red-tail Black Cockatoos *Calyptorhynchus magnificus*.

Timber harvesting only occurs at a low intensity in the Northern Territory (see chapter 8). However, ironwood trees are preferentially harvested and hollow dwelling species could be negatively impacted if this species was particularly rich in hollows. Local impacts could also occur if a large number of trees of any species with hollows were targeted in a local area. This study reports on the occurrence of hollows in different tree species and in different habitats in an area of forest in the north east of the Northern Territory. The Gouldian Finch *Erythrura gouldiae*, a hollow dependent threatened species, nests in rocky hills in the study area and so particular attention was paid to comparing the occurrence of hollows in these areas with those on the flats. Three main questions were addressed by the study:

- How does the hollow resource on rocky hills compare with that on adjacent flats?
- How does the hollow resource in riparian areas compare with other areas?
- How does ironwood compare with eucalypts in relation to hollows present?

Fig. 6.2. Clearwater Billabong

Study Area

The study was undertaken in the Limmen National Park, approximately 180 kms north-west of Borroloola, in the Gulf Falls and Uplands bioregion of the Northern Territory. The climate of the Gulf region is monsoonal. Rainfall typically occurs between October and May with an average annual rainfall of 770 mm for Borroloola. Average temperatures vary throughout the year. Mean temperatures for the hottest months October and November range from 35-40°C maximum to 29-31°C minimum. The coolest month of the year is July, with a mean minimum temperature of 10°C and a mean maximum of 28° C.

The area is comprised of sandstone ranges and broad open savannas (Aldrick and Wilson 1990). The current drainage system was created by slow erosion of mature, laterized surface deposits. The rocky hills carry a low open tree cover with tall eucalypt woodland present on the deep sand at the base of the steeper sandstone outcrops. The flat open savanna sites on cracking clays are dominated by perennial grasses with a tall tree canopy occurring along the margins of freshwater billabongs and open eucalypt woodlands present on the gradual slopes with clay loam soils.

Methods

Sampling

Sampling on the rocky hills and adjacent sandy flats (Fig. 6.1) was undertaken in a series of 50 x 50 m (0.25 ha) plots. All trees greater than 10 cm diameter at breast height (DBH), both alive and dead (including stumps), were sampled in these plots. The hollow resource present in eucalypts along riparian areas was assessed by investigating all trees within one to three metres of the drainage channel along both sides of the 280 m long Clearwater billabong (Grid reference 544292E 8265033N, Fig. 6.2) and for 780 m downstream. Along the section of stream sampled, and along most riparian sections in the study area, large trees were limited to the immediate environs of the drainage line.

There was an insufficient density of ironwood present in the study area to warrant quantification of the numbers of hollows per unit area in this species in the time available. Hence ironwood trees present along tracks and riparian areas were sampled. Tracks were driven until an ironwood was observed and then all trees present in nearby areas within approximately 50 to 100 m of the track were sampled. The ironwood sampled along riparian areas occurred around Clearwater Billabong and down stream for about 200 m.

If the tree branched before breast height the DBH of the largest branch was recorded. If the tree had more than one stem from ground level each trunk was counted as a tree. The number of hollows present in a tree was assessed from the ground. This will probably have led to an overestimation in the number of actual hollows as some hollows assessed as such from the ground may not have had any depth. This overestimate is more likely in taller trees on flat ground where the inside of the hollow could not be observed in a larger proportion of hollows. Hollows were classified on the basis of the smaller of the maximum value of the width and maximum value of the height of the entrance: small, <5 cm; medium, 5 to 10 cm; and large >10 cm. For example, for a hollow with a long narrow entrance the maximum width across the length of the crack was used to define the size.

A hollow index was calculated for each tree by summing the number of small hollows, the number of medium hollows multiplied by two and the number of large hollows multiplied by six. This enabled a single value to be calculated for each tree indicating the extent of occurrence of hollows. Larger hollows were given a greater weighting as they will be able to be used by a greater range of birds and mammals, they take longer to develop and they probably indicate a greater hollowing out of the trees. Large hollows were approximately six times less common than small hollows.

Data analysis
In order to compare the size of different tree species or the same tree species in different locations DBH was firstly log transformed. Two means were then compared using a t-test and more than two by analysis of variance followed by least significant differences to compare individual means if the ANOVA was significant. The Pearson correlation coefficient (r) was calculated to assess the correlation between DBH and the hollow index. Analysis of co-variance was used to test for differences in the relationship between DBH and the hollow index between species.

Results

Numbers of trees sampled for the major eucalypt species and ironwood is given in Table 6.1.

Comparison of hollows in eucalypts on rocky hills and adjacent flats
Mean size of trees varied between eucalypt species on the rocky hills (*E. leucophloia* and *C. ferruginea*) and flats (*E. miniata*) ($F_{(2, 142)}=6.4$, $p<0.01$, Table 6.1) with *E. miniata* significantly larger than *E. leucophloia* ($p<0.01$).

DBH was significantly correlated with the hollow index for the two eucalypt species present on the rocky hills (*E. leucophloia,* $r = 0.61$, n=50, $p <0.001$; *C. ferruginea*, $r = 0.80$, n=22, $p <0.001$) and for the eucalypt species (*E. miniata)* present on the flats ($r = 0.72$, n=75, $p <0.001$). There was no significant difference between the two species on the rocky hills in the relationship between DBH and the hollow index but eucalypts on the ridge had a greater hollow index for a given DBH compared with *E. miniata* ($F = 35.2_{(1,144)}$, $p<0.001$, Fig. 6.3).

On a per area basis there was a greater number of small and medium hollows and a greater hollow index on the rocky hills compared with the flat but only the difference for small hollows was significant (Table 6.2).

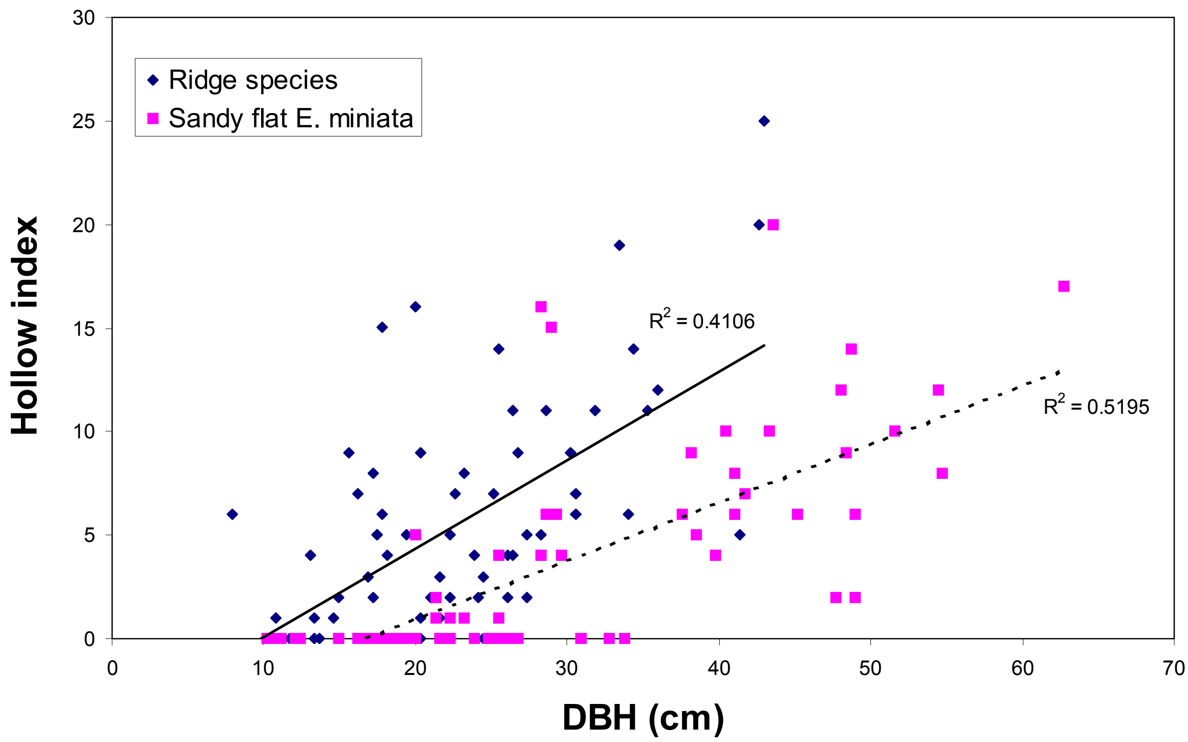


Fig 6.3. Relationship between the hollow index and diameter at breast height (DBH) for species on rocky slopes (*E leucophloia and C. ferruginea,* HI = 0.4276DBH ñ 4.2016) compared with *E. miniata* on sandy flats (HI = 0.2829DBH ñ 4.7438).

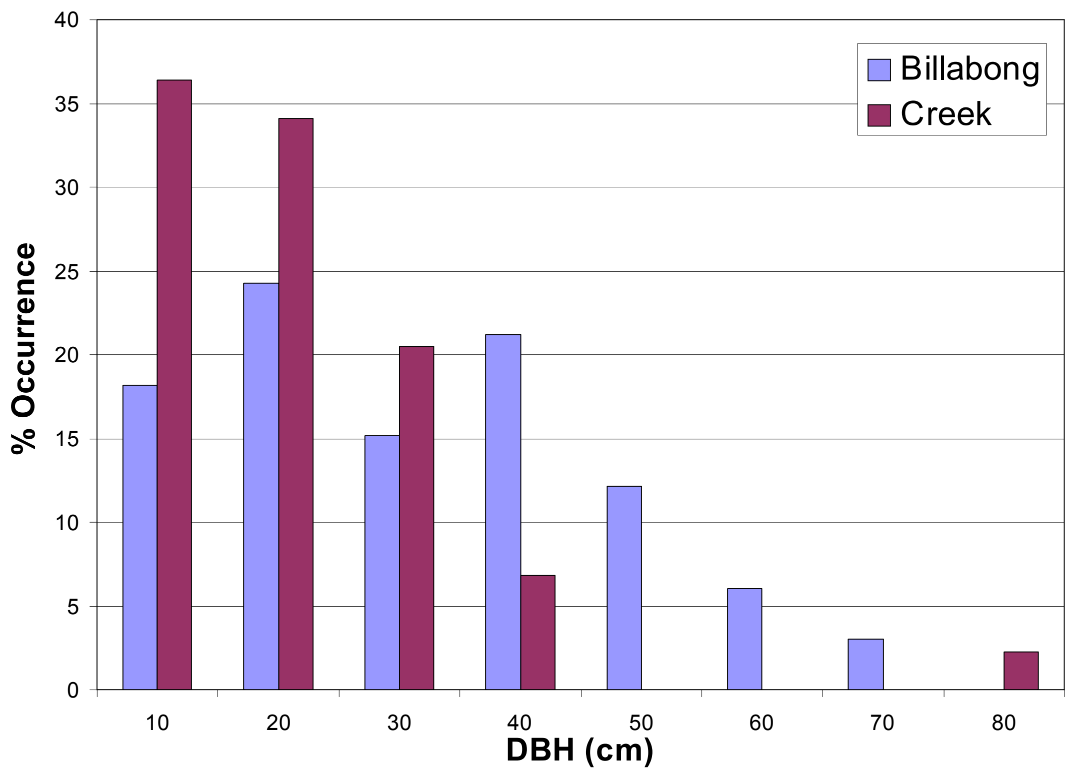


Fig. 6.4. Comparison of the DBH for *E. camaldulensis* occurring along Clearwater Billabong and along the major drainage lines downstream.

Table 6.1. Mean DBH (cm), standard error of DBH, maximum recorded DBH and sample size for eucalypt species and ironwood sampled in the study area. Values were back transformed after analysis using the log values.

Species	**No. of trees sampled**	**Mean DBH**	**Std. error**	**Max. DBH (cm)**	**No. of small hollows/ 100 trees**	**No. of medium hollows/ 100 trees**	**No. of large hollows/ 100 trees**
Riparian							
E. camaldulensis	78	27.2	1.1	87	151	158	41
E. microtheca	11	19.0	1.1	21	127	109	27
E. polycarpa	15	25.9	1.1	30	113	147	53
Rocky hill							
E. leucophloia	50	19.7	1.1	43	164	138	16
C. ferruginea	22	27.2	1.1	15	245	100	5
Flat							
E. miniata	75	25.9	1.1	63	73	73	19
E. chlorostachys	186	19.6	1.0	50	69	22	1

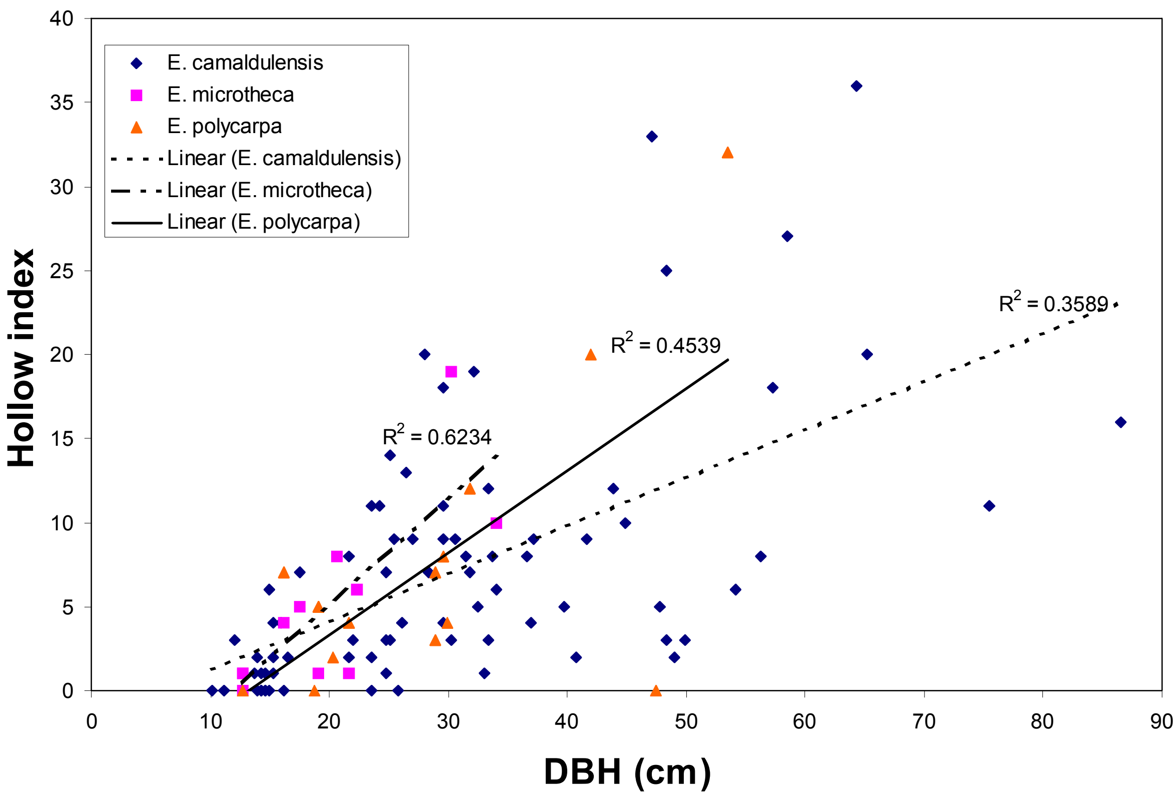


Fig 6.5. Relationship between the hollow index and DBH for three species of eucalypts occurring in riparian areas (*E. camaldulensis* HI = 0.2866DBH ñ 1.6743; *E. microtheca* HI = 0.6387DBH ñ 7.6784; *E. polycarpa* HI = 0.4892DBH ñ 6.4353).

Table 6.2. Mean number of hollows per hectare ± standard error, with number of plots in brackets, on rocky hills and flats. All species (eucalypt and non-eucalypt) and both live and dead individuals were included.

Hollow type	Rocky hill	Flat	Significance of difference
Small	160 ± 40(4)	54 ± 14 (5)	<0.05
Medium	109 ± 31 (4)	47 ± 16 (5)	N.S.
Large	12 ± 4 (4)	14 ± 4 (5)	N.S.
Hollow index	450 ± 123 (4)	230 ± 55 (5)	N.S.

Hollows in eucalypts along riparian areas
Along 1.34 km of stream and billabong banks *E. camaldulensis* predominated (78 trees) with *E. microtheca* (11 trees), *C. confertiflora* (4 trees) and *C. polycarpa* (15 trees) also present. *E. camaldulensis* trees were significantly larger (t = 2.76, df = 76, p<0.01) along the billabong (DBH mean ± standard error (N)) 32.3 ± 1.1 (33)) than along the downstream section of the drainage line (23.9 ± 1.1 (45)) where only small scattered waterholes were present at the time of sampling (Fig. 6.4).

DBH was significantly correlated with the hollow index for *E. camaldulensis* (r = 0.60, p <0.001), *E. microtheca* (r = 0.79, p <0.001) and *C. polycarpa* (r = 0.67, p <0.001) and there was no significant difference in the relationship between the species (Fig. 6.5).

Comparison of eucalypts in riparian areas, on flats and on rocky hills
For a given DBH riparian species had a greater hollow index compared with *E. miniata* ($F = 19.5_{(1,176)}$, p < 0.001, Fig. 6.6). There was no significant difference between the relationship between DBH and the hollow index for eucalypts in riparian areas and those on rocky hills.

Comparison of ironwood with eucalypts
Mean DBH differed significantly among the major tree species ($F_{(6, 428)}$=8.77, p< 0.001, Table 6.1). Mean DBH of ironwood was significantly smaller than *E. camaldulensis* (p<0.001), *C. polycarpa* (p,0.05) and *E. miniata* (p<0.001). The only eucalypt with a smaller mean DBH than ironwood was *E. microtheca* for which sample size was low. The relationship between DBH and the hollow index for ironwood was compared with that of *E. miniata*, the eucalypt with the lowest hollow index for a given DBH of those assessed in the present study. Ironwood had a significantly lower hollow index for a given DBH than *E. miniata* ($F_{(1,258)}$=4.3, p<0.05, Fig. 6.7). All three size classes of hollows were found in ironwood although only one large hollow was found in a live tree (Fig. 6.8) and one in one of 13 dead ironwoods. The proportion of live trees with medium and large hollows is lower in ironwood than in the eucalypts in the largest size class (Fig. 6.9). The proportion of trees with small hollows for ironwood is roughly comparable to the eucalypts (Fig 6.8) but in terms of absolute numbers per tree is lower than most eucalypt species (Table 6.1).

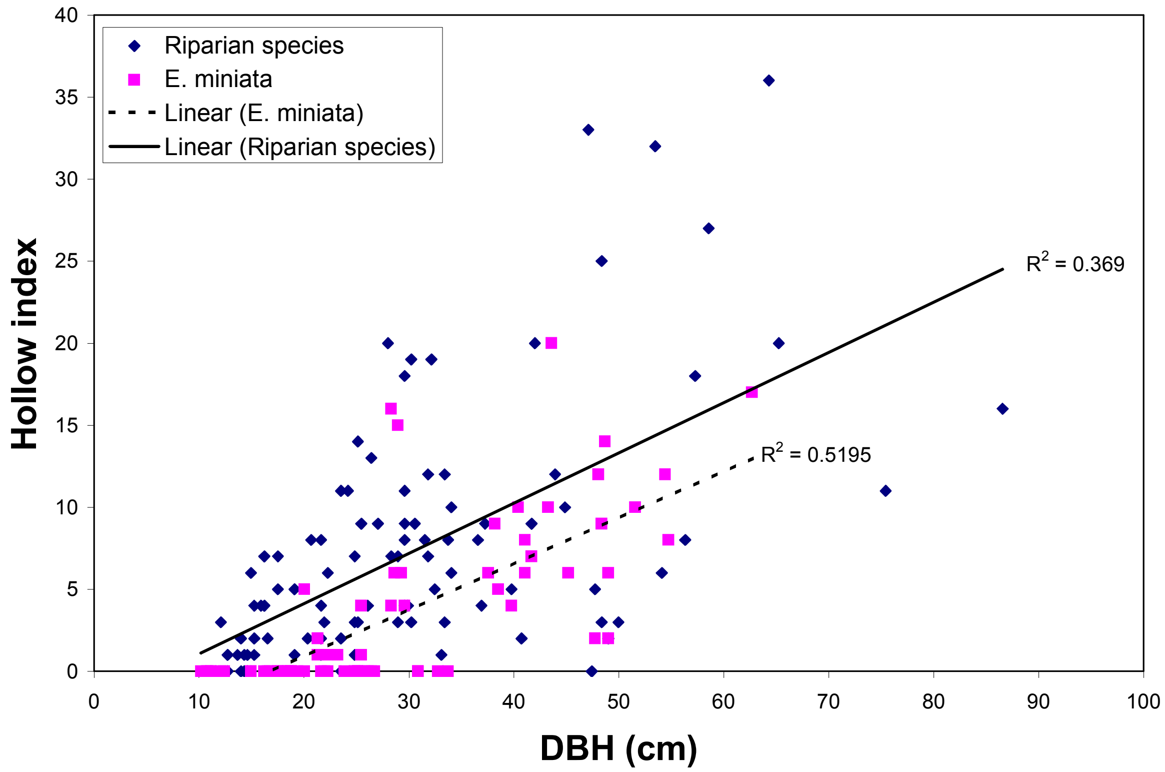


Fig 6.6. Relationship between hollow index and DBH for all major eucalypt riparian species (*E. camaldulensis*, *E. microtheca* and *C. polycarpa* HI = 0.3061DBH ñ 2.002) compared with *E. miniata* on sandy flats.

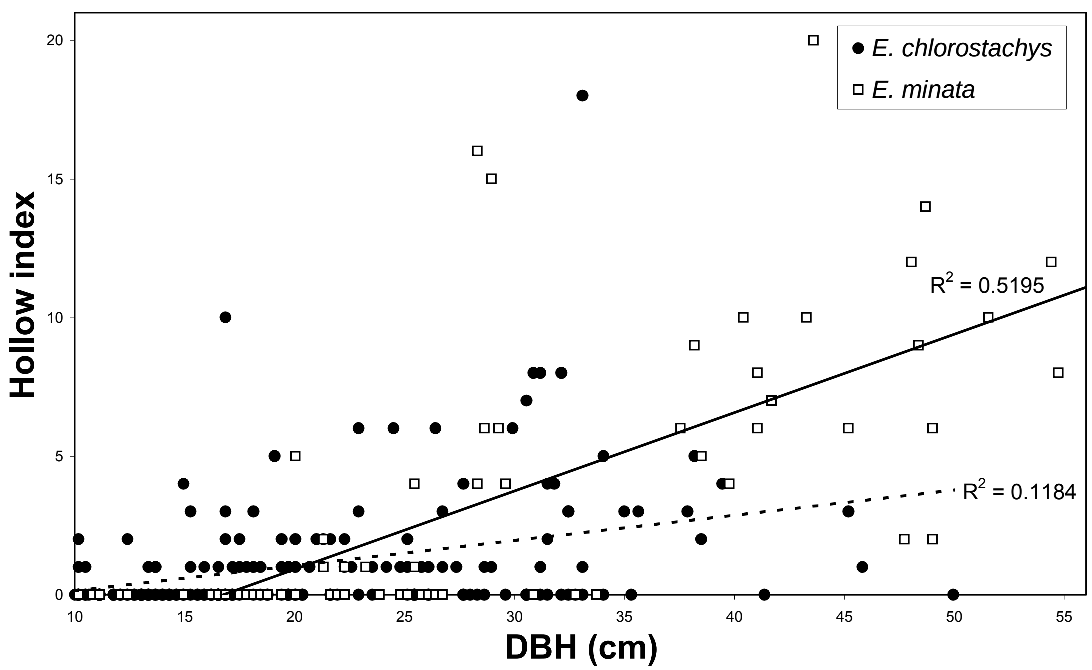


Fig 6.7. Relationship between hollow index and DBH for *Erythrophleum chlorostachys* (HI = 0.0912DBH ñ 0.7729) compared with *E. miniata* on sandy flats.

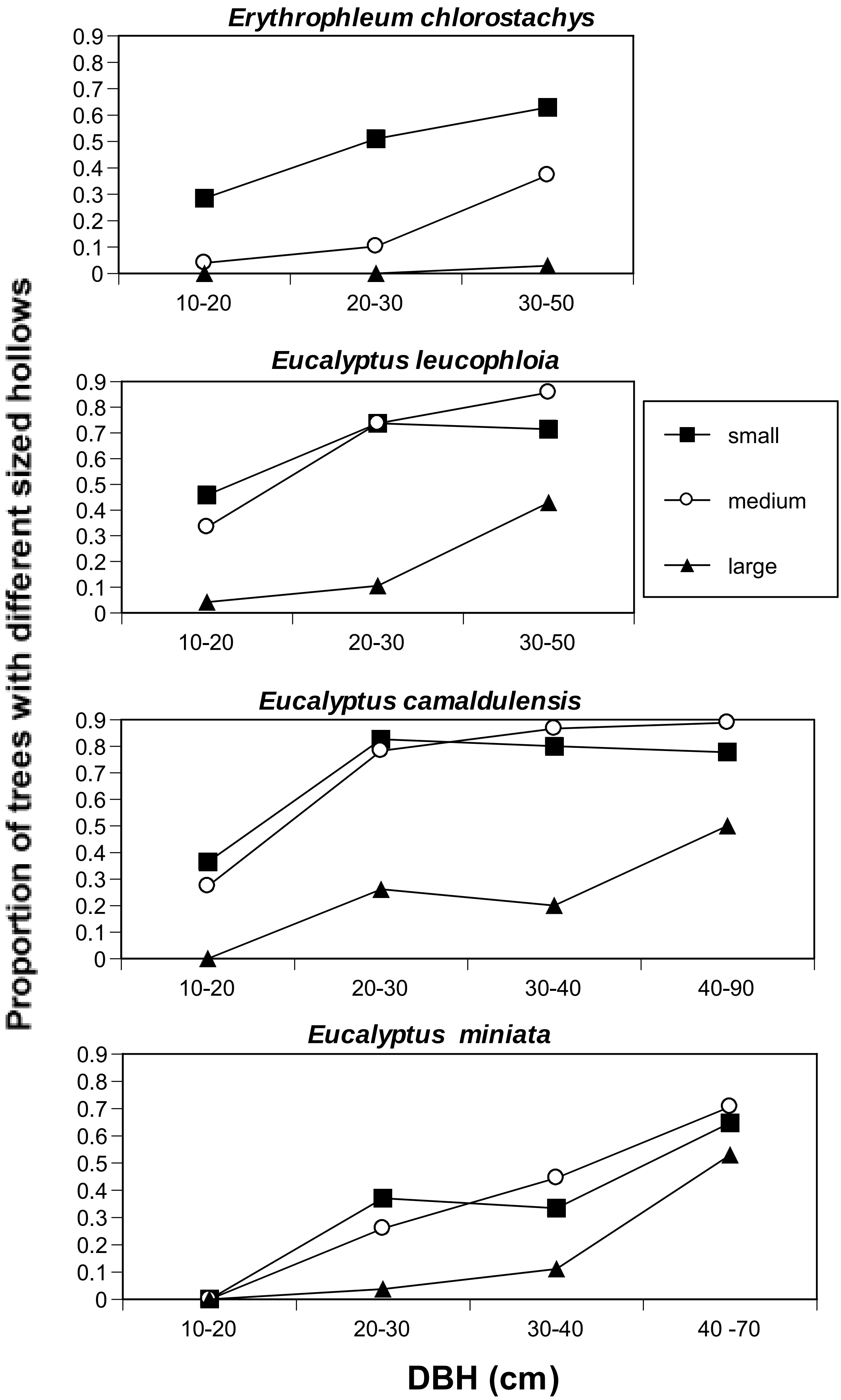


Fig 6.9. Relationship between DBH and the proportion of trees with different sized hollows for major eucalypt species and *E. chlorostachys*.

Fig. 6.8. The only large hollow found in a live ironwood tree.

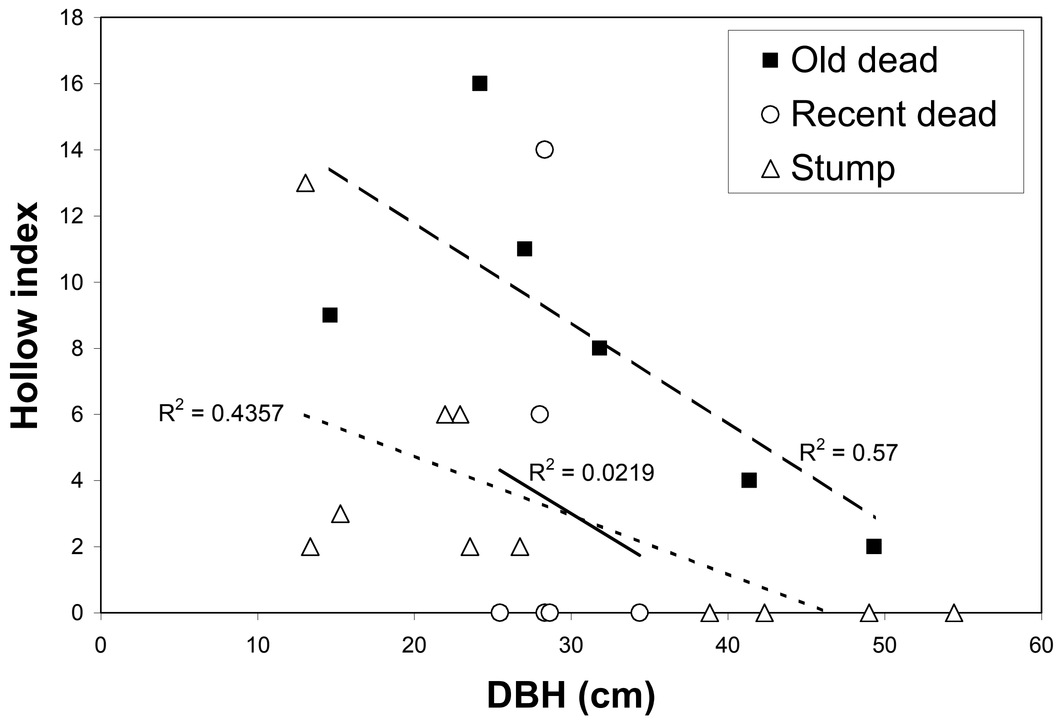


Fig. 6.10. Relationship between DBH and hollow index for dead eucalypts. Regression relationship for recent dead is a solid line, for old dead is a dashed line and for stumps is a dotted line.

Dead trees
In the 2.25 ha of plots on rocky hills and sandy flats there were six recently dead trees (ie those dead trees that still had lots of small twigs on the ends of the branches), nine older dead trees and 12 stumps (dead trees with no branches remaining). One of these was an ironwood and a minimum of three others were not eucalypts. Along the 1.34 km of riparian bank sampled there were two recently dead trees and eight older dead trees. The proportion of dead ironwood (6.5% of 199 trees) was not significantly different than that for the eucalypts (11% of 290 trees). There was no significant difference in the mean DBH of live and dead trees for either eucalypts or ironwoods. The hollow index of dead ironwoods was significantly greater than for live trees ($t=3.3$, $df=197$, $p<0.001$) but the hollow index for live and dead eucalypts was not significantly different. Unlike the relationship between DBH and hollow index for live eucalypts and live and dead ironwoods which has a positive slope, for dead eucalypts the hollow index declines as DBH increases (Fig. 6.9). The hollow index for a given DBH was significantly greater in dead than live ironwoods ($F_{(1,196)}=14.6$, $p<0.001$). However there were only two dead ironwoods greater than 20 cm DBH sampled and further sampling of large dead trees is required to be confidant of this result.

Discussion

Trees of the largest size occurred in riparian areas and particularly next to permanent billabongs. They also contained the highest number of medium and large hollows and the highest probability of a tree containing medium or large hollows. Large size will predispose these trees to having large hollows but disturbance during floods, such as branch breakage, will also probably increase the likelihood of hollows.

On the basis of a piping index, derived from descriptions from Penfold and Willis (1961) on the propensity of different species to suffer termite attack and piping, Braithwaite *et al.* (1985) concluded that hollows are more prevalent in Top End forests compared with other areas of Australia. Trees grow to larger sizes in the temperate, higher rainfall areas in Southern Australia compared with the Top End of northern Australia (cf Gibbons *et al.* 2000). However, the probability of occurrence of hollows in the largest size class of eucalypts in the present study area is generally greater for medium and large hollows than for the equivalent size class in the Gibbons *et al.* (2000) study. The largest size class of *E. camaldulensis* has a greater proportion of trees with medium and large hollows than the largest size class in Gibbons *et al.* (2000) but for *E. leucophloia* and *E. miniata* the proportion in the largest size class with medium and large hollows is less than in Gibbons *et al.* (2000). Even though smaller, the age of trees in Top End forests may be comparable with those in dry forest in southern Australia (Werner 1986). The predominance of termite attack in Top End trees (Fox and Clarke 1972) does not seem to have made a lot of difference in the proportion of trees with medium and large hollow entrances when old trees are compared in the two situations. The comparison with Gibbons *et al.* (2000) does not support Braithwaite *et al.*ís (1985) contention that there is a predominance of hollows in

Top End trees. However on a per hectare basis, there are more hollows with an entrance of <10 cm but fewer hollows with an entrance of >10cm than on Taylor and Haeselerís (1993) dry sclerophyll site in northeastern Tasmania. There was no trend for the proportion of trees with small hollows to be greater in small trees than in larger trees as found by Gibbons *et al.* (2000) for dry forests in NSW and Victoria.

The eucalypt species differed in their propensity to contain hollows. *E. miniata*, the largest non-riparian species, contained the smallest number of hollows for a given size of tree but, because of its large size relative to *E. leucophloia* on the rocky hills, it contained a similar number of large hollows on a per tree basis. The number of small and medium hollows/tree was greater for eucalypts on the rocky hills. The Gouldian finch occurs in the present study area and has been found to only nest on rocky hills in predominantly medium sized hollows (Tidemann *et al.* 1992; S. Tidemann pers. comm.). Other studies have also found eucalypts to differ in their propensity to form different sorts of hollows and hence be used differently by fauna (Manderson 1979; Taylor and Haseler 1993; Bennett *et al.* 1994; Lindenmayer *et al.* 2000). Braithwaite *et al.* (1985) considered that soil fertility influenced the occurrence of hollows through differential susceptibility to termite attack with species on more fertile soils being less prone to attack. In the present study area *E. minata* on flats and *E. leucophloia* and *C. ferruginea* on the rocky hills both occur on very infertile soils but differ in the extent to which they support hollows. However, riparian areas probably have the most fertile soils in the area but trees there have numerous hollows. This is probably related to their large size and the increased disturbance in these areas.

Dead ironwoods appear to support greater numbers of hollows than live trees. Once dead, ironwoods may be more susceptible to termite attack. Dead eucalypts in the present study area do not appear to have more hollows than live trees. Because of the greater susceptibility of eucalypts to termites dead eucalypts may have a shorter life than ironwoods and lose their branches quicker. As DBH of dead eucalypts increased their hollow index decreased. Once the branches of a eucalypt are lost the bole often contains few hollows due to its being filled up with termite nest material.

In the Northern Territory selective logging that concentrates on taking only trees of good form with solid boles should have little influence on hollow availability for fauna. This is particularly the case because of the tendency of harvesters to favour ironwood because of its resistance to termite attack. At this site the occurrence of hollows in ironwood is substantially lower than in the eucalypts, particularly with medium and large hollows. Kerle (1985) found that ironwoods were rarely used for roosting by arboreal mammals. However, in eucalypt forest in the rural fringes of Darwin 3 of 31 den trees used by Black-footed Tree-rats *Mesembriomys gouldii* were in ironwoods with a DBH of 47, 49 and 52 cm (B. Rankmore pers. comm.). Eucalypt trees of a large enough size to mill are frequently affected by termites (Fox and Clarke 1972) and hence contain little useable timber. The findings of Braithwaite *et al*. (1985) in relation to hollow occurrence in tree species from Kakadu National Park are, however, at odds with those from this study and the general perception of ironwood as a termite resistant species. Braithwaite *et al*. (1985) provided data on hollow availability in seventeen tree species from savanna woodland. Ironwood ranked third behind *E. miniata* and *E. tetradonta*, and above four other eucalypt species, in the number of large (>20 cm) hollows present and it ranked highest in terms of the number of small (<20 cm) hollows present. This difference would not have been due to size differences in the ironwoods in Kakadu and the present study area as the mean, coefficient of variation and maximum DBH were similar. Further assessment of the propensity of ironwoods to support hollows in areas where larger trees are more common, and hence where logging may be more likely, is warranted.

References

Aldrick, J.M. and Wilson, P.L. (1990). Land systems of the southern Gulf region, Northern Territory. Conservation Commission of the Northern Territory. Technical Report 42.

Ball, I.R., Lindenmayer, D.B. and Possingham, H.P. (1999). A tree hollow dynamics simulation model. *Forest Ecology and Management* **123,** 179-194.

Bennett, A.F., Lumsden, L.F. and Nicholls, A.O. (1994). Tree hollows as a resource for wildlife in remnant woodlands: spatial and temporal patterns across the northern plains of Victoria, Australia. *Pacific Conservation Biology* **1,** 222-235.

Braithwaite, R. W., Parker, B. S., Wood, J. T. and Estebergs, J. A., 1985. The distribution and abundance of termite-induced tree hollows in tropical forests of northern Australia. Pp. 651-729. In *The Kakadu fauna survey : an ecological survey of Kakadu National Park.* ed by R. W. Braithwaite. Report to ANPWS, Canberra.

Fox, R.E. and Clark, N.B. (1972). The incidence of termites in eucalypts of the Darwin area. *Australian Forest Research* **5,** 29-36.

Gibbons, P. (2000). The effects of slash burning on the mortality and collapse of trees retained on logged sites in south-eastern Australia. *Forest Ecology and Management* **139,** 51-61.

Gibbons, P. and Lindenmayer, D.B. (1997). Developing tree retention strategies for hollow-dependent arboreal marsupials in the wood production eucalypt forests of eastern Australia. *Australian Forestry* **60,** 29-45.

Kerle, J.A. (1985). Habitat preferences and diet of the northern brushtail possum *Trichosurus vulpecula* in the Alligator Rivers region, N.T. *Proceedings of the Ecological Society of Australia* **13**, 161-176.

Kurucz, N. (2000). The nesting biology of the Red-tailed Black Cockatoo (*Calyptorhynchus banksii macrorhynchus*) and its management implications in the Top End of Australia. M.Sc., Northern Territory University, Darwin.

Lindenmayer, D.B., Cunningham, R.B., Tanton, M.T., Smith, A.P. and Nix, H.A. (1990a). The habitat requirements of the mountain brushtail possum and the greater glider in the montane ash-type eucalypt forests of the central highlands of Victoria. *Australian Wlidlife Research* **17,** 467-478.

Lindenmayer, D.B., Norton, T.W. and Tanton, M.T. (1990b) Differences between wildfire and clearfelling on the structure of montane ash forests of Victoria and their implication for fauna dependent on tree hollows. *Australian Forestry* **53**, 61-68.

Lindenmayer, D.B., Cunningham, R.B., Tanton, M.T., Nix, H.A. and Smith, A.P. (1991). The conservation of arboreal marsupials in the montane ash forests of the Central Highlands of Victoria, south-east Australia. III. The habitat requirements of Leadbeaterís possum *Gymnobelideus leadbeateri* and models of the diversity and abundance of arboreal marsupials. *Biological Conservation* **56**, 295-315.

Lindenmayer, D.B., Cunningham, R.B., Pope, M.L., Gibbons, P. and Donnelly, C.F. (2000). Cavity sizes and types in Australian eucalypts from wet and dry forest types - a simple of rule of thumb for estimating size and number of cavities. *Forest Ecology and Management* **137,** 139-150.

Loyn, R.H. (1993). Effects of Previous Logging on Bird Populations in East Gippsland: VSP Retrospective Study. VSP Technical Report No. 18. Department of Conservation and Natural Resources, Melbourne.

Manderson, A.D. (1979). Aspects of forest management for natural hollows in Wombat State Forest. M. Env. Sci. Monash University, Melbourne.

Penfold, A.R. and Willis, J.L. (1961). *The Eucalypts: Botany, Cultivation, Chemistry and Utilisation*. (Leonard Hill: London).

Recher, H.F., Rohan-Jones, W. and Smith, P. (1980). Effects of the Eden woodchip industry on terrestrial vertebrates with recommendations for management. For. Comm. N.S.W. Res. Note No. 42.

Smith, A.P. and Lindenmayer, D. (1988). Tree hollow requirements of Leadbeaterís possum and other possums and gliders in timber production ash forests of the Victorian Central Highlands. *Australian Wildlife Research* **15,** 347-362.

Taylor, R., Woinarski, J. and Chatto, R. (2002). Hollow use by vertebrates in the Top End of the Northern Territory. *Australian Zoologist* submitted.

Taylor, R.J. and Haseler, M. (1993). Occurrence of potential nest trees and their use by birds in sclerophyll forest in north-east Tasmania. *Australian Forestry* **56,** 165-171.

Tidemann, S.C., Boyden, J., Elvish, R., Elvish, J. and OíGorman, B. (1992). Comparison of the breeding sites and habitat of two hole-nesting estrildid finches, one endangered, in northern Australia. *Journal of Tropical Ecology* **8,** 373-388.

Werner, P.A. (1986). Population dynamics and productivity of selected forest trees in Kakadu National Park. Report to Australian National Parks and Wildlife Service, Canberra.

7. Regeneration in logged and unlogged sites

Leigh Granger and Robert Taylor

Introduction

To date studies into regeneration of Top End trees have centred on eucalypts (Lacey 1974; Fensham and Bowman 1992; Setterfield 1996). However, some data are available for other species (e.g. the rainforest tree *Allosyncarpia*, Fordyce *et al*. 1997; ironwood, Iwainde 1998; and *Callitris intratropica*, Bowman and Panton 1993). A feature of juvenile growth of eucalypts in the tropical savanna is the predominance of a lignotuber and a deep root system. This enables them to quickly replace aboveground biomass lost after fire (Fensham 1992) and withstand fires until such time a fire free period allows them to attain a safe height (Lacey 1974). There is often a scarcity of saplings or poles with regeneration being dominated by a woody understorey of juveniles (Werner 1986; Bowman and Panton 1995). In a trial forestry site for *Eucalyptus miniata*, Lacey and Whelan (1976) found juveniles, protected from fire for four years, attained a height of 4m, at which stage they could withstand fire. Lacey and Whelan (1976) believed the presence of even aged stands in the same region that were overmature and inadequately stocked could be explained by fire events.

While it is clear that a fire free period is required for juveniles (<2 m tall) to grow large enough to withstand fire (Braithwaite and Estbergs 1985, Lacey 1974), other factors such as overstorey competition (Fensham and Bowman 1992) and disturbance by feral species such as buffalo (Werner 1986; Braithwaite and Estbergs 1985) may be suppressing juvenile eucalypts. It is often difficult to assess the underlying biological processes affecting regeneration due to the impact of fire (Lacey and Whelan 1976). Soil moisture content possibly controls regeneration by affecting growth rates and fire frequency and intensity. Wilson and Bowman (1987) found both understocked and well stocked areas of eucalypt forests on Howard Peninsula in an area of frequent burning and suggested this was due to differences in soil moisture levels during the dry season.

Ironwood is capable of vegetative reproduction by growth from lignotuber and rootsuckers (Fensham and Bowman 1992; Iwainde 1988). Like the *Eucalyptus* / *Corymbia* species, ironwood is often most prevalent on the forest floor where it forms woody sprouts less than two metres tall (Fensham and Bowman 1992; Fensham 1990; see Fig. 3.1).

Ironwood juveniles can respond well to fire protection. Bowman and Panton (1995) found fire protected sites carried more saplings (>2 cm <5 cm DBH) and poles (>5 cm <10 cm DBH) than corresponding ambient sites while the number of resprouts (<2 m tall) was reduced in fire protected sites. Similarly, Fensham (1990) found that ironwood saplings developed in fire protected sites in two widely separated areas, while all other dominant species failed to respond to fire history alone.

Knowledge of regeneration of ironwood and the impacts of timber harvesting on regeneration is vital in assessing the sustainability of harvesting operations. Harvesting at the Mary River East Station that occurred 5-6 years ago provided an opportunity to assess regeneration after logging events.

Methods

The study was conducted on the Mary River East Station (see section 5.2 for details on this area).

Regeneration assessment
Areas harvested occurred along riverflats. Logging intensity varied within the riparian areas. Due to time limitations plots were only placed in areas where the highest intensity of logging had occurred. Three plots were established along both OíNeil and Eureka Creeks (i.e. total of six plots) within areas harvested in 1996-1997. In harvested areas regeneration plots were located within the quadrats where trees >10 cm DBH had been measured. The regeneration plots were circular with a 20 m radius, the centre point being the nearest stump from the centre point of the quadrat. Regeneration plots were also placed in other areas where there was no evidence that timber harvest had occurred. For the plots in unlogged areas two were placed on the OíNeil creek system and three on the Eureka Creek flat in locations that appeared to have escaped harvest. All vegetation <10 cm DBH were included as juveniles and regeneration counts were divided into three height classes: <1.5m; 1.5-3 m; and >3 m.

Root systems of 10 ironwood juveniles were excavated in an attempt to differentiate between seedlings and vegetative growth (ie shoots from existing roots). We also scratched around many seedlings to look for horizontal roots near the soil surface

Fire Assessment
All plots were assigned a short-term (~6-12 months) fire rating. Unfortunately little is known of the long term frequency or intensity of fires in the study sites. Fire ratings were based on the presence of grasses and other herbage and the visual effects of fire on existing saplings. Ratings were as follows:
1 = grasses not burnt, resprouts >50 cm, saplings >1.5 m unaffected;
2 = pockets of grasses not burnt, resprouts >50 cm, saplings >1.5 m mostly unaffected;
3 = pockets of grasses not burnt, resprouts <50 cm, saplings >3 m sometimes affected, and
4 = most undergrowth burnt, resprouts <50 cm, saplings >3 m affected.
These ratings are a crude index of past fire and are only used in the absence of any other records.

Stump Assessment
Stumps were assessed within the quadrats at each harvest site and in the harvest area as a whole. Diameter and height of the stumps were recorded. Only ironwood regeneration direct from the stump was recorded. It is highly likely that at least some of the ironwood resprouts and saplings nearby to the stump were clones generated from the roots of the stump. However, as this relationship could only be verified by extensive excavation of the root systems, only the coppice growth directly emanating from the stump were assessed. The number of coppice per stump, DBH and height of coppice were recorded. Coppice DBH and individual coppice heights were only measured if the DBH was >5 cm. Where a number of small coppice occurred that were <5 cm DBH the tallest height was recorded.

Data analysis
The data did not display a normal distribution even with transformation. Hence nonparametric tests (Mann Whitney U test and Kruskal Wallis Anova by ranks) were used.

Results

A preliminary assessment of the role of root systems in coppice growth
Excavations of the root systems of ironwood seedlings and saplings (to a depth of approximately 50 cm) disclosed a number of horizontal roots (Fig 7.1). There were usually several possible associations with extant trees and remains of stumps. Without extensive evacuation of the root system it was impossible to accurately determine from which parent tree or stump individuals arose. In many cases the connecting sucker was possibly degenerated (Fig 7.2). In small resprouts a large amount of underground biomass indicated several years of regrowth following fires (Fig 7.2). It was concluded that without major excavations it would be impossible to ascertain the true nature of the regeneration. Thus all regeneration was assumed to be vegetative. As a result regeneration of ironwood was assessed in two ways: assessment of coppice growing directly from the stumps and assessment of saplings and small woody juveniles, all of which were assumed to be vegetative.

Stump Assessment
The maximum heights attained for each ironwood coppice or group of coppice per stump and the average number of coppice per stump were significantly higher at Eureka Creek that at OíNeil Creek ($p<0.001$ and $p>0.05$, Mann-Whitney U Test) but did not differ significantly between fire ratings (Table 7.1). Fire had obviously affected coppices at OíNeil Creek in the recent past (Fig. 7.3) The age of the comparatively intact coppice at Eureka Creek (Fig 7.4) could not be deduced. However, a fire free period must have occurred in recent years that has allowed them to attain a height that afforded a measure of immunity from fire.

Assessment of juveniles and saplings not associated with stumps
Regeneration of ironwood away from stumps was dominated by woody juveniles under 1.5 m with few saplings (>2 m in height with <5 cm DBH) or poles (>2 m in

Fig 7.1. Root system of an ironwood sapling. The major root seen at the arrow point is probably a connection to an adult tree nearby.

height with 5-10 cm DBH) present (Fig 7.5). Sites varied widely regardless of logging. The Eureka Creek sites (logged and unlogged combined) had significantly greater numbers of ironwood individuals in all size categories ($p<0.05$ for juveniles and pole and $p<0.01$ for sapling, Mann-Whitney). There is evidence of some successful regeneration of ironwood in the Eureka Creek harvest site with the presence of a number of individuals in the sapling and pole classes. In comparison it appears that the OíNeil Creek harvest area is failing to regenerate beyond the woody sprout level with less than five ironwood saplings in the three sites combined. Regeneration in the Eucalypt / *Corymbia* group was not significantly different between areas or logged and unlogged sites (Fig 7.6).

Discussion

Mary River East Station is one of the few areas in the Northern Territory where ironwood has been selectively harvested in the past decade. Nearly all other timber permits relate to salvage of timber from areas that are subsequently cleared (Section 8.1). Mary River was therefore the only site available to assess regeneration of ironwood following selective logging. Unfortunately the site is not ideal for several reasons:

- It appears to be highly likely that Ironwood was harvested on Mary River East between 1880-1960 (Iwaide 1998). The construction of the railway from Darwin to Pine Creek required large amounts of ironwood and suitable trees were considered scarce (Hanssen and Wigston 1989). Mary River East Station is 40 km from Pine Creek. Anecdotal evidence suggests that ironwood was harvested on Mary River East for use as sleepers on the railway and in the

Fig 7.2. Root systems of juvenile ironwood. The thick woody root system shown in the photo on the left indicates that this individual has resprouted many times after fire. Over the years it has allocated resources to underground biomass to ensure survival. The position of the pencil in the photo on the left indicates a degenerating root (possibly the remains of an earlier connection to a parent plant or a root sucker) produced by the juvenile that has succumbed to insect attack. The characteristic L shape seen in the photo on the right is probably a remnant of an earlier attachment to a parent plant.

Table 7.1. Characteristics of ironwood coppice associated with stumps in the two areas sampled and in relation to the rating of short-term fire history. Values for height and number of coppice are means ± standard errors with sample sizes in brackets.

	Max. height	**No./ stump**	**% stumps with no coppice**	**% stumps with coppice <1.5m**	**% stumps with coppice >3m**
Area					
Eureka	3.00 ± 0.36 (40)*	19.6 ± 25.3 (40)	8%	18%	40%
OíNeil	1.38 ± 0.32 (47)	2.7 ± 4.4 (47)	55%	19%	19%
Fire rating					
1	2.57 ± 0.36 (51)	9.5 ± 19.7 (51)	27%	20%	35%
2	1.44 ±0.31 (31)	11.2 ± 18.7 (31)	13%	19%	19%
3	1.76 ± 1.02 (5)	15.8 ± 20.9 (5)	40%	0%	20%

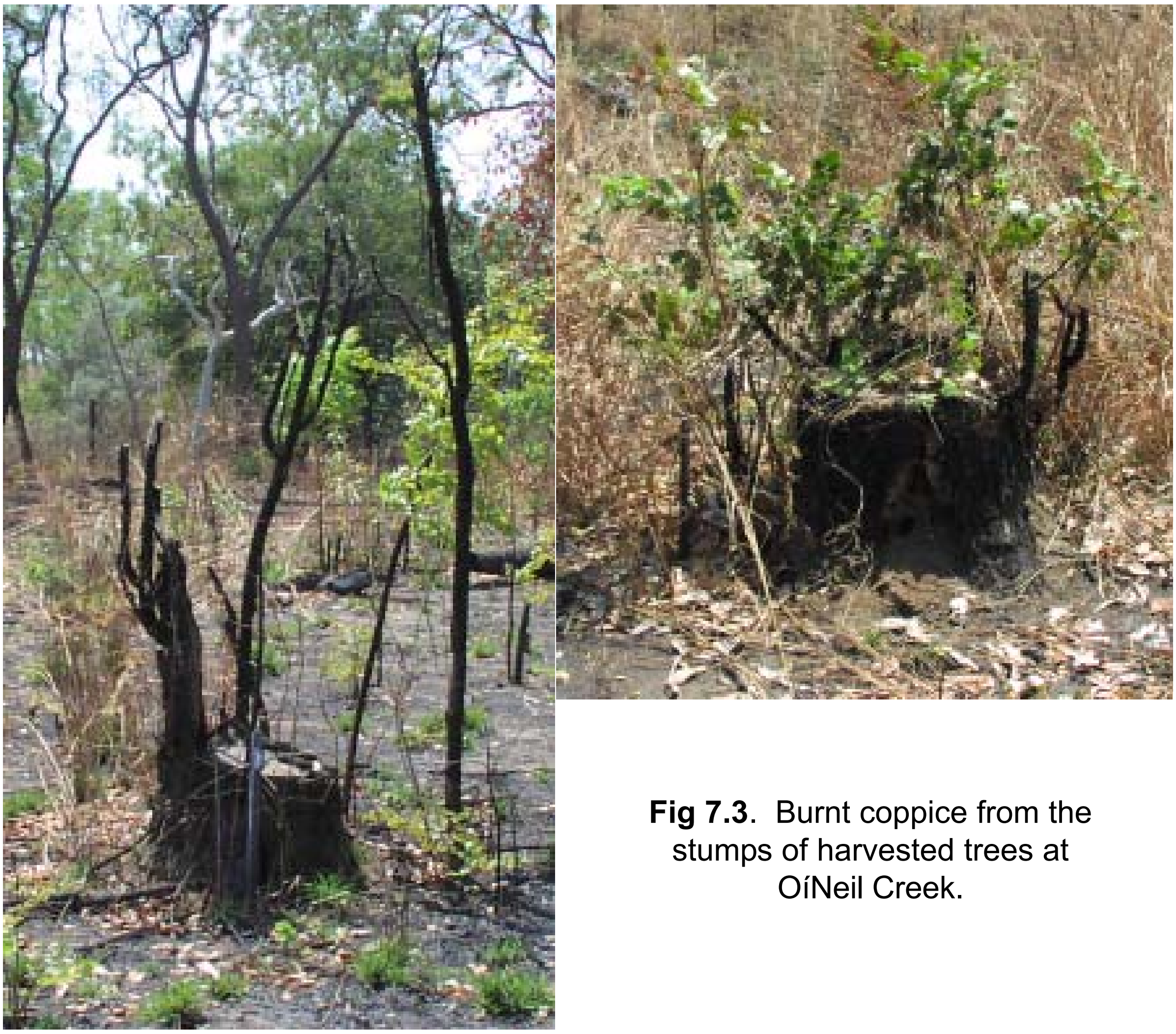


Fig 7.3. Burnt coppice from the stumps of harvested trees at OíNeil Creek.

numerous mining operations that have been a constant theme in the Mary River East area (Iwainde 1998). Evidence of early logging events (prior to 1994) can sometimes be seen in the form of old stumps. Due to the age of the stumps and the affects of fire it was not possible to accurately determine the species of tree harvested. However, ironwood was a sought after timber in the area (Hanssen and Wigston 1989) and it is safe to assume some proportion of the existing old stumps are ironwood. Thus the Mary River East station has probably been exposed to logging events over a period of 100 years or more. This is likely to have altered the structure and composition of ironwood in the region.

- No records were available to allow an assessment of what areas were harvested and the year they were harvested.
- No information is available on fire history, particularly intensity and frequency of fires.
- Ironwood harvesting appears to have only occurred in the alluvial flats adjacent to creeks and all areas of this type have almost certainly been selectively harvested where access is possible. Often only very small numbers of trees have been taken (an average of 7 stumps/ha, see section 8.2) but completely unharvested areas are difficult to find and this renders comparisons difficult.

Fig 7.4. Healthy coppice growing from a stump in the Eureka Creek harvest area.

- Most of the old logging tracks have been washed out during previous wet seasons making access difficult.

The level of regeneration of ironwood after harvesting (both on and away from stumps) was greater at Eureka Creek than at OíNeil Creek. The fire rating, despite being greater at OíNeil Creek, was not significantly related to the level of regeneration in the two areas. The patchy nature of previous fires (particularly around creeklines) often resulted in a number of different fire ratings within a harvest area. It is likely that fire history beyond the past year was influencing coppice survival. To adequately assess the impact of fire on ironwood regrowth, stumps would need to be monitored and fire events recorded, including the intensity and time of fire, until saplings reach a size where they can survive a fire.

Iwainde (1993) found that an early dry season fire, presumably a low intensity fire given the season, affected ironwood coppice on 29% of stumps with coppice on low cut stumps being more susceptible to fire than those on high cut stumps. Monitoring of the effects of fire on ironwood regeneration has been undertaken at

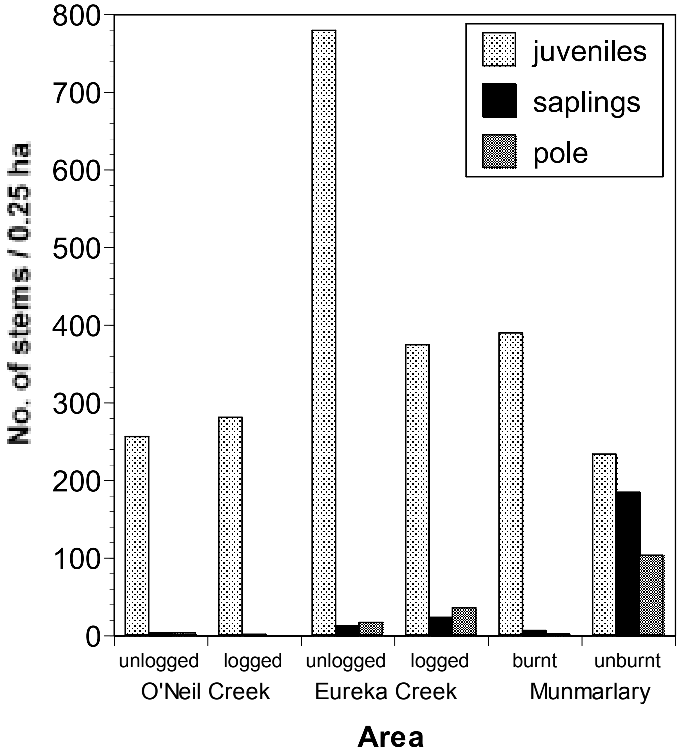


Fig. 7.5. Density (no./0.25 ha) of ironwood juveniles, saplings and poles in logged and unlogged areas at OíNeil and Eureka Creek with a comparison to that obtained by Bowman and Panton (1995) in burnt and unburnt areas at Munmarlarey.

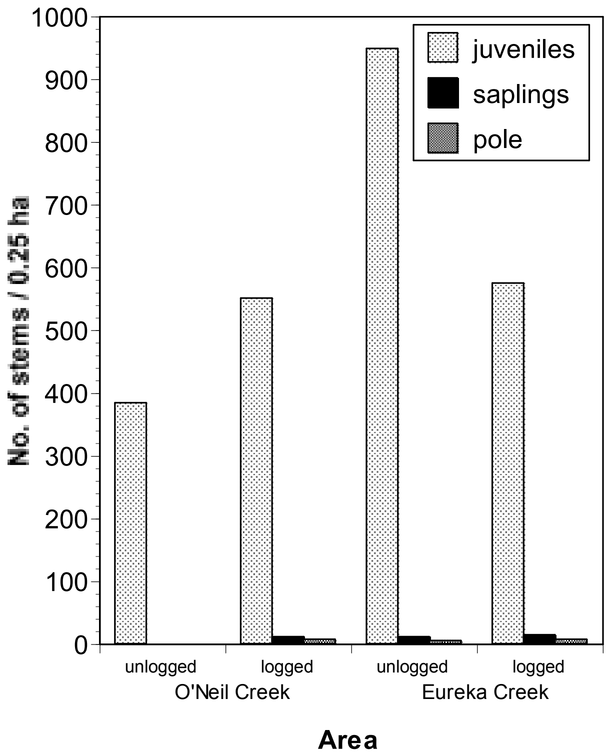


Fig. 7.6. Density (no./0.25 ha) of *Eucalyptus* / *Corymbia* juveniles, saplings and poles in logged and unlogged areas at OíNeil and Eureka Creek.

Munmarlary, where different fire regimes were imposed over a long period (Bowman and Panton 1995). Regeneration was assessed by Bowman and Panton (1995) in fire protected and burnt sites with the fire regime in the burnt sites being generally biennial late dry season fires. Mary River East sites clearly resemble the size distribution of Bowman and Pantonsí (1995) burnt sites (Fig 8.5). Unburnt sites at Munmarlarey have eight times the number of saplings and three times more individuals in the pole size class compared to the best Mary River East sites (Eureka Creek logged). The large number of woody individuals <1.5 m is consistent with the response expected under a high fire disturbance regime by a species that uses coppicing as a regeneration strategy. Excavation of ironwood saplings often revealed extensive horizontal expansion of roots and small juveniles had characteristically large root masses. In many plant species that exhibit root suckering or rhizome development, frequent burning will promote lateral expansion and development of patches of small stemmed clones (Lacey and Whelan 1976).

It is possible that timber harvesting promotes an increased fire frequency. Fuel loads have been shown to increase after areas are opened up due to an increase in grass cover (Bowman and Wilson 1988) and thus consequently increasing the intensity and frequency of fire. Ground disturbance and reduced canopy cover associated with logging and spread of seeds by machinery could also favour exotic grass species. Gamba grass *Andropogon gayanus*, a highly flammable exotic, is present in creeklines adjacent to the OíNeil Creek harvest area. Gamba grass, because of its high biomass, increases the intensity and height of fire and leads to increased mortality of adult trees (Wilson and Mudita 2000). It is evident that fire management will influence the sustainable yield of ironwood. The current lack of fire management at Mary River East is likely to result in a lower resource availability of ironwood in the future.

There was no significant effect of logging on the extent of ironwood regeneration. Slightly higher densities of the sapling and pole classes occurred in logged than unlogged areas at Eureka Creek, but this pattern was not repeated at OíNeil Creek. Fensham and Bowman (1992) found ironwood regeneration did not necessarily occur after clearfelling with ironwood saplings increasing in fire protected clearings but not in frequently burnt clearings. Thus fire regimes are probably masking any influence that logging may have had on regeneration.

Regeneration in the *Eucalyptus* / *Corymbia* group did not differ significantly between the two areas or between logged and unlogged sites. There were high numbers of juveniles present in all areas but low numbers of saplings and poles. Thus there also appears to be a mortality factor operating on juveniles limiting recruitment into the older age classes. Fire protection does not necessarily lead to increased recruitment of juveniles into the canopy (Bowman and Panton 1995). Fensham and Bowman (1992) suggested that intraspecific competition was the cause of suppression of *Eucalyptus* juveniles. The low intensity selective logging in the study area may not have been sufficient to reduce competition between juveniles and mature individuals. Thus Fensham and Bowman (1992) found only a weak association of eucalypt saplings and natural canopy gaps but a marked response of suppressed stems and sapling accession after the production of large gaps in the canopy (sometimes after a delay of 3-5 years). Densities in the sapling and pole classes required to ensure survival of the eucalypt woodland species are not known (Werner 1986). However, there are examples where the size distributions of *Eucalyptus / Corymbia* species suggest a declining population (Werner 1986, Braithwaite and Estbergs 1985).

It is difficult to know what role sexual reproduction has in ironwood regeneration. Williams *et al.* (1999) found sexually reproductive structures were rare in ironwood over a 30-month assessment period. Flowering was occurring at the time of our study but displayed a rather erratic distribution. Flowering and the remnants of seedpods were observed in a range of size classes and the density of flowers on a given tree was also highly variable. Analysis of ironwood root systems at a depth of 50 cm for a small number of individuals indicated all were probably a result of vegetative reproduction. Extensive excavation may have revealed the presence of a small proportion of ironwood seedlings. Survival of seedlings is difficult under a regime of frequent fires. With the absence of underground biomass to support regrowth a fire safe height would be more difficult for a seedling to achieve (Lacey and Whelan 1976). Seed supply may also be affected by fires. Setterfield (1997) found that intensity and timing of fires affected seed supply in two eucalypt species *E. miniata* and *E. tetrodonta.*

It is unlikely that vegetative cloning can occur indefinitely. In *Eucalyptus / Corymbia* species, root decay and herbivory probably affect vegetative reproduction (Fensham and Bowman 1992) and distribution of new individuals will always be restricted to relatively small areas compared to regeneration by seed dispersal (Lacey 1976). Evidence from assessment of *E. tetrodonta* and *E. porrecta* suggest that in areas where vegetative growth has predominated and extensive underground systems exist, the capacity to grow rapidly in the absence of fire has been lost (Lacey and Whelan 1976).

Regeneration may also have been affected by the introduction herbivores such as buffalo (Werner 1986). Disturbance by feral animals in combination with fire events may prevent recruitment of juveniles to the canopy layer and may be contributing to forest decline (Werner 1986). The effects of large grazing animals are especially relevant to Mary River East. Anecdotal evidence suggests that large numbers of pigs, several herds of buffalo and mobs of horses frequent the area. Buffalos and pigs were observed in one of the harvest areas and elsewhere on Mary River East, moving or congregating along creeklines. Damage to the soil surface in the form of pig and buffalo wallows and trampling is widespread throughout the harvest areas and is likely to have some effect on accession of juveniles to older growth stages. Iwainde (1998) believes that feral animals can sometimes promote coppicing by ironwood via disturbance to roots.

References

Bowman, D.M.J.S. and Panton W.J. (1993). Decline of *Callitris intratropica* R.T. Baker and H.G. Smith in the Northern Territory: implications for pre and post-European colonization fire regimes. *Journal of Biogeography* **20**:373-381.

Bowman, D.M.J.S. and Panton W.J. (1995). Munmarlary revisited: Response of a north Australian *Eucalyptus tetrodonta* savanna protected from fire for 20 years. *Australian Journal of Ecology* **20**: 526-531

Bowman, D.M.J.S. and Wilson, B.A. (1988). Fuel characteristics of coastal monsoon forests, Northern Territory, Australia. *Journal of Biogeography* **15:** 807-817.

Braithwaite R.W. and Estbergs J.A. (1985). Fire pattern and woody vegetation trends in the Alligator Rivers region of northern Australia. In *Ecology and Management of the Worldís Tropical Savannas* (eds J.C. Tothill and J.J. Mott) pp. 359-64. (Australian Academy of Science, Canberra).

Fensham R.J. (1990). Interactive effects of fire frequency and site factors in tropical *Eucalyptus* forest. *Australian Journal of Ecology* **15**: 255-266.

Fensham R.J. (1992). The establishment of eucalypt seedlings in tropical savanna forest. *Northern Territory Naturalist* **13:** 30-36

Fensham R.J. and Bowman D.M.J.S. (1992). Stand structure and the influence of overwood on regeneration in tropical eucalypt forest on Melville Island. *Australian Journal of Botany* **40**: 335-352.

Fordyce, I.R., Eamus, D., Duff, G.A. and Williams R.J. (1997) The role of seedling age and size in the recovery of *Allosyncarpia ternata* following fire. *Australian Journal of Ecology* **22**: 262-269.

Hanssen, N.L. and Wigston, D.L. (1989). Approaches to a forest history of the Northern Territory. In *Australiaís ever-changing forests.* (Eds: K.J. Frawley and N. Semple). (Department of Geography and Oceanography, University College, Australian Defence Force Academy: Campbell, ACT).

Iwainde F. (1998). *Regeneration of Cooktown Ironwood in Mary River East Station in the Northern Territory of Australia.* PhD thesis. Northern Territory University: Darwin.

Lacey C.J. (1974). Rhizomes in tropical eucalypts and their role in recovery from fire damage. *Australian Journal of Botany* **22**:29-38.

Lacey C.J. and Whelan, P.K. (1976). Observations on the ecological significance of vegetative reproduction in the Katherine ñ Darwin region of the Northern Territory. *Australian Forestry* **39**: 131-139.

Setterfield S.A. (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 S.A. (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

Werner, P.A. (1986). *Population Dynamics and Productivity of Selected Forest Trees in Kakadu National Park.* Final Report to Australian National Parks and Wildlife Service. (CSIRO Tropical Ecosystems Research Centre: Darwin).

Williams R.J., Myers B.A. Eamus D. and Duff G.A. (1999). Reproductive phenology of woody species in a north Australian tropical savanna. *Biotropica* **31:** 626-636.

Wilson D.M.J.S., and Bowman B.A. (1987). Fire, storm, flood and drought: The vegetation ecology of Howard Springs, Northern Territory, Australia. *Australian Journal of Ecology* **12**: 165-174.

Wilson C., and Mudita W. (2000). Fire and Weeds: Interaction and Management Implications. In *Fire and Sustainable Agricultural and Forestry Development in Eastern Indonesia and Northern Australia.* ACIAR proceedings 91. (Eds: J Russell-Smith, G. Hill, S. Djoeroemana, B. Myers). (Australian Centre for International Agricultural Research: Canberra).

8. Timber harvesting in the Northern Territory

Robert Taylor, Leigh Granger and Leonie Perry

8.1. Trends in the use of native trees for timber

Timber harvesting as a full time occupation began in the Northern Territory with the establishment of Darwin (then Palmerston) in the 1860s (Hanssen and Wigston 1989). Small scale harvesting has been undertaken for a long time with depletion of particular species such as ironwood and *Callitris* pine occurring in some areas (Hanssen and Wigston 1989). The formation of a forestry research station in 1959 led to a push to develop a timber industry utilising both native species and plantation grown timber. Plantations were established on Melville Island and a mill was established at Maningrida as a means of providing an independent source of income for the Aboriginal community. None of these or other subsequent ventures proved viable.

Government involvement in forestry ended in 1978 after it was found that the Forestry Branch had exaggerated the potential of a forest industry in the Territory. Today harvesting of native forests is regulated by the Parks and Wildlife Commission of the Department of Infrastructure, Planning and Environment with the Department of Business, Industry and Resource Development overseeing a small farm forestry plantation program. A medium size plantation development

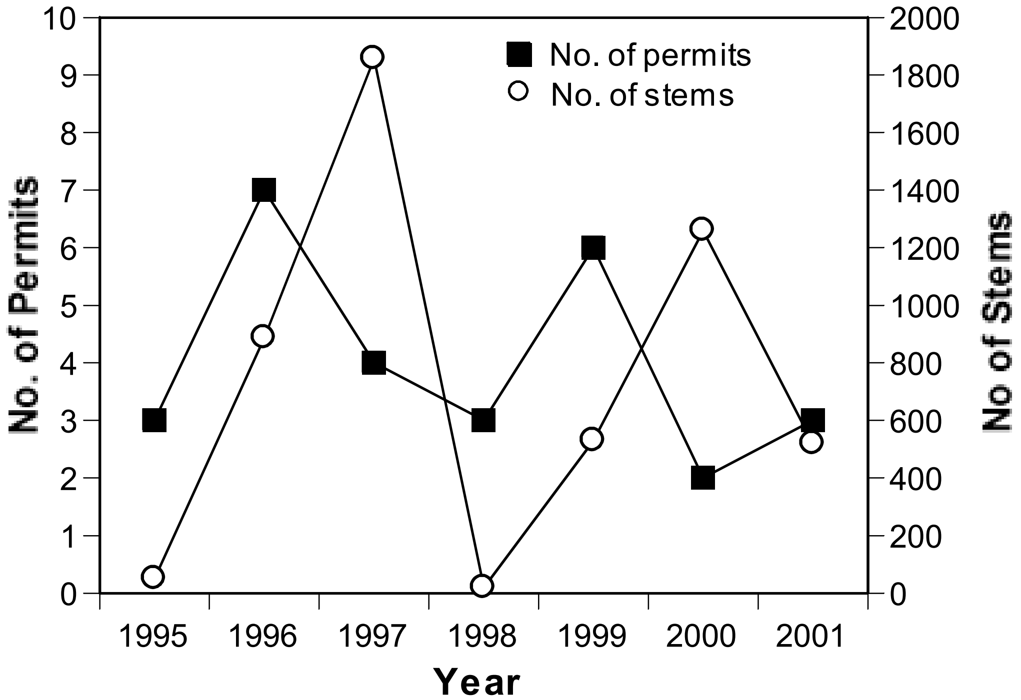


Fig. 8.1. Number of permits issued for timber harvesting in the Northern Territory and number of stems allowed under these permits.

using an exotic acacia, *Acacia mangium* is proceeding on Aboriginal land on Melville Island.

Data on harvesting of native timbers from permits issued between 1995 (when electronic record keeping commenced) and 2001 is given in Fig. 8.1. In 1997 four permits were issued to the same person for the same area. This was recorded as a single permit. In 1998 a permit was issued to the Tiwi Land Council to harvest 40,000 stems as salvage from plantation development on Melville Island. However no timber ended up being used commercially and so this permit was not included. Permits for the collection of dead wood were also not included.

Ironwood *Erythrophleum chlorostachys* is the most frequently harvested species (54% of stems) with smaller numbers of eucalypts (40%) and a range of other species taken (Fig. 8.2). Ironwood is favoured because of its termite resistance. The species taken and the numbers of stems permitted for harvesting was as follows (+ indicates that some permits were issued for these species with no quantities and hence the totals are smaller than the actual):

Acacia aneura	49	*Corymbia polycarpa*	548
Acacia auriculiformis	28	*Erythrophleum chlorostachys*	2757+
Acacia georginae	2	*Eucalyptus atrovirens*	25
Allocasuarina decaisneana	25	*Eucalyptus bigalerita*	+
Alstonia actinophylla	14	*Eucalyptus camaldulensis*	20
Avicennia marina	1	*Eucalyptus foelscheana*	100
Bruguiera gymnorrhiza	8	*Eucalyptus latifolia*	+
Callitris intratropica	107	*Eucalyptus miniata*	268+
Campostemon schultzii	1	*Eucalyptus phoenicea*	+
Corymbia bleeseri	765+	*Eucalyptus tetrodonta*	217+
Corymbia bella (E. papuana)	+	*Lumnitzera racemosa*	8
Corymbia confertiflora	30+	*Melaleuca leucadendra*	6
Corymbia porrecta	25	*Santalum lanceolatum*	20
Corymbia ptychocarpa	25	*Terminalia arostrata*	45
Corymbia latifolia	25	*Xylocarpus granatum*	6

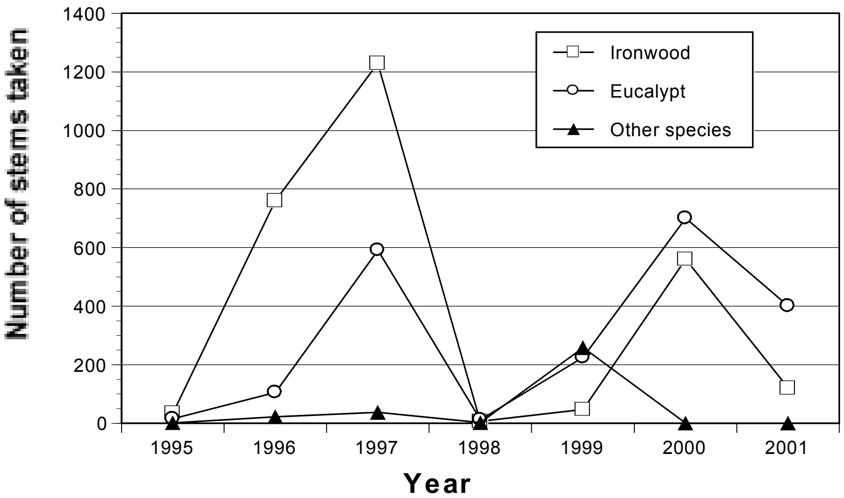


Fig. 8.2. Number of stems of different species categories issued for timber harvesting in the Northern Territory. The eucalypt category includes both *Eucalyptus* and *Corymbia*.

Fig. 8.3. Examples of the use of ironwood as craftwood. Sculptues by Riambawa Marawili in the Buku Larriygay Nwlka Arts Centre at Yirrkala, north east Arnhem Land

The numbers of stems permitted to be harvested is not necessarily the same as the number actually harvested. Permit holders are required to supply returns indicating the numbers of stems actually cut. However, the major harvester of ironwood over most of the time period did not supply adequate returns and was eventually refused another permit. Hence return data is probably more unreliable than the number of stems requested. 57% of the stems taken in the period 1995-2001 were from the Mary River East property. In 1999 76% of the stems taken were for woodchipping (probably for garden use). Ironwood is also used as a craftwood (Fig. 8.3). Harvesting of stems (principally *E. phoenicea, E. miniata* and *E. tetrodonta)* also occurs for didgeridoo production but these are not included in the figures given above.

8.2 Pattern of harvesting at Mary River East

Introduction

This section details information on the pattern of harvesting in relation to topography and the size of trees that were harvested on the Mary River East Station. Harvesting was undertaken under permit from 1995 until 2000. The conditions of the initial permit were that only trees greater than 30 cm DBH that were greater than 10 m from a stream channel or incised watercourse and on slopes that did not exceed 10% could be harvested. This was changed after the first year to be only trees greater than 35 cm DBH that were greater than 20 m from a stream channel or incised watercourse and on slopes that did not exceed 10% could be harvested.

Methods

Logging intensity was assessed for the quadrats from harvested areas in Eureka Creek and OíNeil Creek (described in Chapter 5). Harvesting only appears to have occurred in flatter areas associated with drainage lines. Hence only such areas were assessed. The number and diameter of stumps was recorded for each quadrat and compared with the number and DBH of extant trees in the quadrats. Further data on number and diameter of stumps was also collected from areas surrounding the quadrats to increase sample size. The diameter at stump height (DSH) is an overestimation of the DBH of logged trees because of taper effects but the figures give some idea of the sizes of tree taken.

Measurements of 58 ironwood, 40 *E. polycarpa* and five *E. papuana* logs from the Mary River East Station that were present at the Red Ebony Mill or in a nearby area were obtained by Parks and Wildlife Officers in September 2000. The diameter measurements would be equivalent to those obtained from stumps in quadrats sampled on the property.

Criteria used to assess commercial acceptability of trees are given in chapter 5.

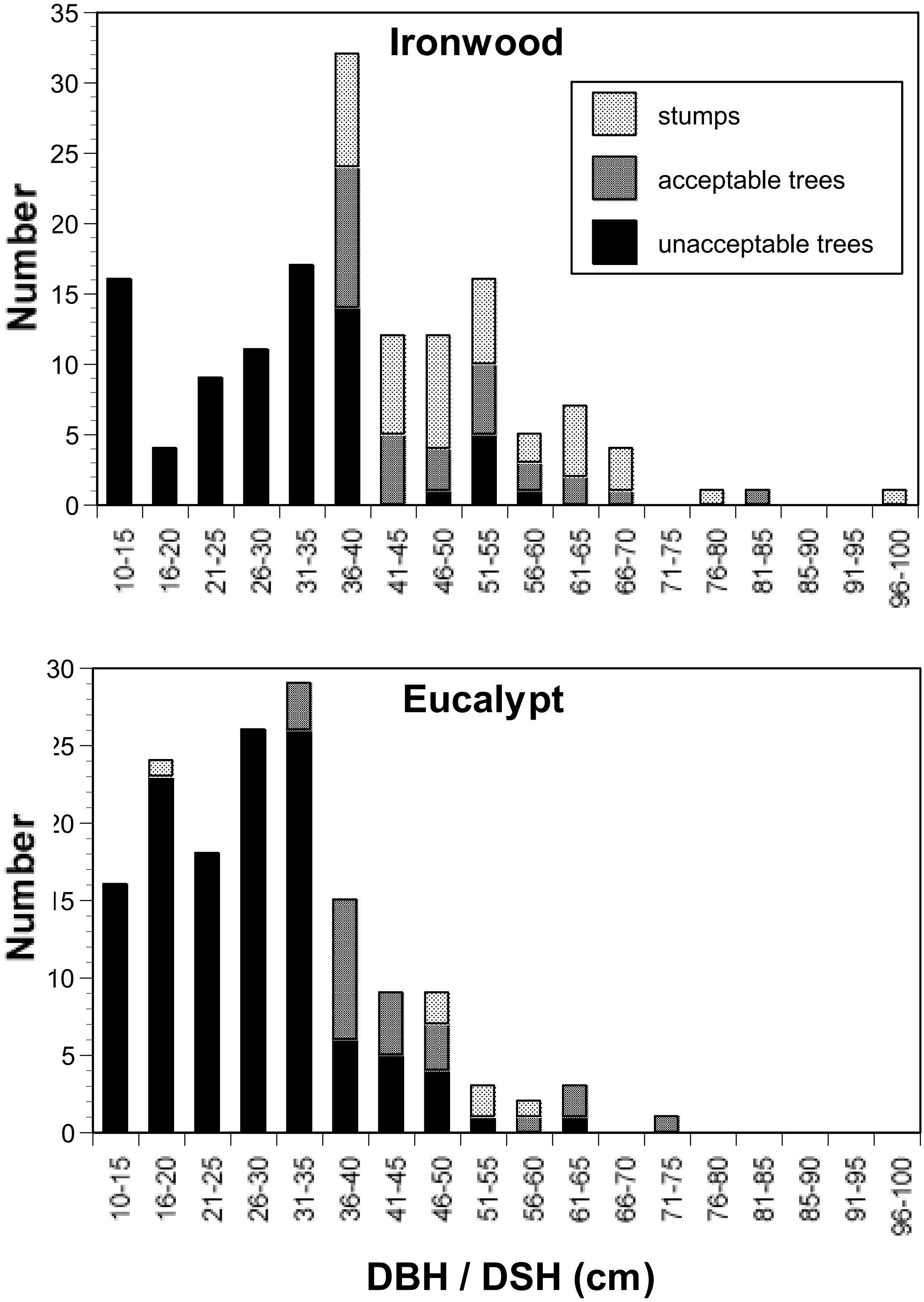


Fig 8.4. Size classes for ironwood and eucalypts for commercially unacceptable trees, commercially acceptable trees and stumps (ie harvested trees) from quadrats at OíNeil and Eureka Creeks, Mary River East Station.
DBH is the diameter at breast height for extant trees; DSH is the diameter at stump height. When comparing the two groups it is important to recognise that the DSH of a tree will generally be larger than the DBH due to taper.

Results

The average number of ironwood stumps in harvest areas at OíNeil and Eureka Creeks was 7.3 and 7.7 stumps/ha respectively. This represents 59% of the commercially acceptable ironwood trees and 28% of the ironwood trees >10 cm DBH that would have been present on the site prior to the recent logging (Fig 8.3). When the larger sample, obtained from both in and out of quadrats, at OíNeil and Eureka Creeks was combined with samples from the mill, 4.5% of the ironwood

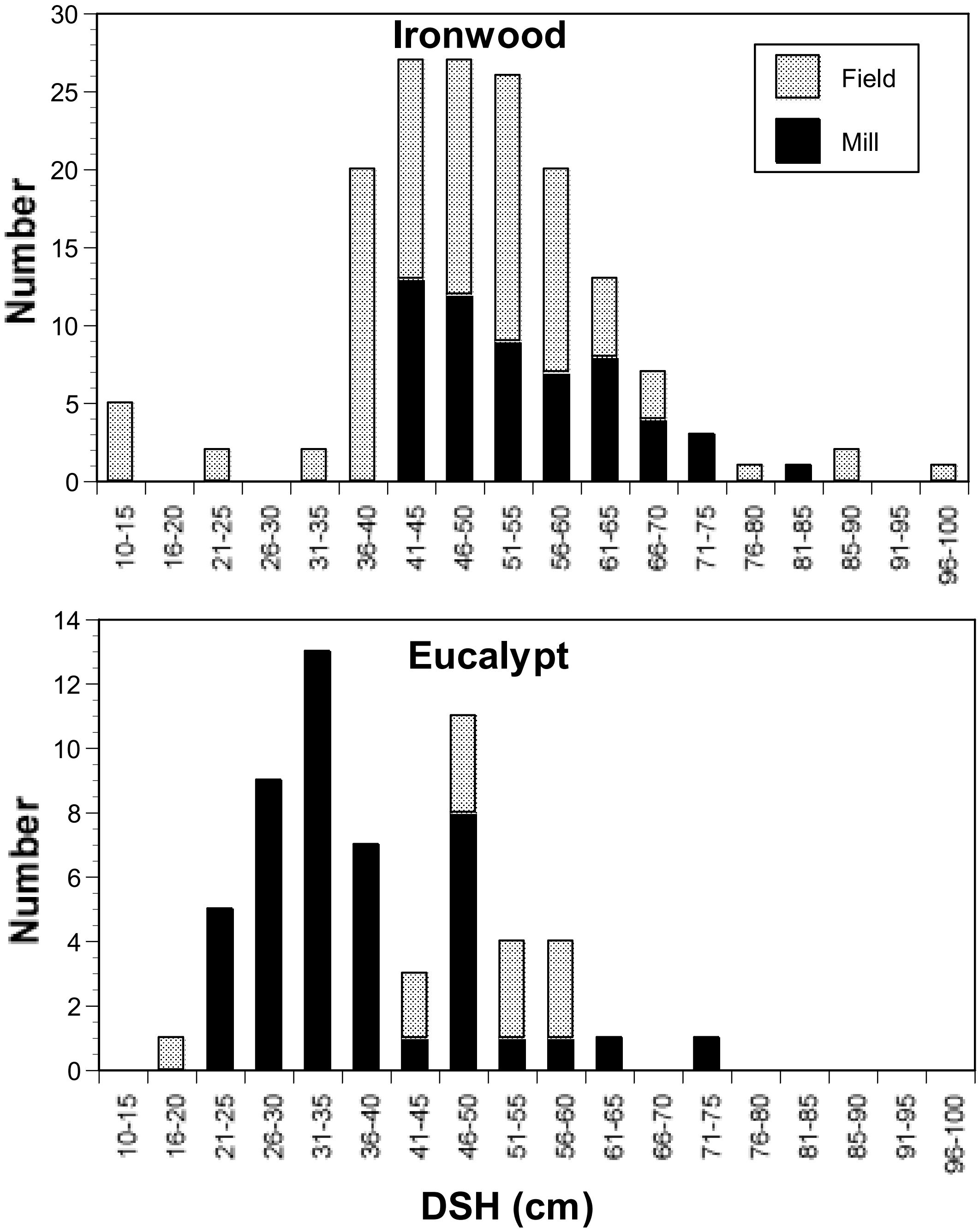


Fig 8.5. Diameter at cut for stumps (ie harvested trees) in the field (OíNeil and Eureka Creeks both within and outside of quadrats) and a sample of logs from Mary River East measured at the Red Ebony Mill.

trees taken were under the size limit of 35 cm DBH specified on the logging permit (Fig 8.5). There was no significant relationship between the DSH and the lengths of the logs from the sample at the mill. Mean log length for ironwood was 3.74 m.

The average number of eucalypt stumps in harvest areas at OíNeil and Eureka Creeks was 1.0 and 1.4 stumps/ha. respectively. This represents 21% of the commercially acceptable eucalypt trees and 4% of the eucalypts ≥10 cm DBH that would have been present on the site prior to the recent logging (Fig 8.4). When the larger sample, obtained from both in and out of quadrats, at OíNeil and Eureka Creeks was combined with samples from the mill, 34% of the trees taken were under the size limit of 35 cm DBH specified on the logging permit. DSH was significantly correlated with the lengths of eucalypt logs (product moment correlation $r=0.29$, $p<0.05$). Mean log length for eucalypts was 4.0 m. Five of the 45 eucalypt logs were under the 2.2 m length thought to be required for milling by the Red Ebony Mill. There was no significant difference between the lengths of ironwood and eucalypt logs.

Discussion

Timber harvesting on the Mary River East property was diffuse. Ironwood suitable for harvesting are only located along creeklines (chapter 5). Commercially acceptable trees apparently still exist in the harvested areas. However, it may be that the harvesters are better able to assess a tree for its timber quality and the apparently acceptable trees remaining may not in fact have economic quantities of timber. 16% of trees greater than 10 cm DBH had been logged in the areas surveyed. As the trees taken are generally the larger ones present the proportional reduction in the canopy may be around 30%. Diameters of cut logs showed a greater range in sizes for ironwood from the field sample than from the mill sample. It is possible that some of the smaller diameter logs (less than the 35 cm DBH prescribed in the permit) could have been taken for use on the property and would not be milled. However, the opposite pattern occurred for the eucalypts with a larger proportion of the logs being less than 35 cm DSH in the mill sample. The significant correlation between the DSH and log length in eucalypts and not in ironwoods probably reflects the tendency for eucalypts to grow to greater heights than ironwoods. The largest DSHs were recorded in the ironwood logs, possibly reflecting a longer life span for this species. Its greater resistance to termite attack may assist it to live longer.

The diameters of the ironwood stumps and log ends are greater than the DBH for this species recorded in other studies. The largest ironwood reported by Braithwaite *et al.* (1985) from Kakadu National Park was 55 cm DBH, 50 cm from the Limmen region (chapter 6), while OíGrady *et al.* (2000) considered a tree with a 25 cm DBH to be unusually large. Part of the difference between our results and these two studies may be due to the larger diameters recorded at the cut point which is lower down the log than the location where DBH is recorded. However given that DSHs up to 96 cm were recorded and that 32% of those over 35 cm were greater than 55 cm (the largest reported by Braithwaite *et al.* (1985)), it appears likely that the ironwood on the present sites can attain unusually large sizes. 14% of the trees remaining in logged areas that had a BDH greater than 35 cm were greater than 55 cm. However these ironwood were growing on the most favourable locations along drainage flats and ironwood outside these areas did not attain these sizes (chapter 5).

Breaches of permit conditions were evident in the diameter of trees taken, particularly with the eucalypts. Numerous breaches also occurred in relation to exclusion of harvesting within 20 m of incised watercourses (reports on file from inspections carried out by Parks and Wildlife Commission rangers). Logging has now ceased on the Mary River East property.

References

Braithwaite, R.W., Parker, B.S., Wood, J.T. and Estebergs, J.A. (1985) The distribution and abundance of termite-induced tree hollows in tropical forests of northern Australia. In *The Kakadu fauna survey : an ecological survey of Kakadu National Park.* (ed. R.W. Braithwaite), pp. 651-729. Report to Australian National Parks and Wildlife Service. (CSIRO Tropical Ecosystems Research Centre: Darwin).

Hanssen, N.L. and Wigston, D.L. (1989). Approaches to a forest history of the Northern Territory. In *Australiaís Ever-changing Forests.* (Eds: K.J. Frawley and N. Semple). (Department of Geography and Oceanography, University College, Australian Defence Force Academy: Campbell, ACT).

OíGrady, A.P., Chen, X., Eamus, D. and Hutley, L.B. (2000) Composition, leaf area index and standing biomass of open eucalypt forest in the Northern Teritory, Australia. *Austrailan Journal of Botany* **48**, 629-638.

Werner, P.A. (1986). Population Dynamics and Productivity of Selected Forest Trees in Kakadu National Park. Report to Australian National Parks and Wildlife Service. (CSIRO Tropical Ecosystems Research Centre: Darwin).

9. Ecological sustainability of timber harvesting in the Northern Territory

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Introduction

The rate of use of ironwood in the Northern Territory in the past, at least at a regional level, has clearly been unsustainable. Inadequate resource inventory and lack of management planning and protection contributed towards the rapid depletion of ironwood in the Darwin-Katherine area within the first few decades of European settlement (Hanssen and Wigston 1989; Woinarski and Dawson 2001). As the settlements, cattle stations and mining enterprises grew, ironwood was utilized without any thought of sustainability or any considerations as to its regeneration (Hanssen and Wigston 1989).

> ì*Ironwood trees, although only found in relatively small scattered stands, fell by their tens of thousands up to 1889 to act as sleepers to support the steel narrow gauge track to Pine Creek. Although ironwood logs have been known to last for up to 100 years, the species is slow growing, of poor timber form, and has a low regeneration rate. The poor form leads to much waste of material; the scattered remains of branches around a cut stump used to make perhaps one to four sleepers can still be observed in the bush in a broad sweep along the old route of the railway* Öî (Hanssen and Wigston 1989).

This section discusses the requirements for implementing a harvesting regime for ironwood that meets the criteria of ecological sustainability. Ecological sustainability takes account of the impact of timber harvesting on environmental, economic and social values, not just those related to the sustainability of wood production. The determination of ecological sustainability requires that harvesting is undertaken in a manner and at a rate that does not lead to unacceptable or long-term detriment to the environment.

Sustainable harvest rates

The sustainable yield of a forest is the maximum level of commercial timber that can be maintained under a given management regime. The determination of the sustainable rate of harvesting requires a knowledge of the following:

- Standards of utilisation i.e. what constitutes a useable tree for utilisation as timber. This will in turn govern rotation length. Also relevant are silvicultural prescriptions that require retention of trees e.g. large mature trees retained as seed trees.

- Area of forest available for harvesting. This potentially includes areas with forest whose tenure allows timber harvesting. Areas such as gazetted conservation reserves would not be included. Areas excluded by regulation for environmental reasons would also not be included e.g. areas >10% slope or within riparian reserves or excluded to ensure protection of biodiversity or other values. Also excluded would be areas that were unavailable for other reasons e.g. areas uneconomic to access due to being too far from roads or having insufficient resource to warrant utilisation.
- Inventory and growth. Inventory data required are volumes of timber in different stratum that have similar growth rates eg saplings, poles, adults. Growth rates across the life span of the species are required. Inventory data would need to be updated to take account of major mortality factors such as logging and cyclones.
- Regeneration and recruitment. Recruitment rates for seedlings into the sapling stage and subsequent survival rates into adulthood are required to assess recruitment of trees to a size where they are commercially utilisable. These values would differ depending on site factors (soil and moisture are likely the most important factors) and environmental conditions (fire regime is likely to be the most important factor).

Standards of utilisation

Boland *et al.* (1992) describe ironwood as ìa medium-sized tree, often poorly formed and short-boledî but reported good growth habit in ìwell drained soil, lowland country and river flatsî. This disparity in growth form of ironwood is important when assessing the actual resource available for sustainable harvesting in different areas. Thus a good straight bole height of at least 2.2 metres was required for ironwood trees processed by the Red Ebony Mill. Sometimes upper branches can be used but mostly the upper branches are crooked and many were observed left in the field. In the present study trees were scored as acceptable if they were greater than 35cm DBH and with bole heights > 2.2 m and had no visible hollows or irregularities. However, different processors may have different requirements. David Clark (pers.comm.) reports that trees with a DBH of 40 cm or greater are normally required for furniture production. Portable sawmills are also available that could process logs of shorter length than 2.2.m. Thus sustainable yield calculations will vary depending on the type of logs required by the industry.

Area available for harvest

Using the modelled distribution of the incidence of ironwood from chapter 4, conservation reserves were calculated to constitute 9.9% of the area of the range of ironwood (at a 70% probability of occurrence) in the Northern Territory. In section 4 it was estimated that 11.2% of the ironwood resource fell within these reserves. Thus, an adequate proportion can be assumed to be protected from any commercial use.

On the Mary River East station commercially utilisable trees were not present in sampled sites outside of riparian areas and this is probably generally the case (e.g. Boland *et al.* 1984). However, for some areas the distribution of non-commercial and commercial stands may not follow this pattern. Bowman *et al.* (1991), for example, found ironwood to be most abundant on ridge lines in an area north of Katherine. Thus it would be difficult to determine what proportion of the area with ironwood has stands that could be subject to utilisation.

Areas will also need to be excluded to protect a range of other values. Two restrictions currently being placed on harvesting permits are exclusion of areas with greater than 10% slope as a erosion control measure and retention of riparian reserves of 20 m width to protect water quality and minise bank erosion. The mapped models for the Mary River catchment (chapter 5) were overlayed with grids representing buffered riparian corridors to estimate resource discounts that may apply for this environmental constraint. The occurrence of conservation reserves were ignored for the purposes of this exercise. Twenty-five metres either side of all drainage lines was used as the minimum riparian reserve rather than the presently regulated 20 m as 25 m was the minimum resolution possible based on all GIS datasets. 25 m buffers reduced availability of areas with a greater than 80% probability of occurrence of ironwood by 12% and reduced the biomass of ironwood available by 9% (Table 9.1). The actual discounts that would apply will be greater than shown in the table due to inadequate mapping of drainage lines in the GIS layer used (version 1 of the Auslig 250k digital geodata series). The regulation for riparian reserves relates to all incised watercourses whereas the drainage lines in the GIS layer were those with water for most of the year.

Inventory

In section 4 we derived an estimate of the total woody biomass of ironwood in the Top End of the Northern Territory of almost 100 million tonnes. This is a ball-park rather than a precise estimate. Our analyses suggested that the total biomass figure is composed typically of small basal areas smeared over very large areas, rather than of a relatively few highly productive pockets. This is supported by published values of basal area of ironwood from various studies of small areas (Table 3.1). From the flora data used for the modelling in chapter 4, only 2.1% of sites iwhere ironwood was present had basal areas of >5 m^2/ha, and mean basal area of ironwood across sites where it was present was 1.4 m^2/ha. For the Mary River East station commercially acceptable trees seemed to be restricted to riparian flats. Within all of the riparian plots measured in this area basal area averaged 1.7 m^2/ha. Within riparian plots where data on the occurrence of stumps was collected basal area of remaining ironwood was 2.02 m^2/ha and 3.6 m^2/ha when the diameters of stumps were included. In these plots 48% of the ironwood trees (>10 cm DBH) in the unharvested forest would have been commercially

Table 9.1. The effect of riparian buffer width on the availability of ironwood using resource estimates from the model of distribution in the Mary River catchment.

	Entire catchment	% outside 25 m buffer	% outside 100 m buffer
Entire Catchment	8063(km^2)	79%	69%
Areas with >80% probability of occurrence	1644 (km^2)	88%	66%
Ironwood woody biomass	354,517 tonnes	91%	75%

acceptable, having a basal area of 2.7 m^2/ha. These figures are meagre compared with most commercial timber resources. For example, ForSci (1999) reports a range from 9 to 25 m^2/ha for 4-5 year old *Acacia mangium* plantations on Melville Island. In Tasmania basal areas of dry forests range around 30 to 40 m^2/ha with 60 to 90% of that taken during harvesting (J Hickey, Forestry Tasmania, pers. comm.). These comparisons suggests that ironwood harvesting is likely to always be only a local small-scale industry.

Growth

Growth rate data for ironwood were obtained from CSIRO for a sample of trees from Kapalga in Kakadu National Park. The soils in the area the trees were sampled in were ironstone gravels and lateritic red earths in level to gently undulating lowlands. The trees were about 500 - 800 m from the nearest ephemeral stream and on well drained soil 1.2-1.5 m deep. DBH of seventeen trees were measured, the earliest measurement taken in June 1989, and remeasured between 3.03 to 5.17 years later, the last remeasurement being in May 1995. The best fit for growth rate as a function of initial DBH was logarithmic (Fig. 9.1). This relationship was just short of being significant at the 0.05 level ($r = -0.44$, $p=0.076$). However, because it is the only data available the relationship was used to estimate age of trees at different DBH. It was assumed that a tree with a 3.5 cm DBH was 10 years old. The increment of DBH over a year was calculated from the regression equation in Fig. 9.1. This was then added to the initial DBH to give a DBH at the commencement of year 11. The process was repeated for successive years (Fig 9.2). This produces at age of 100 years for a tree with DBH of 20 cm, 145 years for 25 cm, 202 years for 30cm, 273 years for 35 cm and 367 years for 40 cm. Further data on the growth of the marked trees at Kapalga will be collected when access is available to the site and CSIRO staff are available. This extra data will hopefully allow a more precise growth rate function to be calculated.

Further support for the slow growth rate of ironwoods comes from an ironwood tree in the Coomalie region just east of the Stuart Highway near the turnoff to Batchelor. A photo of an ironwood tree was discovered that was next to a hospital site used during world war two (probably somewhere between 1941 and 1945). Another photo was taken of the tree in March 2002 i.e. approximately 57 years later. The two photos are shown in Fig. 9.3. The cycad stem (labelled as A) in the photos to the left of the ironwood tree (labelled as B) provides a scale for the ironwood tree. It is likely that the cycad stem has changed very little in diameter with most of the growth likely to be in a change in height (D. Liddle pers. comm.). The actual diameter of the cycad stem in 2002 was divided by its diameter in the photo and multiplied by the diameter of the tree in the photo to get the actual diameter of the tree. This gave a figure of 49.4 cm for the 2002 photo and the actual DBH was 42 cm. This technique applied to the historic photo gave a DBH for the ironwood of 33.6 cm. Comparison of the 33.6 cm to 49.4 cm gives a growth rate of 0.28 mm/year and a comparison of the present actual 42 cm DBH with a corrected historic value of 28.6 (i.e. the present value of 42 divided by the calculated value of 49.4 multiplied by the calculated historic value of 33.6) gave a growth rate of 0.24 mm/year.

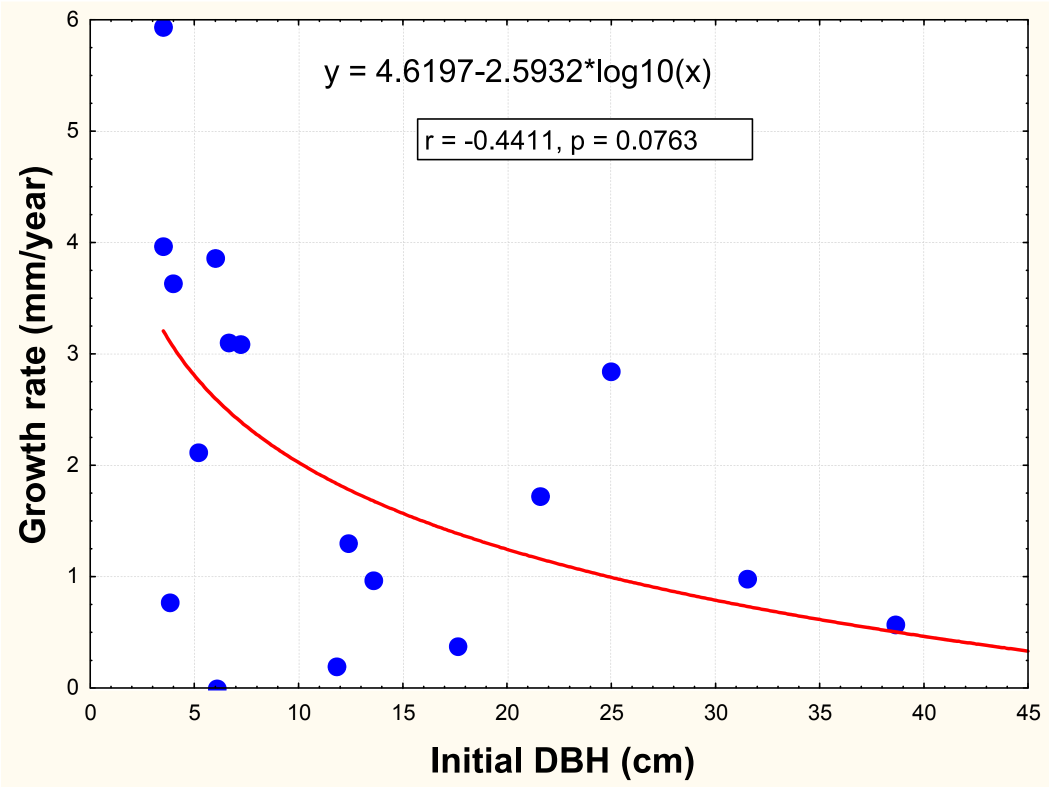


Fig 9.1. Relationship between initial DBH (cm) and growth rate (mm/year) for ironwood trees at Kapalge in Kakadu National Park.

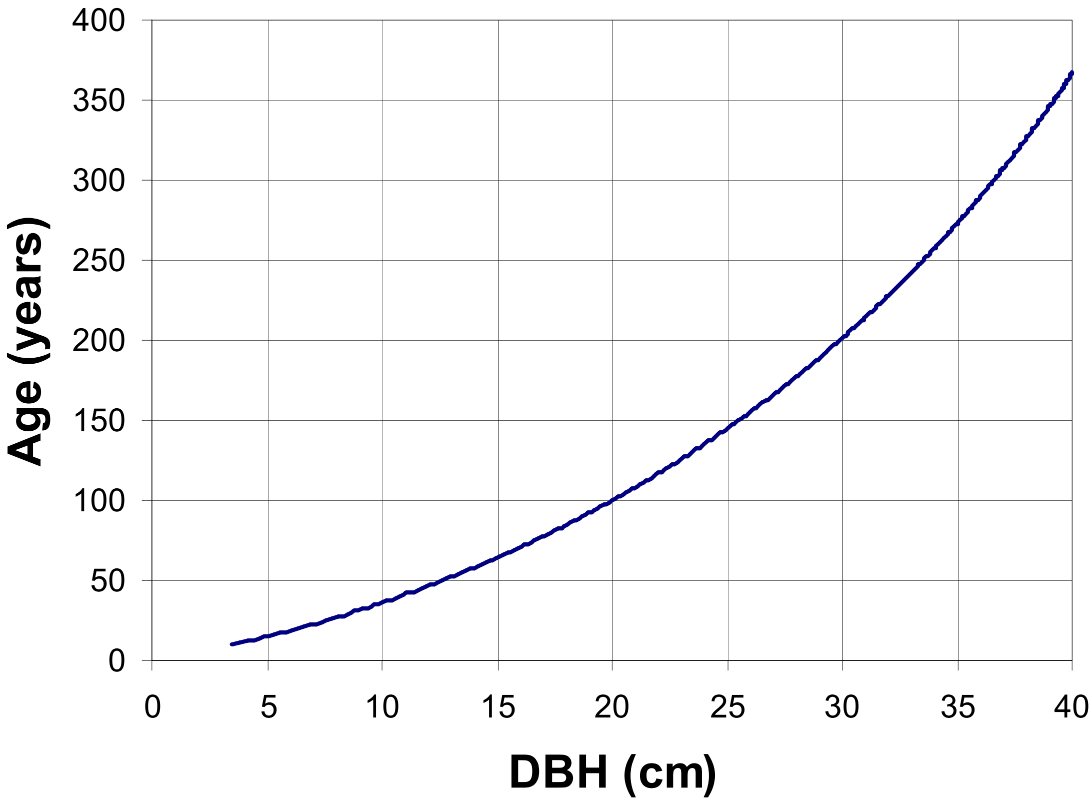
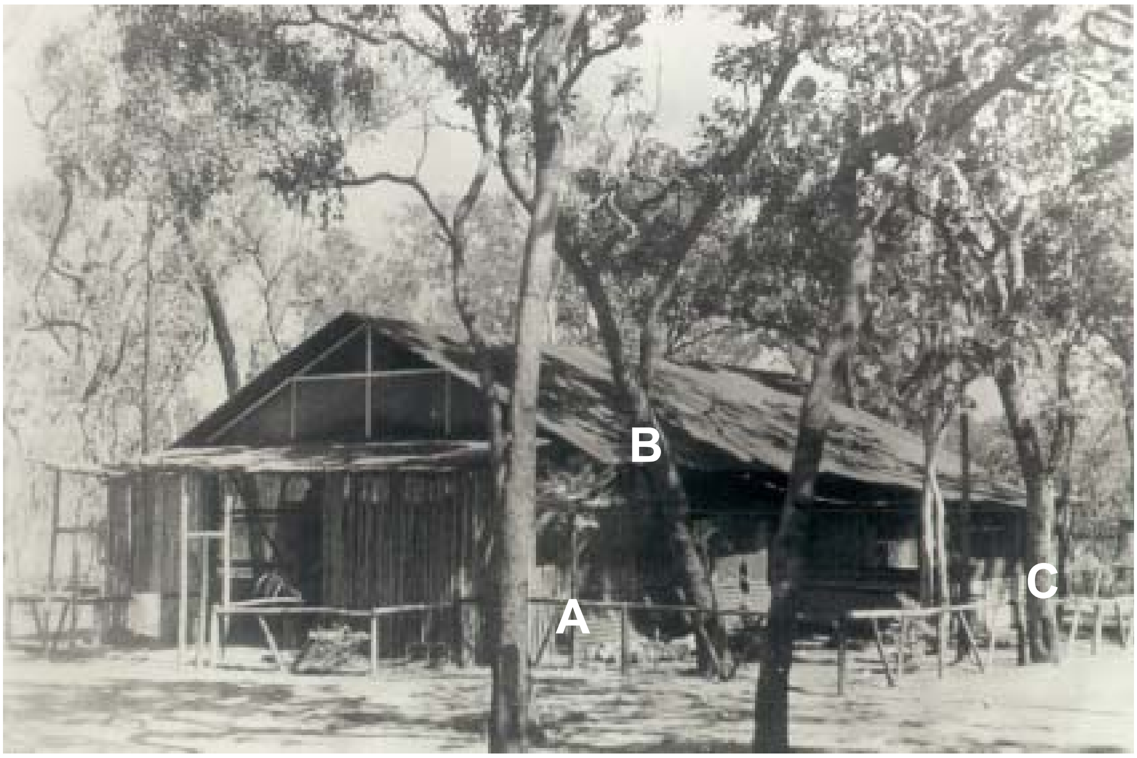


Fig. 9.2. Relationship between DBH (cm) and age of ironwood trees derived from growth rate data from Kapalaga in Kakadu National Park.



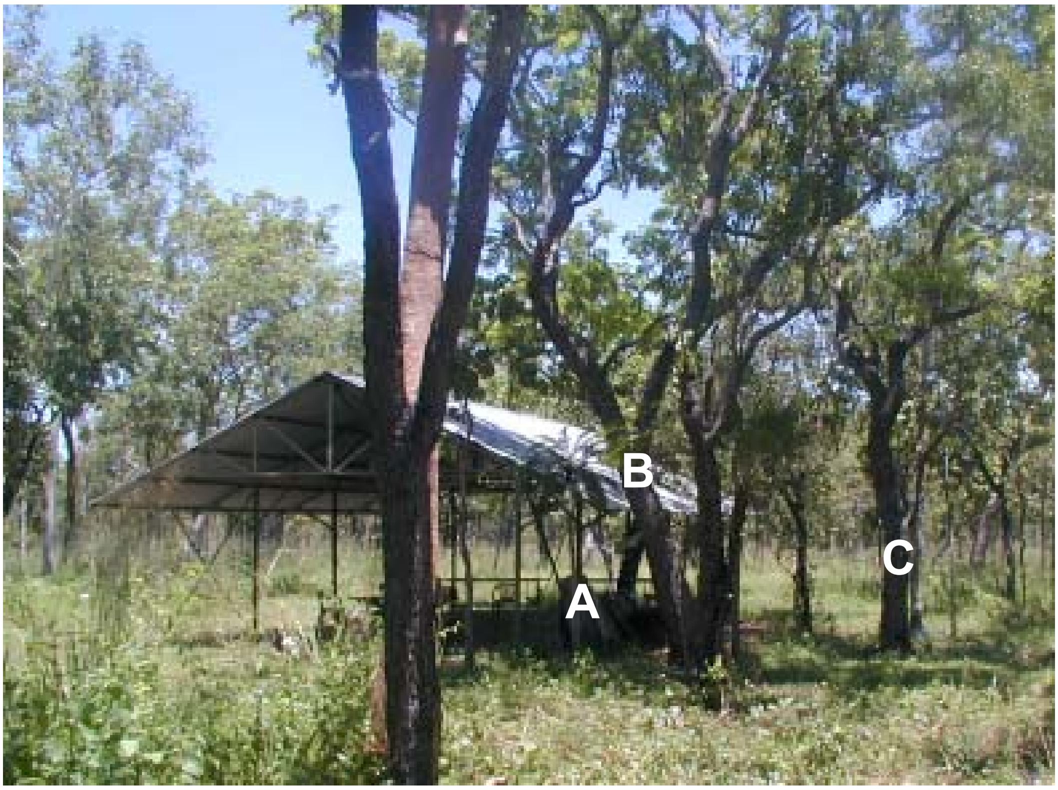


Fig. 9.3. Photos of the same ironwood tree taken at least 57 years apart (1945 - 2002). A = cycad plant whose stem was used to calibrate the DBH of the tree in the early photograph; B = ironwood tree; C= another ironwood tree present in both photos.

Fig 9.4. Purported know age ironwood tree on Mary River East property. Information from Parks and Wildlife Commission file. Caption to photo reads ìTree grown in a car wreck (1962) at least 34 years old, DBH ~41 cmî.

This analysis is, however, in marked contrast to antidotal information contained in a Parks and Wildlife Commission file on ironwood logging at Mary River East. The file contains a photo of an ironwood growing out of the wreckage of an old car (Fig 9.4). The caption to the photo reads ìTree grown in a car wreck (1962) at least 34 years old, DBH ~41 cmî. This gives an average growth rate of 12.06 mm/year. Iwainde (1998) provides growth rates for coppice from logged trees at Mary River East. He measured DBH of coppice on stumps in two areas logged nine and thirty years prior to measurement. Coppice from 11 stumps in the nine year old site had DBHs ranging from 10.5 to 16.4 cm with an average of 13.4 cm (growth rate of 14.9 mm/year). Coppice from 24 stumps in the thirty year old site had DBHs ranging from 15 to 41.8 with an average of 23.4 cm (growth rate of 7.8 mm/year). These growth rates are in accord with the claimed age of the ironwood tree in the photo mentioned above.

Two ironwood seedlings were planted 10 years ago by Greening Australia on the roadside reserve next to the Stuart Highway in Berrimah (Mike Clark pers. comm.). This was a grassy area with a line of tree plantings. The DBH of these two trees was 9.2 and 9.7 cm, giving an average growth rate of 9.2 and 9.7 mm/year. If this growth rate was maintained (which is unlikely as growth rate probably declines with age (Fig 9.1)) then these trees would be around 45 years old when they were 40 cm DBH.

Some of the difference between the growth rate of trees at Kapalga and Coomalie compared with that from other areas (i.e. road side trees, logged or cleared sites at Mary River East) could possibly be due to site differences (ie soil or topographic location). However, the differences appear too large for this to be the sole reason. The difference is more likely to be due to competition effects. The trees at Kapalga are growing in a multi-age stand. From the photo of the tree at Mary River East it appears that this tree is growing in an area that has been cleared of trees. Growth rates of savanna trees in areas that have been clearfelled have been shown much higher growth rates (from 10 to 25 mm e.g. Mucha 1979, Fensham and Bowman 1992, Chidumayo 1988, Chidumayo and Frost 1996) than in mature, multi-size stands. Annual increments in tree girth of less 5 mm are typical in mature *Eucalyptus* forests in northern Australia, southeast Queensland and New South Wales and in forests of *Brachystegia spiciformis* and *Julbernardia globiflora* in Zimbabwe (both related to Ironwood)(Grundy 1995 cited by Chidumayo and Frost 1996, Curtin 1970 cited by Grimes and Grigg 1979, Grimes and Grigg 1979, Guinto *et al* 1999, Werner 1986). These much lower growth rates suggest that the maximum ages of large trees in uncleared savannas have been substantially underestimated. Measurements of growth following clearing put large trees in the Darwin region at rarely more than 100 years old (Mucha 1979), whereas measurements of growth in mature savannas estimate large trees to be up to 400 years old (Werner 1986).

A sample of the trunk of a ironwood with a DBH of 37 cm has been forwarded to Dr John Banks of the Australian National University. Dr Banks will endeavour to counts the rings from this tree. If this fails carbon dating on the inner most wood will be used to try to obtain an age. This tree was growing at Palmerston in an area near a drainage soak with a loam soil. Hence the growth rate of this tree would be expected to be at the upper end of that possible for the species growing in a forest/ woodland situation. Until the information is obtained on this tree it is not possible to resolve the question of the age of large ironwood trees growing in undisturbed savanna. However, the historical evidence of rapid overexploitation during the first surge of harvesting in the late nineteenth century leads us to suspect that growth rates for the species in such situations will be slow.

Flowering and recruitment

Dick Williams (unpublished data) collected information on flowering of ten mature adults ironwoods (>10 m tall) at the Solar Village near Darwin at bimonthly intervals between September 1992 and February 1995. There was only one record of fruiting (in December) over the period. A similar finding of low frequency and unpredictable flowering was obtained from a sample of trees at Kapalga (Dick Williams pers. comm.). It thus seems likely that suckers, and coppice where logging occurs, provide the main source of recruits.

The limited information suggests that only occasional recruitment of suckers or seedlings to the sapling level occurs and then only occasional recruitment of saplings to the tree stratum. The most important factor affecting recruitment of ironwood is likely to be fire regimes. Evidence suggests that limiting the effects of fire eventually leads to a marked increase in recruitment of poles and presumably eventually also adults (Bowman and Panton 1995). However recruitment will also probably be limited by competition with existing adults, at least for eucalypts (Fensham and Bowman 1992). Frequent burning that results in a canopy species existing as a short woody growth on the forest floor, occupying space but not reaching the overstorey is obviously not advantageous to a forestry industry (Lacey and Whelan 1976). The presence of exotic grasses with high biomass can lead to higher intensity fire and increased mortality of saplings and poles (Wilson and Mudita 2000). Disturbance from logging events may even benefit the establishment and spread of weed species.

Feral animals may also play a role in recruitment, particularly in riparian areas. (Werner (1986) believes that disturbance of the soil surface and physical destruction of small trees by large feral animals could cause local extinction of some tree species. The operation of these environmental factors are obviously hard to take account of when determining sustainable yield at a territory-wide scale.

Suggestions for an approach to sustainable harvesting in the Northern Territory

Currently timber harvesting of native forests in the Northern Territory is a very minor industry operating a low levels. The comparisons with timber volumes in plantation operations in the Northern Territory and native timber harvesting in Tasmania suggests that ironwood harvesting is likely to always be only a local small-scale operation. The following views from David Clark of Transoceanic Pty. Ltd (pers. comm.) are worth noting:

ìIt has been my belief that Cooktown ironwood is one of the world class timbers, despite its density. However it has several major disabilities:

- itís location in the Northern Territory (being isolated from the main Australian markets);
- possible problems with colour variation in the timber (the preferred red-brown colour as against the less preferred ìoatmealî;
- possible difficulties in kiln drying. To my knowledge nobody has actually attempted to kiln dry this species. All timber needs to be kiln dried unless sawn boards have been air dried for a very long time (probably 24-48 months) to allow the timber to naturally season; and
- it is not available in veneer. Commercial buyers will only use a timber if it is available in both solid and veneer. Equally as nobody has bothered doing anything about promoting the timber to the specialist buyer off-takes will remain small.

  Kiln dried boards at 0.50 mm reach should be worth between $2500-$2800/cbm. In the longer term we plan to try and capture part of the American craft market, which is huge in volume. However, I do note that we have attempted to break into this market from Australia for several years by dealing with USA based merchants without any notable success. Craft timbers prices in the States can be extraordinary and this commands our long term attention.î

Given the likelihood that the industry will remain at a low level it is unrealistic to think that the financial resources would ever be available to determine sustainable harvest levels at a Territory wide or regional level. The discussion of sustainable yield calculations given above has highlighted the major difficulties in carrying out such an exercise. Given this the following is proposed as a mechanism to regulate the offtake of timber in the Northern Territory.

- Permits should be issued for specific areas of land smaller than has currently been the case. Permits often cover the whole of a pastoral property. The size of the land should equate to an area suitable to supply the needs of the harvester for a year. The size of this area would obviously depend on the size of the operations and the stocking of ironwood.
- No re-logging should be allowed to occur on logged areas until the regeneration and/or growth of a sufficient number of suitable sized trees of commercial size has occurred. This will obviously depend on what the size of a commercially suitable tree is and on the site conditions and hence growth rates achievable on the area. Until we have a better estimate of growth rates of ironwood, particularly for selectively logged areas, it is not possible to nominate what time period should elapse until harvesting should again be allowed.
- A condition of the permit should be that suitable management measures are undertaken for 6 years after logging to ensure adequate regeneration. Protection burning is required to ensure high intensity fires do not destroy young regrowth. This would involve burning areas surrounding those containing commercial timber stands (e.g. areas surrounding riparian lines and flats at Mary River East) and burning within these stands to reduce fuels at times when fires would burn at low intensities (early dry season). Whether this had been successful could be assessed by Parks and Wildlife after the 6 year period. If it was determined that inadequate measures had been taken to protect regeneration then the issue of future permits to the landholder or harvester would be subject to review.
- Permit conditions should be set in relation to size of trees harvested. At present this is 35 cm DBH. There is no reason related to sustainability of yields that smaller trees could not be allowed to be harvested. However it would be preferable if the minimum sizes of trees taken was not less than the size at which flowering will occur. This is currently unknown for ironwood. Potentially, harvesting of smaller trees would mean a greater proportion of the trees at a site could be harvested. There is unlikely to be major implications for hollow dependent fauna as occurs in southern States because of the probable low availability of hollows in ironwood (see chapter 6) and because the occurrence of hollows in ironwoods and eucalypts is probably highly likely to be associated with commercial unsuitability for harvesting. The level of termite infestation in the smaller eucalypts (Fox and Clark 1972) is probably sufficient to ensure a reasonable component would not be logged and hence could grow onto a larger size. No data is available to indicate the relative impacts on fauna of removal of different amounts of canopy.

Fig. 9.5. Erosion of a stream bank at Mary River East associated with a stream crossing to access timber resources.

- Issue of a permit should be dependant on the applicant demonstrating that they had consulted the appropriate authorities and taken account of environmental issues that could arise as a result of timber harvesting activities. This would include such matters as access to the timber, soil erosion, water quality, riparian protection at stream crossings and protection of archaeological sites. At present permits contain the requirement that no logging occur on slopes greater than 10% as a soil protection measure. However, a more comprehensive assessment of this issue would be required taking account of issues such as soil erosion hazard, access requirements, and impacts of machinery. An example of bank erosion resulting from a road crossing of a stream for access to timber at Mary River East is shown in Fig. 9.5.

  Another standard prescription included in permits to protect soil and water resources is the requirement to exclude logging from within 20 m of incised watercourses. There have been much wider riparian reserves called for in recent documents e.g. (Price *et al.* 2000; Woinarski *et al.* 2000). However these relate to situations where extensive clearing will occur and reserves are required that function as viable biodiversity reserves as well as protecting soil and water resources. In situations where selective harvesting is occurring within large natural areas such buffers are probably not required. There is much debate about buffer widths required for protection of water quality in streams and widths are probably likely to vary according to forest type, slope and soil conditions. A review by Clinnick (1985) concluded that a general buffer requirement of 30 m was reasonable and such widths also appear to cater for the protection of aquatic invertebrates (Davies and Nelson 1994). Hence it is recommended that riparian reserve width be increased to 30 m in future permits. Given the open nature of forest canopies subject to harvesting in the Northern Territory it is likely that 30 m would provide adequate protection. However, this requirement could be increased if advice from soil or water experts (to be required under recommendations given above) deemed this necessary. Based on the calculations of discounts that might apply from the model results and the inadequacies in the drainage layer used to buffer streams it is estimated that losses to resource availability of approximately 15% could apply for a 30 m buffer.

The measures outlined above do not match those operating in most of the southern states. In those jurisdictions detailed Codes of Practice have been developed and dedicated government staff and financial resources are available to assess impacts, develop appropriate prescriptions and provide advice and draw up detailed logging plans for individual harvesting units. However, given the parlous state of government resources and the small scale of the timber industry in the Northern Territory it is believed that the measures outlined above provide a better pathway towards the goal of ecologically sustainability than presently exists. We believe the evidence argues for conservative harvest levels, at least until more information is available on demography and growth rates, and until more sympathetic fire management practices can be established.

Conclusion

Despite its wide geographic and environmental range, the area that supports large ironwoods suitable for present industry requirements is limited. Often such trees will occur in riparian flats and a reasonable proportion will be excluded from logging due to riparian buffer prescriptions to protect water quality and minimise soil erosion. Thus the Northern Territory will not be able to support large scale logging of ironwood. The small scale of the industry means that resources will not be available to support detailed inventory and extensive regulation, monitoring and overview as occurs in southern States. Collection of further information on growth rates is a high priority in order to better assess sustainable yield. Control of fire regimes after logging is essential to ensure adequate recruitment and hence maintenance of an on-going supply of timber.

Future Studies

It is desirable that further studies be undertaken to fill remaining knowledge gaps. The priority that should be given to this work will depend on the extent to which logging of ironwoods occurs. With the demise of logging at Mary River East the numbers of ironwoods that are logged each year may be limited. Suggested projects are listed below.

Growth

The growth data available are limited and somewhat conflicting. It is important to determine whether logging stimulates growth of remaining younger trees, as suggested by present limited data. This information is important in determining the time between harvesting events and is vital for the determining sustainable yield. The influence of soil type and location also needs to be investigated. Many stands are not suitable for harvesting because poor soils (such as on rocky hills) probably limit the size attained by trees. However, potentially harvestable stands may occur on a range of soils and sometimes in areas outside of riparian influence as well as in riparian areas.

Occurrence of hollows in large ironwoods

The findings on the occurrence of hollows in the present study were at odds with those of Braithwaite *et al.* (1985). Further work should be conducted in an area with large ironwoods (where commercial logging could potentially be carried out) to assess the comparative value of ironwoods for hollows.

Flowering and the importance of regeneration from seed

The size at which ironwoods flower is unknown. If the industry were to lower the diameter of logs that were commercially acceptable it would be important to determine at what size ironwood flowered and produced viable seed. This information would be required to ensure that trees large enough to produce seed would remain in an area after harvesting. At present it appears that ironwood relies principally on suckering and coppicing for regeneration. A genetic study of trees in an area could be used to determine the extent to which regeneration from seed occurs.

Validation of the model of the distribution of basal area.

If an estimate of the area of land supporting harvestable stands and the volume of timber present is required it would be important to undertake some assessment of the validity of predictions from the models presented in chapters 4 and 5. This would involve checking sites of predicted high and low basal areas of big ironwood trees.

Impact of logging on biodiversity

An assessment of ecological sustainability requires that the impact of harvesting on biodiversity is taken into account. The only assessment of the potential impact of harvesting on biodiversity values to date is the information on the occurrence of hollows in chapter 6. Ideally a study would be undertaken to assess the impacts of logging on both flora and fauna species. This would involve either comparing unlogged and logged areas or comparing areas before and after logging.

Comparison of logging with natural events

Cyclones can cause major disturbance to Top End forests. It would be useful to compare the response of ironwoods to logging with that of a major natural disturbance event such as a storm or cyclone. Logging will never equate exactly to a natural disturbance at an ecosystem level because logging involves removal of biomass wheras natural disturbance produces standing stags and coarse woody debris. However it could be the case that growth responses by ironwoods to the natural and unnatural disturbance are comparable.

Montreal Criteria and Indicators of Sustainability

The data collected in this study allows reporting against the following indicators under the Montreal Process:

2.1.a Net area of forest land available for timber production

The total area of land supporting a basal area of large (>20 cm DBH) ironwood trees at greater than 0.05 m^2/ha (see Fig. 4.12) is 74,243 km^2. This is the best estimate available of the distribution of trees of a commercial size. Of this area an estimated 12,879 km^2 (17.3%) falls within conservation reserves. Further areas are excluded from logging for environmental reasons. 2.2% of land within the distribution of large trees has a greater than 10% slope. For the Mary River catchment a 12% area discount was calculated for riparian buffers of 25 m. The discount value for riparian buffers would be greater if the recommended 30 m buffer were adopted and is a minimum estimate as many drainage lines were not mapped on the GIS layer. Thus a discount of 15% may be more realistic for riparian buffers. A total discount figure of 17.2% then applies to the total area figure after the area in conservation reserves is excluded. Thus the estimate for forest land available for timber production for ironwood is 50,809 km^2. A greater area will be available for timber harvesting if other trees such as eucalypts are included.

2.1.d Annual removal of wood products compared to the sustainable volume

The sustainable volume cannot be calculated because the data on growth rate is presently conflicting. However the annual removal of logs under permit from Parks and wildlife Commission between 1995 and 2001 averaged 394 ironwood logs/annum, 293 eucalypt logs/annum and 46 logs/annum of other species. On the Mary River East property the average volume of an ironwood log was 0.5995 ± 0.3073 (SD) m^3 and 0.5192 ± 0.4461 m^3 for a eucalypt. Using these figures gives an annual removal of 236 m^3 of ironwood and 152 m^3 of eucalypt. Additional illegal harvesting may occur and other uses additional to timber also occur. Examples of these are didgeridoos and craftwood.

2.1.g Area and per cent of harvested area of native forest effectively regenerated

No comprehensive assessment of regeneration on all areas logged was undertaken. However a sample of logged areas on the property where most of the harvesting has occurred was assessed. It appeared that fire regimes were influencing the level of regeneration. Regeneration at Eureka Creek was slightly greater than at OíNeil Creek. It is unlikely that recruitment at OíNeil Creek would have been adequate to ensure future timber supplies. Whether recruitment at Eureka Creek is adequate is unable to be assessed without information on future mortality rates expected for the individuals that have reached pole stage and the the fire regimes that are likely for the area in the future. Because there is no specific management of fire regimes to assist regeneration, adequate future stocking cannot be guaranteed. Thus although ironwood readily produces suckers indicator 2.1.g on regeneration should probably be scored as ìno mechanisms in place to guarantee adequate regeneration and many areas likely not to regenerate adequately due to inadequate management of fire impacts on juvenilesî.

References

Boland, D.J., Brooker M.I.H, Chippendale, G.M., Hall, N., Hyland, B.P.M., Johnstone, R.D., Kleinig, D.A. and Turner, J.D. (1984). *Forest trees of Australia.* Fourth edition. (Thomas Nelson and CSIRO: Melbourne).

Bowman, D.M.J.S. and Panton W.J., (1995). Munmarlary revisited: Response of a north Australian *Eucalyptus tetrodonta* savanna protected from fire for 20 years. *Australian Journal of Ecology* **20**, 526-531.

Bowman, D.M.J.S. Wilson, B.A and Woinarski, J.C.Z. (1991) Floristic and phenological variation in a northern Australian rocky Eucalyptus savanna. *Proceedings of the Royal Society of Queensland* **101**, 79-90.

Braithwaite, R. W., Parker, B. S., Wood, J. T. and Estebergs, J. A., 1985. The distribution and abundance of termite-induced tree hollows in tropical forests of northern Australia. Pp. 651-729 In *The Kakadu fauna survey : an ecological survey of Kakadu National Park.* ed by R. W. Braithwaite. Report to ANPWS, Canberra.

Chidumayo, E.N. (1988). A re-assessment of the effects of fire on miombo regeneration in the Zambian Copperbelt. *Journal of Tropical Ecology* **4:** 361-372.

Chidumayo, E.N. and Frost, P. (1996). Population biology of miombo trees. In *The Miombo in transition: woodlands and welfare in Africa*. (ed. B. Campbell). (Center for International Forestry Research, Bogor).

Grimes, R.F. and Grigg, R.E. (1979) *Growth data for a spotted gum - ironbark forest in south east Queensland.* Queensland Department of Forestry Technical Paper No 17.

Clinnick, P.F. (1985) Buffer strip management in forest operations: a review. *Australian Forestry* **48**, 34-45.

Davies, P.E. and Nelson, M. (1994) Relationships between riparian buffer widths and the effects of logging on stream habitat, invertebrate community composition and fish abundance. *Australian Journal of Marine and Freshwater Research* **45**, 1289-1305.

Fensham R.J. and Bowman D.M.J.S, (1992). Stand structure and the influence of overwood on regeneration in tropical Eucalypt forest on Melville Island. *Australian Journal of Botany* **40**, 335-352.

Fox, R.E. and Clark, N.B. (1972). The incidence of termites in eucalypts of the Darwin area. *Australian Forest Research* **5,** 29-36.

ForSci Pty Ltd (1999) *Environmental Impact Assessment of Establishment of Fast Grown Plantations on the Tiwi Islands.* ForSci: Sydney.

Guinto, D.F., House, A.P.N., Xu, Z.H. and Saffingna, P.G. (1999) Impacts of repeated fuel reduction burning on tree growth, mortality and recruitment in mixed species eucalypt forests of southeast Queensland, Australia. *Forest Ecology and Management* **115,** 13-27.

Hanssen, N.L., and Wigston, D.L. (1989). Approaches to a forest history of the Northern Territory. In *Australiaís Ever-changing Forests.* (Eds: K.J. Frawley and N. Semple). (Department of Geography and Oceanography, University College, Australian Defence Force Academy: Campbell, ACT).

Iwainde, F. (1998) Regeneration of Cooktown Ironwood in Mary River East Station in the Northern Territory of Australia. Masters of Tropical environmental Management. Northern Territory University, Darwin.

Lacey C.J. and Whelan, P.K. (1976). Observations on the ecological significance of vegetative reproduction in the Katherine ñ Darwin region of the Northern Territory. *Australian Forestry* **39**, 131-139.

Mucha, S.B. (1979) Estimation of tree ages from growth rings of eucalypts in northern Australia. *Australian Forestry* **42,** 13-16.

Price, O., Milne, D., Connors, G., Harwood, R., Woinarski, J., and Butler, M. (2000). *A conservation plan for the Daly basin bioregion.* Report to Natural Heritage Trust. (Parks and Wildlife Commission of the Northern Territory: Darwin.)

Werner, P.A. (1986). *Population Dynamics and Productivity of Selected Forest Trees in Kakadu National Park.* Final Report to Australian National Parks and Wildlife Service. (CSIRO Tropical Ecosystems Research Centre: Darwin).

Woinarski, J., Brennan, K., Hempel, C., Firth, R., and Watt, F. (2000). *Biodiversity conservation on the Tiwi Islands: plants, vegetation types and terrestrial vertebrates on Melville Island.* 245 pp. Report to the Tiwi Land Council. (Parks and Wildlife Commission of the Northern Territory: Darwin.)

Woinarski, J.C.Z. and Dawson, F. (2001) Limitless lands and limited knowledge: coping with uncertainty and ignorance in northern Australia. In *Ecology, uncertainty and policy: managing ecosystems for sustainability* (ed. T.W. Norton, J.W. Handmer and S.R. Dovers). (Longmans; London).

Wilson, C. and Mudita W., (2000). Fire and Weeds: Interaction and Management Implications. In *Fire and Sustainable Agricultural and Forestry Development in Eastern Indonesia and Northern Australia.* ACIAR proceedings 91. (Eds: J Russell-Smith, G. Hill, S. Djoeroemana, B. Myers). (Australian Centre for International Agricultural Research: Canberra 2000).

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