6. Species performance and site relationships for rainforest timber species in plantations in the humid tropics of Queensland

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Abstract

The performance of 32 tropical rainforest and eucalypt tree species grown in private, mixed species plantations was examined. There were two objectives: 1) to summarise the growth of species by soil and rainfall classes, 2) to investigate the degree of variability in growth rates with respect to environmental variables. Data were collected from 112 plots established in the Community Rainforest Reforestation Program (CRRP) plantations across sites in the humid tropics of central and north Queensland. Sites ranged from sea level to 1160 m above sea level, with annual rainfall from 800 mm to 4300 mm, on soils derived from basalt, metamorphic and granite parent material. Species performance was significantly related to climatic and edaphic variables but the strength of these relationships differed among taxa.

Introduction

Foresters involved with timber plantation development in the tropics have traditionally focused on fast-growing species with good form and desirable wood characteristics that can yield a marketable commodity (Evans 1992). Throughout most of the twentieth century Australia followed this trend, establishing fast growing softwoods in plantations while there was a plentiful supply of hardwood timber from native forests. While there is a growing trend to privatisation and private ownership (Wood *et al.* 2001), the plantations, on the whole, have been publicly owned and established on crown land. In Queensland a large estate of tropical exotic conifers (*Pinus* species) and smaller areas of the native *Araucaria cunninghamii* (hoop pine) have been established under this approach. More recently, establishment of hardwood plantations and plantations of rainforest and other high-value species has gained momentum following the cessation of logging in rainforest areas throughout Queensland. Importantly, private interests have, to some extent, driven this development on privately owned land.

Historically, foresters tried a wide range of species in plantations in north Queensland (Anon. 1983), and there has been some analysis and integration of the results of this experience from older (Cameron and Jermyn 1991, Russell *et al.* 1993) and more recent plantings (Applegate and Bragg 1989, Keenan *et al.* 1995, Keenan 1998, Keenan and Annandale 1999, Annandale and Keenan 2000). However, there has not been a planned, well-coordinated and replicated set of trials as is required to match species to site (e.g. see Butterfield 1995, Butterfield 1996, Harwood *et al.* 1997a, Lee *et al.* 2001) for Australian tropical rainforest timber species grown in plantations. A number of surveys have predicted growth rate using expert opinions (Russell *et al.* 1993, Herbohn *et al.* 1999, Herbohn *et al.* 2000) but growth rates and site suitability are not well known for many of these species.

The considerable area of plantations established under the CRRP (1780 ha, Skelton and Sexton pers. comm.) provides an opportunity to investigate the performance of species across a wide range of sites. Preliminary descriptions of growth in CRRP plantations across regions highlight promising species (Keenan and Annandale 1999), and have alluded to relationships between climatic and edaphic factors and early growth rates of rainforest species (Bristow 1996, Merkel 1996, Keenan and

Annandale 1999). However, growth is not uniform over time and there is considerable risk in basing species selection on growth performance during the plantation's establishment phase, where trees are experiencing relatively free-growing conditions (Evans 1992, Haggar and Ewel 1995). This study uses a dataset extended from McNamara (2003) to assess performance across more site types, for eight year old trees. At this age, the faster-growing, early successional species will have concluded their accelerated juvenile growth phase. Indeed by age eight, many species planted in the CRRP will have captured the site and growth rates of individual trees may well be slower than in the first three to five years. At age eight years, growth patterns are affected by between-tree competition and species are beginning to differentiate into crown classes. By using these measurements we are likely to more accurately predict annual growth increments for mature trees.

Knowledge about the influences of genetics, altitude, soil, climate and competition on the growth of a species is crucial for a successful plantation program. For most Queensland rainforest timber species the legacy of 100 years of timber harvesting provided knowledge of timber properties, but very little was known about the silvicultural requirements of these species before the CRRP plantations were established (Lamb and Borschmann 1998, Bristow *et al.* 2000). The CRRP nevertheless provides a range of sites and species to begin considering climatic and edaphic influences on species performance across the landscape. Plantations were established between Mackay and Cooktown, along the coastal lowlands and foothills, and on the tropical upland areas of Atherton and Ravenshoe (see Figure 1).

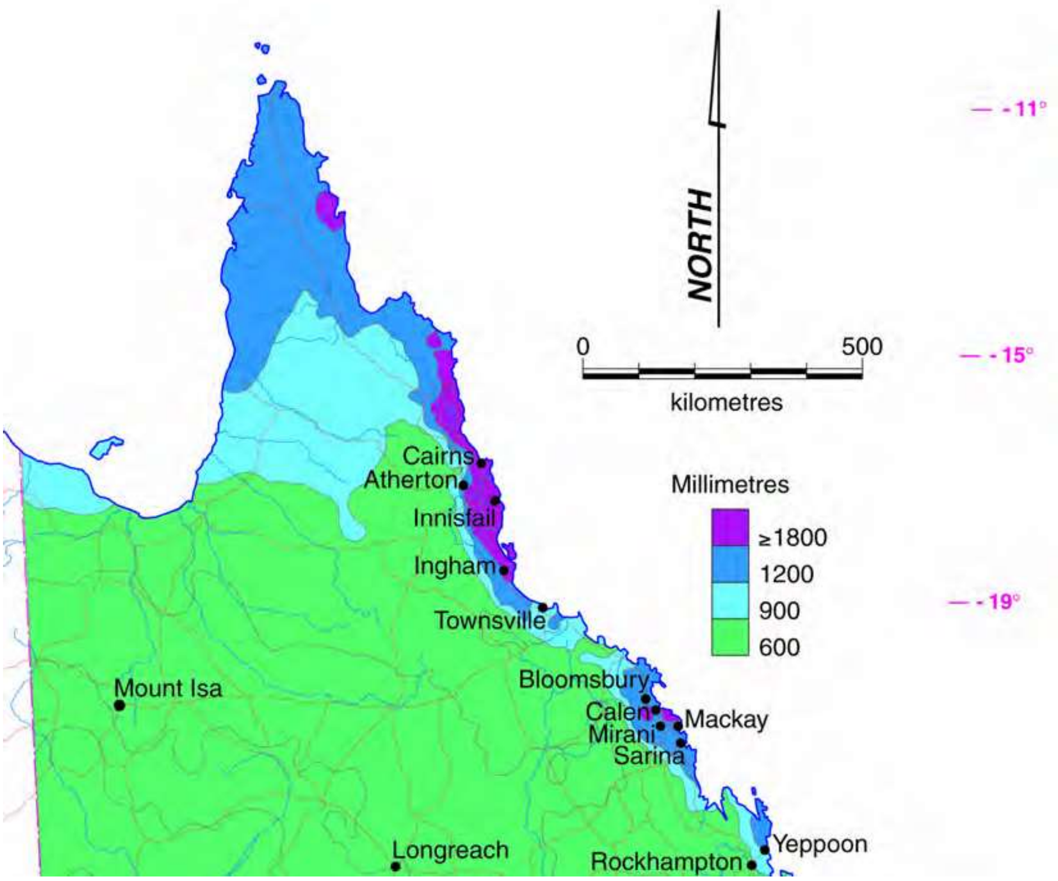

Figure 1 Higher rainfall regions of the humid tropics where rainforest timber species are grown in plantations.

Sites ranged in altitude from 10 m to 1160 m.a.s.l., mean annual temperature varied from 19 to 26°C, and mean annual precipitation from 800 to 4300 mm (Table 1). Soils in this region are derived from basaltic, granitic and metamorphic parent materials of a range of ages (Isbell and Edwards 1988, Murtha and Smith 1994). Previous land use on these sites varied considerably. Many CRRP plantations were located on agriculturally marginal land or subdivided farmland and hobby farms. In some cases, trees were planted as windbreaks and in wide-spaced plots with the intention of grazing cattle under the trees. Further variability is introduced to CRRP plantations through the use of a wide range of species and species mixes, provenances and seedling sources, and variable stocking rates and silvicultural inputs.

Table 1 Locations and climatic ranges of sites sampled from the CRRP.

Parameter	Minimum	Maximum
Latitude	15° 26’	18° 51’
Longitude (East)	146° 13’	145° 02’
Altitude	10 m	1160 m
Mean annual temperature	19° C	26° C
Maximum annual temperature of the warmest week	28° C	33° C
Minimum annual temperature of the coldest week	8° C	15° C
Annual precipitation	800 mm	4300 mm
Precipitation in the wettest week	39 mm	169 mm
Precipitation in the driest week	0 mm	20 mm

Source: ANUCLIM (Houlder et al. 2000).

A study commenced by Queensland Department of Primary Industries and Fisheries’ Agency for Food and Fibre Sciences (DPI&F-AFFS) Forestry Research (formerly QFRI) and Rainforest CRC established a series of permanent sample plots to measure growth of trees across a range of sites in CRRP plantations across the region. The growth and performance of species in CRRP plantation plots is reviewed in this paper.

Objectives

Species performance in this study is a simple combination of growth rate and form whereby faster growth is equated with better performance. If growing these species is to become a commercial reality, it will be necessary to develop cost-effective, quality timber plantations. By summarising performance of species, this study aims to identify a range of preferred species for soil and rainfall classes. The effect of site characteristics on growth can be considered using correlation coefficients (Nichols *et al.* 1997, McNamara 2003). This technique was used as a cost-effective method of matching species to site. In short, the objectives of this study are to: summarise growth of species by soil and rainfall classes; and investigate the degree of variability in growth rates of individual species across different sites with respect to environmental variables derived from ANUCLIM (Houlder *et al.* 2000).

Methods

CRRP Silviculture

Most CRRP plantations are mixed species stands consisting of eucalypts or rapidly growing rainforest pioneer species, together with early or late successional rainforest species and historically well-recognised ‘rainforest timbers’, e.g. cabinet timbers (Keenan and Annandale 1999).

In earlier plantings (those established 1992–1994), species were mixed along rows whereas after 1995 the general configuration was a row of a single pioneer species alternating with a row of mixed later-successional rainforest species. A few plantations consisted of single species, mainly eucalypts or mixtures of eucalypt species, or *Araucaria cunninghamii* monoculture stands. As a result of this variable silviculture, tree stocking at the time of measurement plot establishment also varied, where some plots had trees growing at 1100 stems/ha and others had relatively sparse stocking rates of 470 stems/ha. A list of species commonly planted is shown in Table 2, however not all taxa were planted in each site.

The methodology for plantation and measure plot establishment is described thoroughly in Keenan and Annandale (1999).

Increment plots and measurement

112 permanent measure plots were established on a range of sites planted between 1992 and 1997. Sites were selected to represent the range of plantation conditions, soil and rainfall gradients across the region, described further in Keenan and Annandale (1999). Plots were positioned within block plantations and edge trees were avoided. When established, each plot aimed to include 60 trees typically in 6 rows x 10 tree configuration, but occasionally in 4 rows x 15 trees or 3 rows x 20 trees. Tree measurements consisted of diameter of the stem at breast height over bark (DBHOB (cm)); total height (m); and a qualitative assessment of stem form classified into one of five categories: 1- very poor (extensive branching, very twisted and bent bole), 2- poor (significant branching, some twisting or bends in the bole), 3- average (mostly straight with some branching/forks), 4- good (straight bole with few branching/forks), 5- excellent (straight bole with no forking or bending). Individual trees were measured in 1998, 1999, 2000, 2001(incomplete) and 2002, although this study only summarises the most recent interval.

Estimates of growth rates were calculated using a linear regression growth model to standardise age to eight years, either interpolated or extrapolated to take account of the variation in planting years across the dataset. Average growth estimates from sites were then summarised into nine soil and rainfall classes, which on the whole, reflect naturally occurring, distinct site types that forest growers can easily recognise. Specifically, sites were separated by soil parent material; basalt, metamorphic, alluvial or granite, and three rainfall classifications; less than 1500 mm per annum, 1500 to 2500 mm per annum, and greater than 2500 mm per annum. To account for natural variation in individual tree growth rates, species that were poorly represented, or those with fewer than ten individuals in a soil and rainfall class, were excluded from the performance to site summaries.

Pearson correlation coefficients were used to describe the strength and direction of the relationships between the growth of species across all the sites and the mean annual rainfall, mean annual temperature and soil nutrient supply (Mackey 1993). As multiple environmental factors were tested, a Bonferroni correction was used to adjust significance levels.

Table 2 Species commonly planted in the CRRP.

Species	Common Name
Acacia mangium	sally wattle
Agathis robusta	kauri pine
Alphitonia petrei	pink ash
Araucaria cunninghamii	hoop pine
Blepharocarya involucrigera	rose butternut
Cardwellia sublimis	northern silky oak
Castanospermum australe	black bean
Cedrela odorata	West Indian cedar
Corymbia citriodora	lemon-scented gum
Corymbia torelliana	cadaghi
Elaeocarpus grandis	silver quandong
Eucalyptus acmeniodes	white mahogany
Eucalyptus camaldulensis	river red gum
Eucalyptus cloeziana	Gympie messmate
Eucalyptus drepanophylla	grey ironbark
Eucalyptus dunnii	Dunn’s white gum
Eucalyptus pellita	red mahogany
Eucalyptus resinifera	red mahogany
Eucalyptus tereticornis	forest red gum
Eucalyptus tetradonta	Darwin stringybark
Eucalyptus urophylla	Timor white gum
Flindersia brayleyana	Queensland maple
Flindersia pimenteliana	maple silkwood
Flindersia schottiana	Queensland silver ash
Grevillea robusta	southern silky oak
Khaya spp.	African mahogany
Melia azedarach	white cedar
Nauclea orientalis	Leichhardt/ cheesewood
Paraserianthes toona	Mackay cedar / red siris
Tectona grandis	teak
Terminalia sericocarpa	damson

Results

Survival

Survival in the growth plots was highly variable. Average tree survival across sites from planting to eight years old was 61%, but ranged from 5% to 100% (19% st. dev). The variations in original planting density and survival have contributed to inconsistent growth conditions between trees, species, sites and regions.

Diameter, height and form growth all sites

Table 3 shows species performance estimated at age eight years and ranked by mean diameter over bark (DBHOB) (where $n>10$ in each defined soil and rainfall class) for 32 of the most commonly planted taxa. Growth estimates of DBHOB, mean height and mean form across all soil and rainfall classes are shown in this table. The total numbers of individual trees (n) and sites used in this calculation varied and species that occurred in limited plantings are marked.

The ten fastest growing species (based on diameter) include five eucalypts and five rainforest taxa. The fastest growth was recorded for the Indonesian/Timorese eucalypt *Eucalyptus urophylla*, although this species was planted on only one site type represented by a small number of trees (n = 11). As expected, the fastest growing rainforest timber species were generally the early pioneer species such as *Acacia mangium* (ranked 2), *Elaeocarpus grandis* (ranked 8) and *Alphitonia petrei* (ranked 12). Well-known for their cabinet timber properties from native forests, the mid successional species *Grevillea robusta*, *Melia azedarach* and *Flindersia brayleyana* also showed rapid growth ranked 6, 7 and 14 respectively. Similarly, the native conifers, *A. cunninghamii* and *Agathis robusta* had consistently moderate growth and good form across sites. However, other mid to late successional species featured amongst the slowest growing species and included *Castanospermum australe* (ranked 31) and *Flindersia pimenteliana* (ranked 32). Other than *E. urophylla*, there were four exotic cabinet timber species, *Cedrela odorata*, *Khaya nyasica*, *Tectona grandis* and *Khaya senegalensis*, with overall diameter growth ranked 15, 24, 28, and 30 respectively.

The poorest average form was that of the slow-growing *Paraserianthes toona* (average form score 2.7) closely followed by the fast growing *A. mangium* (3.0). Damage by insect pests (such as borers) and pathogens were regularly recorded and at least partially responsible for poor form in these species. The eucalypts exhibited good to excellent form, apart from the two *Corymbia* species and *E. drepanophylla*. These eucalypts have broad natural distributions (Boland *et al.* 1992, Brooker and Kleinig 1994), that have recently been separated into a number of different taxa with noted differences in form across provenances (Nikles *et al.* 2000, Lee *et al.* 2001). It is probable that across different nurseries, planting regions and planting years, different provenances were used. However, it is not possible to test inter-provenance differences in this study.

Preliminary species to site matching

Table 4 demonstrates preliminary species to site matching where sites were grouped into nine broad soil and rainfall classes. Mean annual DBHOB increment was classified as either fast (> 2.0 cm per year), moderate (1.0 to 2.0 cm per year) or slow (< 1.0 cm per year). Growth rate is ranked in descending order both within and between these categories.

Some species were represented by relatively few individuals, growing on only a few, or even one site (e.g. all *E. urophylla* trees are on one site). Consequently comparison between species is confounded by number of individuals, number of sites and variability across sites. Table 4 therefore only provides a general guide to species which have potentially compatible growth rates at a particular site. Thus, to establish a plantation at a site with alluvial soils receiving more than 2500 mm annual rainfall, a potentially compatible combination of moderately growing species would be *Eucalyptus pellita, Flindersia brayleyana* and *Araucaria cunninghamii.*

Table 3 Mean of estimated growth rates, form and numbers of individuals (*n*) represented for all species across all site types ranked by mean diameter (where *n*>10 in each soil and rainfall class) generalized to age 8 years. Species with an asterix (*) occur in limited plantings, on few site types (this is not necessarily the same as a low *n*), results for which should be interpreted with care.

Rank	Species	Mean DBHOB (cm)	Mean Ht (m)	Form	n
1	*Eucalyptus urophylla**	26.9	21.6	4.3	11
2	*Acacia mangium*	26.0	15.7	3.0	93
3	*Eucalyptus dunnii**	19.9	16.8	4.5	21
4	*Eucalyptus resinifera*	18.5	13.7	3.5	71
5	*Eucalyptus pellita*	17.8	14.6	4.0	565
6	*Grevillea robusta*	17.7	12.0	3.8	46
7	*Melia azedarach*	17.7	13.2	3.2	25
8	*Elaeocarpus grandis*	17.6	13.0	4.2	248
9	*Nauclea orientalis*	17.0	9.8	4.1	38
10	*Eucalyptus cloeziana*	16.9	15.3	3.9	409
11	*Eucalyptus camaldulensis*	15.6	14.0	3.5	135
12	*Alphitonia petrei*	15.0	9.9	3.4	27
13	*Eucalyptus acmeniodes**	15.0	10.0	3.2	46
14	*Flindersia brayleyana*	14.7	12.1	4.0	393
15	*Cedrela odorata*	14.2	9.2	3.2	57
16	*Eucalyptus tereticornis*	13.9	12.3	3.5	194
17	*Eucalyptus drepanophylla*	13.3	12.5	3.7	58
18	*Araucaria cunninghamii*	12.5	8.3	4.2	307
19	*Cardwellia sublimis*	12.5	9.6	3.8	13
20	*Terminalia sericocarpa*	12.1	8.8	3.6	53
21	*Corymbia torelliana**	11.8	8.3	3.3	78
22	*Corymbia citriodora**	11.3	12.8	3.7	57
23	*Eucalyptus tetradonta*	10.8	8.5	3.9	20
24	*Khaya nyasica*	10.6	9.2	4.1	48
25	*Blepharocarya involucrigera*	10.6	7.0	3.3	31
26	*Agathis robusta*	9.2	6.6	4.1	291
27	*Flindersia schottiana*	9.2	7.4	3.7	74
28	*Tectona grandis**	9.1	7.8	4.3	10
29	*Paraserianthes toona**	8.1	5.9	2.7	80
30	*Khaya senegalensis**	7.8	5.3	3.5	55
31	*Castanospermum australe**	7.6	7.4	3.5	134
32	*Flindersia pimenteliana**	7.5	7.0	3.5	21

Table 4 Species to region matching: species are ranked in descending order of performance of DBHOB increment both within and between these classes of soil and rainfall. The number of trees used to calculate this value is shown in brackets. Cells that are blank show where no growth measure plots were established, or where n<10, or where no CRRP plantations occur.

Soil type	Diameter growth rate	< 1500mm	1500 – 2500mm	> 2500mm
Basalt	Fast >2.0 cm yr^{-1}		E. dunnii [21] Ela. grandis [77] E. pellita [123] E. cloeziana [85]	E. urophylla [11] Ela. grandis [21] E. pellita [186] E. cloeziana [35]
	Moderate 1.0-2.0 cm yr^{-1}	E. cloeziana [99] E. resinifera [15] E. drepanophylla [45]	A. petrei [17] T. sericocarpa [12] A. cunninghamii [141] F. brayleyana [63] C. odorata [21] B. involucrigera [15] A. robusta [197]	C. odorata [11] F. brayleyana [77] A. cunninghamii [52] C. sublimis [10] A. robusta [38] C. australe [38]
	Slow <1.0 cm yr^{-1}		F. schottiana [32] C. australe [25]	
Metamorphic	Fast >2.0 cm yr^{-1}	E. pellita [49] E. cloeziana [16]	A. mangium [12] Ela. grandis [10] F. brayleyana [44] E. pellita [41] C. torelliana [10]	
	Moderate 1.0-2.0 cm yr^{-1}	F. brayleyana [50] K. nyasica [19] E. tereticornis [41] Ela. grandis [44]	C. odorata [12] F. schottiana [12] E. tereticornis [65] E. tetradonta[17] T. grandis [10]	
	Slow <1.0 cm yr^{-1}	C. torelliana [36] Aga. robusta [14]	K. nyasica [10] P. toona [16]	
Alluvial	Fast >2.0 cm yr^{-1}	G. robusta [25] E. camaldulensis [91] E. cloeziana [63]	A. mangium [70] Ela. grandis [51] E. resinifera [46] E. pellita [91] G. robusta [18] E. cloeziana [86] E. tereticornis [88] C. torelliana [30]	N. orientalis [11] Ela. grandis [29] E. cloeziana [17]

	Moderate 1.0-2.0 cm yr^{-1}	E. pellita [59] A. cunninghamii [30] E. acmeniodes [28] F. brayleyana [43] A. robusta [12]	F. brayleyana [87] N. orientalis [26] E. drepanophylla [10] E. camaldulensis [44] T. sericocarpa [31] A. robusta [19] B. involucrigera [10] C. citriodora [38] P. toona [27]	E. pellita [16] F. brayleyana [22] A. cunninghamii [17]
	Slow <1.0 cm yr^{-1}	K. senegalensis [54] C. australe [14]	C. australe [45]	
Granite	Moderate 1.0-2.0 cm yr^{-1}		Ela. grandis [13] F. schottiana [14] A. cunninghamii [60] P. toona [28]	

Environmental influences on growth

For species that were planted in sufficient numbers across several sites the CRRP provides an opportunity to investigate the influences of environmental factors on growth. Earlier studies have shown there is significant covariation of soil, rainfall classes and temperature across the study region (Bristow 1996, McNamara 2003). For example, high rainfall sites with alluvial soils are located on the coastal lowlands and experience warmer mean annual temperatures, while lower rainfall metamorphic sites are often found in upland areas and have cool mean annual temperatures. Significant relationships describing the amount of variation in diameter growth that can be attributed to mean annual rainfall, mean annual temperature, and soil nutrient supply are displayed in Table 5. Species with no significant correlations between growth and environmental factors are not shown.

Highly significant relationships with mean annual rainfall were found for five species: *Acacia mangium* ($r = -0.39$, $p < 0.001$), *Agathis robusta* ($r = 0.23$, $p < 0.001$), *Elaeocarpus grandis* ($r = 0.34$, $p < 0.001$), *Eucalyptus resinifera* ($r = 0.52$, $p < 0.001$), *Eucalyptus tereticornis* ($r = 0.27$, $p < 0.001$), with all but *A. mangium* showing increased growth with increased rainfall. The other environmental factors, soil nutrient supply and mean annual temperature, describe significant trends in the growth of nine and eleven species respectively.

Most significant relationships between diameter growth and temperature are positive, suggesting that these species grow better on sites with warmer mean annual temperatures. For *A. cunninghamii*, the variability in diameter growth is highly correlated with lower mean annual temperature ($r = -0.51$, $p<0.01$), with better growth on cooler sites. Interestingly, for several species the variation in growth has a negative relationship with the soil nutrient supply factor derived by Mackey (1993), suggesting these species grow faster on poorer sites. *G. robusta* has a highly significant negative correlation with nutrient supply ($r = -0.57$, $p < 0.001$). This is also the only species in Table 5 which has proteiod roots, a root type which are adapted to nutrient poor soils (Lamont 2003).

Comparisons with earlier studies

In their survey of performance of rainforest timber species in 1991, Cameron and Jermyn sourced growth rates from both long-term native rainforest species grown in manipulated natural stands (in Queensland) and some exotic species tested in early Australian and international plantation research. This review also highlighted species that warranted further attention and many of these were included in the CRRP.

Table 6 shows the range of annual diameter increments reported in Cameron and Jermyn (1991), compared with the mean DBHOB annual increment at all CRRP study sites, and the mean DBHOB increment of the best ten trees observed for some key rainforest species at age eight years in this study. Priority listings are those suggested by the authors (Cameron and Jermyn 1991). The mean growth rates of species fell within the range reported by Cameron and Jermyn (1991), however the ten best trees of local species in CRRP have growth rates up to twice those reported by Cameron and Jermyn (1991).

Discussion

Four eucalypts (*E. pellita*, *E. cloeziana*, *E. tereticornis* and *E. camaldulensis*) and five rainforest cabinet timber species (*F. brayleyana*, *A. cunninghamii*, *A. robusta*, *Elaeocarpus grandis* and *C. australe*) were widely planted within the CRRP and the number of individuals in the growth plots (Table 3) are broadly indicative of the relative importance, or popularity, of these species in the CRRP plantations. For these species there is reasonable confidence in the reliability of the figures presented. For species represented by a low number or only recorded in one or two regions, growth figures must be interpreted with caution as these data are estimates of growth despite varied silvicultural and genetic inputs.

Many species have performed well across a range of sites. In the early years of the CRRP, the selection of species for planting and their matching to sites were often determined by factors such as availability of seedlings (see Lott *et al.* Chapter 3). After the Program became better established and managers gained more experience, site selection criteria were introduced, and plantation establishment reportedly became more successful (Creighton and Sexton 1996a, Vize and Creighton 2001). However, the measure of 'success' in these earlier reports does not necessarily relate to survival rates. The average survival of trees in growth plots at age eight years (61%) was significantly less than the 85% described by Vize and Creighton (2001) and did not change significantly between establishment years (data not shown).

The widely planted *E. pellita* and *E. cloeziana* consistently grew well across most sites in the CRRP and in a range of rainfall classes and soil types (Tables 3 and 4), thus reflecting these species' wide natural distributions (Boland *et al.* 1992, Brooker and Kleinig 1994). While earlier studies (Dickinson and Sun 1995, Semple *et al.* 1999) have recommended *E. pellita* for more fertile soils (basalt and alluvial), and *E. cloeziana* for poorer soils, these distinctions were not observed in this study. This could be due to the précis inherent in the factor 'soil nutrient supply' derived by Mackay (1993).

Otherwise, as other studies have shown, the variation in growth of these species could be correlated with genetic or provenance differences (Harwood *et al.* 1997a, Harwood *et al.* 1997b, Semple *et al.* 1999, Nikles *et al.* 2000, Lee *et al.* 2001).

Even though not planted across many sites, *E. dunnii* and *E. urophylla* were the fastest growing species on basalt soils in the medium and high rainfall classes, respectively (Table 4). These species have been included in tree improvement and preliminary wood properties studies and, as has been suggested elsewhere, they may warrant further study on other sites (Dickinson *et al.* 2000, Nikles *et al.* 2000, Muneri *et al.* in review). *Corymbia torelliana*, a eucalypt that grows naturally on metamorphic soils with higher rainfall on the margins of rainforests (Boland *et al.* 1992), displayed similar growth rates in comparable CRRP plots (Table 4).

Table 5 Pearson correlation coefficients for environmental variables and DBHOB of at age eight years for key species. How much of the variation in growth is governed by a factor, is summarised for a number of species using correlation coefficients. The closer the coefficient value is to 1.0, the more the variation in diameter growth is related to that variable. Positive or negative correlations are shown and significance levels are shown by asterix markings.

Species	Mean Annual rainfall	Mean annual temperature	Soil nutrient supply
Acacia mangium	-0.39 ***		-0.29 *
Agathis robusta	0.23 ***	0.31 ***	0.20 **
Araucaria cunninghamii		-0.51 **	0.53 **
Castanospermum australe		0.39 ***	
Cedrela odorata		0.31 *	
Elaeocarpus grandis	0.34 ***	0.26 ***	0.30 ***
Eucalyptus cloeziana		0.26 ***	0.26 ***
Eucalyptus pellita		0.14 *	-0.13*
Eucalyptus resinifera	0.52 ***	0.41 ***	
Eucalyptus tereticornis	0.27 ***	0.47 ***	0.59 ***
Flindersia brayleyana		0.34 ***	
Flindersia schottiana		0.34 **	-0.29 *
Grevillea robusta			-0.57 ***

*Significance adjusted for Bonferroni = *p<0.05, **p<0.01, ***p<0.001*

Table 6 Comparison of performance results from this study and Cameron and Jermyn (1991) for annual diameter increment (cm yr^{-1}) of rainforest timber species in plantations.

Species	Cameron and Jermyn (1991)*	This study age 8 years	
		Mean of all sites	Mean of 10 best trees
Priority 1 Species*			
Castanospermum australe	1.0	0.9	2.1
Cedrela odorata	1.3 – 3.9	1.8	3.1
Elaeocarpus grandis	1.2 – 3.0	2.2	4.2
Flindersia brayleyana	0.6 – 1.7	1.8	3.4
Grevillea robusta	0.7 - 3.0	2.2	3.0
Tectona grandis	1.2 – >3.0	1.1	1.1
Priority 2 Species*			
Flindersia pimenteliana	0.6	0.9	1.2
Flindersia schottiana	0.8 - 1.2	1.1	2.4
Khaya nyasica	1.3 – 1.9	1.3	2.2

**Cameron and Jermyn (1991) growth figures were sourced from literature (both domestic and international) and data extracted from Queensland databases (priority levels suggested by Cameron and Jermyn).*

As expected, eucalypts had the fastest growth on the drier sites (e.g. *E. cloeziana* and *E. resinifera* on basalt soils, *E. pellita* and *E. cloeziana* on metamorphic soils, *E. camaldulensis* and *E. cloeziana* on alluvial soils). Also, the cabinet timber species *G. robusta* was the fastest growing species on alluvial soils with rainfall less than 1500 mm/annum (Table 4). Smaller numbers of some eucalypts that were planted on particular sites, achieved moderate to fast growth rates, i.e. *E. camaldulensis* (low rainfall alluvial soils, northern Atherton Tablelands region), *E. drepanophylla* (low rainfall basalt soils, southern Atherton Tablelands, and medium rainfall alluvial soils Ingham region), *E. tetradonta* (medium rainfall metamorphic soils, Cooktown region) and *E. acmeniodes* (lower rainfall alluvial soils, Ingham region). As a result of their site-specific plantings we are unable to compare these species across sites.

The native softwoods *A. cunninghamii* and *Agathis robusta* were widely planted across site classes and showed, as expected, moderate to slow growth. *A. cunninghamii* has been considered somewhat a generalist in its natural distribution, extending from northern New South Wales in scattered forest patches along the entire coast of Queensland, and into the uplands of Papua New Guinea (Webb and Tracey 1967, Boland *et al.* 1992). *A. cunninghamii* was originally prized as a plantation species for its tolerance of a wide range of environmental conditions including drought (Webb and Tracey 1967, Holzworth 1980). Even though its natural distribution covers a broad rainfall gradient, previous studies of *A. cunninghamii* indicate that low rainfall may be a major factor causing low site indices when this species is grown in plantations (Holzworth 1980). In this study rainfall may have been a less important factor as all sites where *A. cunninghamii* was planted received >1200 mm annual rainfall and the only significant correlations were between diameter growth of *A. cunninghamii* and temperature and soil nutrient supply. This suggests that *A. cunninghamii* prefers cooler, more fertile sites such as the uplands where it is most commonly planted. *A. robusta* is not as well researched as *A. cunninghamii*, but has recognized growth and timber properties that justified its inclusion in the CRRP. *A. robusta* does not occur naturally higher than 900 m elevation (Boland *et al.* 1992), which may explain why its growth was positively correlated with warmer sites.

Among the cabinet timber rainforest species *Elaeocarpus grandis* showed reliably good performance on the higher rainfall sites, with greater diameter growth than *E. pellita* and *E. cloeziana* wherever it was planted. This is consistent with earlier studies which included this species (Cameron and Jermyn 1991, Bristow 1996, Keenan 1998, Ibell *et al.* 2001, McNamara 2003, Bristow *et al.* 2005).

Another successful species of the CRRP is *F. brayleyana*. On some sites, metamorphic soils in particular, *F. brayleyana* displayed good growth rates and form when compared with the more traditionally planted eucalypts. The mean diameter increment across all sites for this species is greater than that reported by Cameron and Jermyn (1991); the mean of the best ten trees across all sites is twice as large as earlier reports (Table 6). Furthermore the growth of *F. brayleyana* is positively correlated with temperature, with better growth at warmer mean annual temperatures, and we can therefore recommend it for humid tropical, coastal lowlands sites (Keenan *et al.* 1995, Keenan 1998, Keenan and Annandale 1999, Bristow *et al.* 2003, Bristow *et al.* 2005).

Other studies have noted that *F. brayleyana* was very site specific, requiring sites within the higher rainfall areas (Creighton and Sexton 1996b, Brown 2001), that are fertile and well drained (Creighton and Sexton 1996b). However this study did not find any relationship between this species and rainfall or nutrient supply.

In comparison, *F. schottiana* and *F. pimenteliana* are slower growing. *F. schottiana* had generally slow growth (rank 27, Table 3), but grew moderately fast on the metamorphic and granite derived soils (Table 5). There is a significant correlation between the variability in diameter growth and increasing temperature and decreasing nutrient supply, which might be expected: It is these sites where it has been more commonly planted, such as the poorer soils of the coastal lowlands around the Mackay (central Queensland) region. Like other species in this genus *F. pimenteliana* was included in the CRRP for its beautiful, highly prized cabinet timber. It was the slowest growing of all the 32 species examined and was not planted widely enough to be used in further species to site analysis (n = 21). However the growth of the ten best of these trees across all sites is twice as fast as expected by Cameron and Jermyn (1991) (see Table 6), and deserves further attention.

Table 4 suggests that *C. australe* showed consistently slow growth across sites. This species was widely planted in the CRRP and some of the variation in growth rates across sites is related to temperature (Table 5); at warmer temperatures this species grows faster. This is consistent with the photosynthetic characteristics of *C. australe* – the optimum temperature for photosynthesis has been determined be between 23.7 ºC and 25.6 ºC (Swanborough *et al.* 1998). Warmer temperatures are experienced more often on the coastal lowland areas, where the mean diameter increment of the top ten trees of *C. australe* was relatively fast (Table 6).

For young trees competition with weeds and grasses, especially *Brachiaria decumbens*, which has been established in many improved pastures, appears to be particularly strong. In plantations that are well maintained grasses and weeds are removed from around the young trees to reduce competition. Slower growing species like *C. australe* require weed control for longer than faster growing species.

Small numbers of some rainforest species were only planted on one or two soil types, and it is not possible to compare their performance across sites in this study. More sites are needed to determine whether these species perform differently in other conditions, that is, whether they may be regarded as specialist site species. On basalt soils with medium rainfall, *A. petrei*, *Terminalia sericocarpa* and *Blepharocarya involucrigera* grew moderately fast, as did *Cardwellia sublimis* on high rainfall basalt soils. On some lower rainfall, poorer soil sites around the Mackay region, *Melia azedarach* and *G. robusta* performed very well, although the form of *M. azedarach* is not satisfactory. Corresponding well with its natural habitat, the riparian-zone early pioneer rainforest tree *Nauclea orientalis* is well suited to plantations on very high rainfall alluvial coastal sites (Table 4). *Paraserianthes toona* was included in the CRRP for its beautiful cedar-like timber and its tall, straight form when grown in native forest from Cooktown to Mackay. In CRRP growth plots it was one of the worst performing species with slow growth rates and poor form (resulting at least partially from insect attack) across all sites. Rather than excluding this species from plantations, it may be that *P. toona* may not be suited to this style of plantation; it could benefit from nurse crops or perhaps there are mycorrhizal associations that are unknown for this species.

Previous studies have recommended a number of exotic rainforest timber trees for investigation in tropical Australia (Cameron and Jermyn 1991, Russell *et al.* 1993, Herbohn *et al.* 1999). Four exotics species were measured in this study, three from the Meliaceae family (*Cedrela odorata*, *Khaya nyasica*, *K. senegalensis*) and *Tectona grandis*. They were planted in low numbers and on few sites. Compared with the native species, none had “fast” growth rates (Table 4). Excluding *K. senegalensis* (not discussed in Cameron and Jermyn (1991)), they grew within previous expectations (Table 6) and similar to other studies in this region (Keenan 1998, Annandale and Keenan 2000).

Conclusions

The choice of plantation species is dependent on a range of factors including timber markets, management costs, site factors, land availability and species attributes such as seed availability, propagation costs, growth rates and timber properties. To support a processing plant or export business, plantation growers need to have large estates or a critical mass of timber in a region is required. To achieve this, tree species that perform relatively well across a wide range of sites are preferred. In this study, species that grew consistently across sites include *E. pellita*, *E. cloeziana*, *Elaeocarpus grandis*, *A. cunninghamii*, and *C. australe*. Where there are ‘niche markets’ or diverse demands for timber and other values (e.g. habitat or site protection), particular species may be preferred. Site specialists are more difficult to define at only eight years of age, but results from this study indicate that *F. brayleyana*, *F. schottiana*, *G. robusta*, *A. mangium* and potentially some of the exotic species can grow well at particular sites.

After four remeasures of growth plots on these sites, observations by various researchers confirm that only the better maintained CRRP sites have the potential to produce timber, and the usefulness and viability of poorly maintained sites is questionable (Bristow 1996, Keenan and Annandale 1999, McNamara 2003).

Notwithstanding the variable nature of this dataset, it is useful to ascertain trends in species performance across sites. Results should ideally be confirmed with a further set of replicated trials. Continued measurement and maintenance of these increment plots would allow further investigations of silviculture of mixed rainforest timber species plantings. Permanent growth plots may, in time, provide opportunities to forecast harvests, and plan sustained flow of timber (and other products) into the market place (Vanclay *et al.* 1995).

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