Effects of sapling density on *Eucalyptus obliqua* sapling architecture in a clearfell and a dispersed retention coupe

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Abstract

High sapling densities are generally believed to have a positive influence on timber quality through improved apical dominance and reduced branch size. This study compared the architecture of Eucalyptus obliqua *saplings in two coupes: one with a higher initial density (9918 stems/ha at 1 year after establishment) that resulted from a clearfell, high-intensity burn and sowing treatment, and another with a lower initial density (2075 stems/ha at 2 years after establishment) that resulted from a 10% dispersed-retention harvest, low-intensity burn, and natural seedfall. Five years after establishment, sapling density in the clearfell coupe was still more than twice that in the dispersed retention coupe 6 years after that coupe was established. Diameter at breast height over bark, total height, live crown height and number of branches greater than 1 cm diameter, as well as size and angle of the three largest branches, were recorded for dominant saplings at each coupe, at age 5 and 6 years after establishment respectively, and related to sapling density.*

Saplings at both coupes were generally of good form with small branches, and severe stem defects like forks or kinks were rare with less than 5% of dominant saplings affected. Despite the differing sapling densities, branching patterns were nearly identical in both coupes when comparing saplings of similar height. Size and number of branches were not correlated with local stand density at either coupe. At the clearfell coupe, the live crown ratio (proportion of total tree height occupied by the live crown) decreased significantly with increasing local stand density, but no such relationship existed across a smaller range of local stand densities at the dispersed retention coupe. Later re-sampling may indicate whether factors such as the young age of the regeneration, the moderate to high sapling density, or the density of other vegetation were relevant to the lack of correlation between sapling density and branching pattern.

Introduction

Sapling density has a major influence on sapling architecture in young eucalypt stands. Research in plantations has shown that the number and diameter of branches increases with lower stand density, while the height to the base of the green crown decreases (Marks *et al.* 1986, Neilsen and Gerrand 1999, Henskens *et al.* 2001). The number and size of branches are important factors in log classification, with branches having a significant impact on the economic value of the crop. The chance of infection by decay-causing fungi also increases with increasing branch size (Wardlaw 2003). Pruning, often undertaken in plantations to limit branchiness of the crop trees, is not a common practice in native forest management in Tasmania. Therefore stem quality in native forests must be maintained by silvicultural systems that use stand density to limit the number and size of the branches of crop trees.

In Tasmania's lowland wet eucalypt forests, the standard silvicultural system of clearfelling, high-intensity burning and aerial sowing (Forestry Tasmania 1998) usually leads to dense regeneration. The high sapling density and strong intraspecific competition limit branch size during stand development (Florence 1996). The clearfell, burn and sow (CBS) technique has been criticised for various reasons such as poor initial aesthetics, and harvesting of partly immature timber in mixed-age forests. When rotations of about 90 years are used, there are concerns of a reduction in late-successional species and structures and a decline in special timbers and leatherwood nectar resources (Hickey *et al.* 2001). Alternatives to clearfelling, including dispersed and aggregated forms of variable retention, are being investigated for wet *Eucalyptus obliqua* forest at the Warra silvicultural systems trial in southern Tasmania (Hickey *et al.* 2001). Variable retention harvest systems retain structural elements of the harvested stand for at least the next rotation in order to achieve specific management objectives (Franklin *et al.* 1997).

Experimental trials of non-clearfelling systems indicate that regeneration burns should be less intense than those in the CBS system (Hickey and Neyland 2000) so that retained trees can survive the burn. Less-intense burns are likely to result in sub-optimal seedbeds and thus a lower regeneration density (although this may be partially offset by a continuing seed source from retained trees). This in turn raises concerns about possible adverse effects on sapling architecture and stem quality. The first variable retention coupe at Warra was established as a dispersed retention treatment in 1998. This offered an opportunity to test the hypothesis that reduced intraspecific competition resulting from a lower sapling density has a negative impact on sapling architecture, especially branch size, at an early stage of stand development.

Table 1. Chronology of treatments and measurements at WR001B and PC024A.

	WR001B	PC024A
Silvicultural system	Dispersed Retention	Clearfell, Burn and Sow
Harvest completion	1998	1998
Burnt	April 1998	March 1999
Sown	-	March 1999
Seedling density	2075 stems/ha (age 2)	9918 stems/ha (age 1)
Sapling survey	November 2004 (age 6)	November 2004 (age 5)

Methods

Study sites

The two sites used in this study were the dispersed retention coupe Warra 001B (WR001B) and the clearfell, burn and sow coupe Picton 024A (PC024A). Table 1 provides a chronology of treatment and measurement dates for the two coupes.

WR001B is located within the Warra Long-Term Ecological Research (LTER) site (latitude 43°04′ S, longitude 146° 40′ E) in southern Tasmania. Average precipitation is about 1450 mm and mean daily maximum and minimum temperatures are 17.4 and 6.7°C, respectively. WR001B, a 16 ha coupe, is located on a gentle south-facing slope on soils derived from Jurassic dolerite. Prior to harvesting, the stand was multi-aged *E. obliqua* tall wet forest with a dense understorey of tall shrubs (mainly *Nematolepis squamea, Acacia verticillata, Leptospermum* spp.) over cutting grass (*Gahnia grandis*) and bauera (*Bauera rubioides*). The nomenclature for botanical species follows that of Buchanan (2005). The coupe was harvested to a dispersed retention prescription, leaving about 10-15% of the original standing basal area as evenly dispersed trees (an average of 9 stems/ha at a retained basal area of 8 m^2/ha). Harvesting was completed in March 1998, and the coupe burnt with a low-intensity fire in April 1998 and regenerated by natural seedfall from the retained trees (Hickey *et al.* 2001). In 2000 (age 2 years) seedling density measured using a systematic grid of circular 16-m^2 plots in a previous project was 2075 seedlings/ha (Lutze 2003). With 73% of the 16-m^2 plots having at least one seedling, the regeneration at WR001B met Forestry Tasmania's minimum stocking standard of 65% but was below the 85% stocking level that is recommended for maximum clearwood production (Forestry Tasmania 2001).

PC024A is a 60-ha coupe approximately 1 km from WR001B. Site conditions in PC024A as well as original forest type are comparable to WR001B although the aspect of PC024A is north-easterly rather than southerly. The coupe was clearfelled in 1998, and sown with 71 kg of *E. obliqua* seed 6 days after high-intensity burning in March 1999. A 20-ha section in the north of the coupe was intensively surveyed in 2000 for regeneration in a previous project (Lutze 2003), which provided data on initial stocking and seedling density. Seedling density in PC024A at age 1 was 9918 seedling/ha (Lutze 2003). With 93% of the 16-m^2 plots stocked, the regeneration was within the range considered optimal for maximum clearwood production (Forestry Tasmania 2001, 2003).

Measurements

In November 2004 a sample of about 100 saplings was sought for measurement at each coupe. At WR001B an existing 100-m by 10-m grid (144 grid points) established for studying regeneration was used (Neyland 2003). At PC024A a 100-m by 20-m grid was followed (98 grid points), similar to that used in a previous regeneration study (Lutze 2003). At each grid point, the height of the tallest (locally dominant) sapling, where present, within a 40-m^2 circular plot (radius 3.57 m, centred on the grid point) was recorded, and the sapling was selected for further measurement of its branches if it was taller than 3 m (the average height of the surrounding cutting grass, *Gahnia grandis*, was about 2 m). Measuring the dominant sapling in a 40-m^2 circular plot corresponds to measuring the best 250 stems/ha; this plot size was derived from the thinning specifications for regrowth stands, which aim to retain between 150 and 250 crop trees/ha (Forestry Tasmania 2001). Due to the non-homogeneous nature of the regeneration at WR001B, no saplings were found at 36 grid points and the dominant sapling was taller than 3 m at only 84 grid points. Only two saplings on the regular grid were taller than 8 m. Therefore we sampled an additional 10 saplings greater than 8 m tall, in order to have a sufficient number of trees for comparison within this height class. At PC024A all 98 grid points contained saplings, and there were 96 grid points where the dominant sapling was taller than 3 m.

Diameter at breast height over bark, total height (Photo 1), and the height of the junction of the lowest living branch with the main stem, were measured on each locally dominant sapling. Live crown ratio was calculated as total height minus height of the lowest living branch (that is, the length of the live crown), divided by total height. For each of the three biggest branches, branch diameter 1 cm from the main stem, the angle of the branch from the stem axis above the branch (to the nearest 5 degrees), and the height of branch origin were recorded. The number of live branches greater than 1 cm diameter was counted in order to calculate branch density (number of such branches per metre of tree height). Obvious stem defects like forks, kinks or sweeps were noted.

The local stand density was calculated by counting the number of eucalypt saplings within a 16-m^2 circular plot (radius

Photo 1. A.R. measuring the total height of a eucalypt sapling at Warra 001B. Note the retained tree in the background.

2.26 m) surrounding the locally dominant sapling, both for the grid plots and for the 10 additionally selected tall saplings at WR001B. The radius of the plot was approximately double the crown radius of dominant saplings. Since competition for light is influenced by the height ratio of competing trees, we differentiated between surrounding saplings taller than two-thirds of the dominant sapling's height (deemed competing saplings) and those lower than two-thirds of the dominant sapling's height (deemed non-competing saplings). The two-thirds height distinction was used after Bigging and Dobbertin (1995), who reported that optimal heights for modelling growth rates with the CC_p-competition index (crown cross-sectional area at p% of tree height) are between 66% and 75% of tree heights. At WR001B the basal area of retained trees was also estimated using a factor 2 wedge.

Data Analysis

Pearson's product-moment correlations were calculated to test the bivariate relationships between measures of local stand density (independent variables) and tree parameters (dependent variables). Significant correlations ($p < 0.001$) were compared using scattergrams and regression coefficients. The non-parametric Wilcoxon test was performed to compare branching parameters for different height classes at the two coupes. Analyses were calculated using Statgraphics Plus 2.1 (Statistical Graphics Corp.).

Coupe average values were not compared as the analyses would be confounded by the more rapid development of saplings at Picton compared to Warra.

Results

Six years after burning, regeneration at the dispersed retention coupe WR001B was highly uneven in terms of spatial distribution and height development. At 25% of the 40-m^2 plots no eucalypt sapling was present, and 58% of the plots did not contain a sapling taller than 4.0 m (Figure 1). Average total height, height of origin of the largest branches and live crown ratio of dominant saplings were 4.9 m, 2.5 m and 71% respectively (Table 2). On average, there were 3200 total saplings/ha and 1.7 competing saplings per dominant sapling (Table 2). Intraspecific competition experienced by the dominant saplings was low with nearly 56% of the dominant saplings having none or only one competing sapling (Figure 2) within the surrounding 16-m^2 plots.

Table 2. Sapling data for coupes WR001B (sampled at age 6 years) and PC024A (sampled at age 5 years).

	WR001B Dispersed Retention	PC024A Clearfell, Burn and Sow
Total saplings/ha	3200	7700
Mean number of competing saplings[#] per dominant sapling	1.7	4.4
Mean dominant sapling height (m)	4.9	6.1
Mean height of largest branch (m)	2.5	3.0
Mean live crown ratio (%)	71	72

[#] *Competing saplings are defined as saplings of height greater than two-thirds of the height of the locally dominant sapling, within a 16-m^2 plot around the locally dominant sapling.*

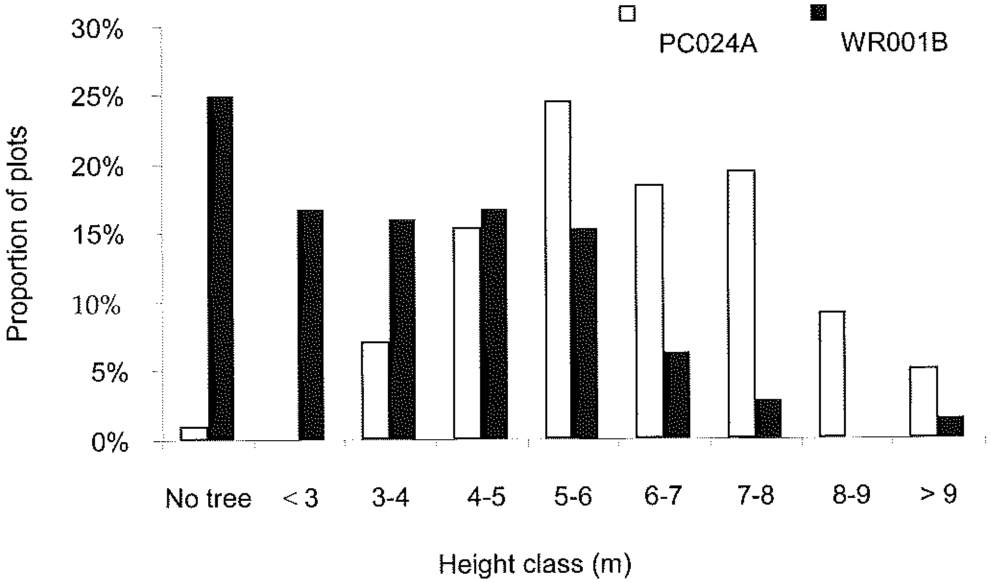

Figure 1. Frequency distribution of dominant saplings by height classes within 40-m^2 plots (regular grid points).

Regeneration at the CBS coupe PC024A was more homogeneous, with practically all of the 40-m^2 plots being stocked (Figure 1). Dominant saplings were generally taller than at WR001B (Table 2) although maximum heights were similar at both coupes. Average total height, height of origin of the largest branches and live crown ratio of dominant saplings were 6.1, 3.0 m and 72% respectively (Table 2). On average, there were 7700 total saplings/ha and 4.4 competing saplings per dominant sapling (Table 2). Intraspecific competition was high at PC024A with most dominant saplings having 2 to 5 competing saplings within the 16-m^2 plots (Figure 2).

In 2004, PC024A had a dense sedge and shrub layer similar to WR001B. However the understorey competition at PC024A was probably lower because most saplings had already overgrown these layers.

Sapling diameter at breast height over bark (DBHOB) was closely correlated with both sapling height and size of the three largest branches, in both coupes (Figure 3). No significant differences were found between regression lines of the two coupes, indicating comparable growth patterns. Severe stem defects such as forks or kinks were rare at both coupes (< 5% of dominant saplings affected).

The size of the three largest branches and the branch density were not significantly correlated with the number of competing saplings (Figure 4), nor were branch angles or the height of origin of branches (data not shown). The live crown ratio decreased with increasing number of competing saplings at PC024A but not at WR001B (Figure 5a). Sapling height increased slightly with increasing number of competing saplings but the correlation was not significant at either coupe (Figure 5b). Despite the strongly differing densities of competing saplings between the coupes (Figure 2) and the different mean dominant sapling heights between the coupes (Table 2), the height of the first living branch as well as the size and number of branches were nearly identical when comparing dominant saplings of similar height (Table 3).

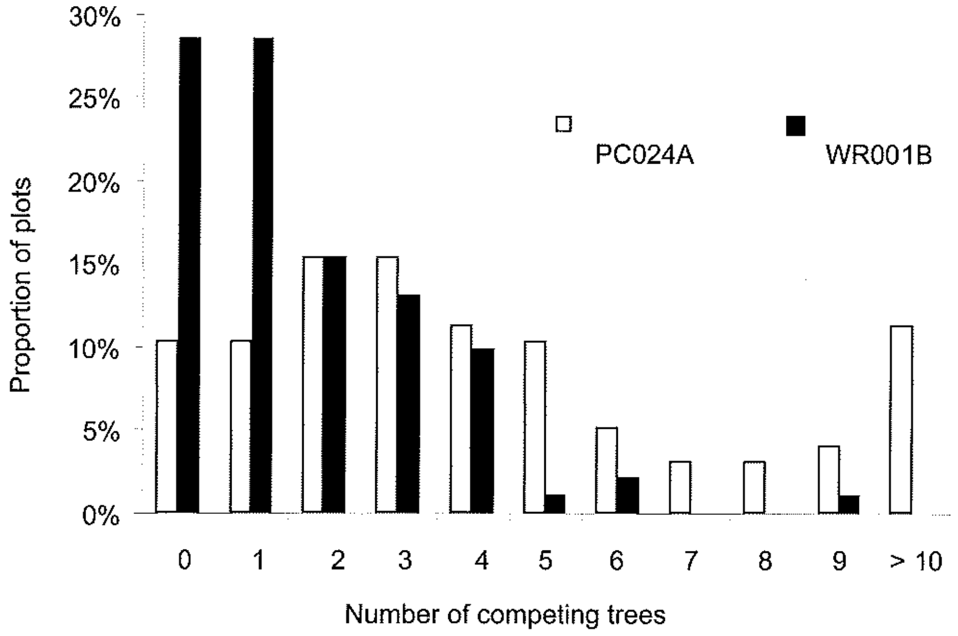

Figure 2. Frequency distribution of number of competing saplings within 16-m^2 plots around each dominant sapling (regular grid points).

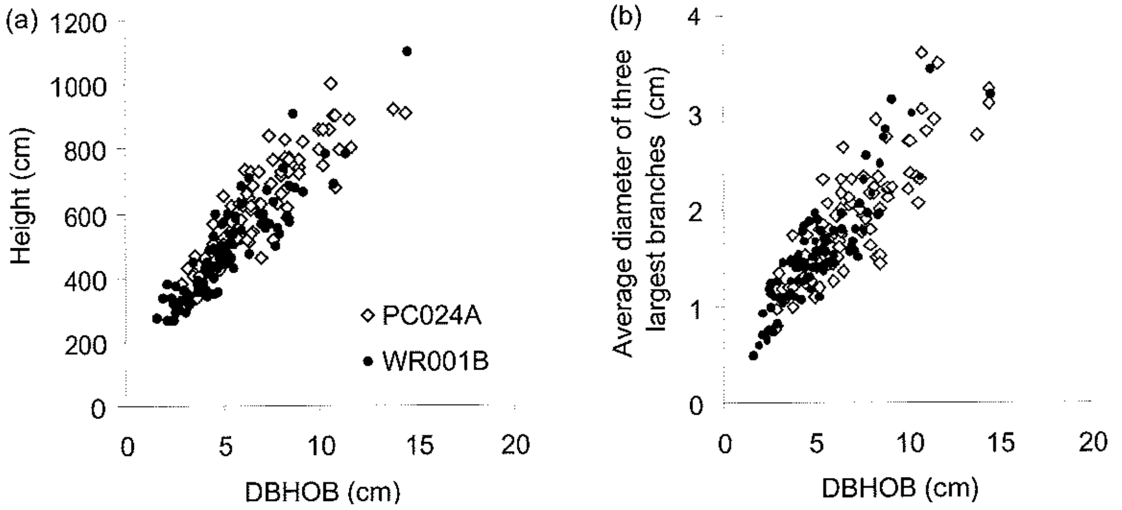

Figure 3. Scattergrams of DBHOB and (a) height and (b) average diameter of the three largest branches of dominant saplings. All correlations are significant ($p < 0.001$) with r^2 values of 0.81 (WR001B) and 0.80 (PC024A) for height, and 0.80 (WR001B) and 0.70 (PC024A) for branch diameter.

Discussion

The initial seedling density and the sapling density at age 5-6 years were markedly different at the CBS coupe (PC024A) and the dispersed retention coupe (WR001B), and probably reflect key differences in seed supply (quantity and timing) and seedbed availability between the two silvicultural treatments. Initial seedling density (one year after burning) of 9918 stems/ha at the CBS coupe reduced to 7700 saplings/ha at age 5. In contrast, the dispersed retention coupe had an initial seedling density of only 2075 stems/ha, which increased to 3200 saplings/ha at age 6. These opposing trends

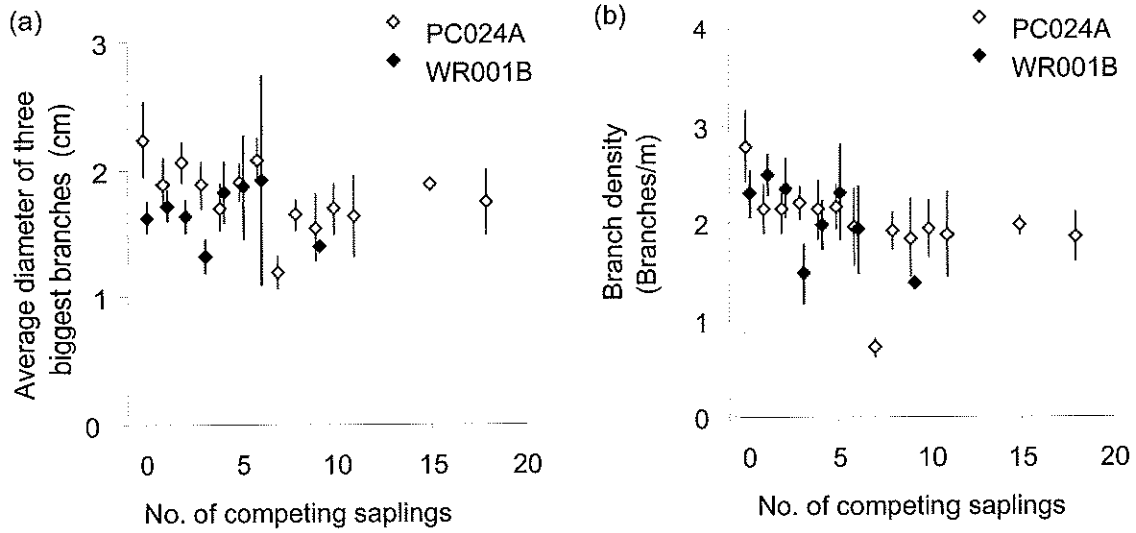

Figure 4. Plots of number of competing saplings and (a) average diameter of the three largest branches on dominant saplings, and (b) branch density of dominant saplings (number of branches > 1 cm diameter per metre of tree height). Bars show standard errors. None of the correlations were significant ($p > 0.1$).

Table 3. Branching parameters for different height classes of dominant saplings. Standard errors in brackets. There were no significant differences between the two coupes in any parameter in any height class.

Height class (m) of dominant saplings	Coupe	3.0-3.9	4.0-4.9	5.0-5.9	6.0-6.9	7.0-7.9	> 8.0
Number of dominant saplings in each height class	PC024A	7	15	23	18	19	14
	WR001B	23	24	22	9	4	12[#]
Height of first living branch (m)	PC024A	1.18 (0.16)	1.23 (0.07)	1.60 (0.10)	1.96 (0.18)	1.84 (0.13)	2.15 (0.28)
	WR001B	1.00 (0.05)	1.24 (0.07)	1.56 (0.10)	1.93 (0.19)	2.23 (0.28)	2.41 (0.29)
Diameter of three largest branches (cm)	PC024A	1.1 (0.1)	1.4 (0.1)	1.6 (0.1)	2.0 (0.1)	2.2 (0.1)	2.6 (0.1)
	WR001B	1.1 (0.1)	1.5 (0.2)	1.7 (0.1)	2.1 (0.2)	2.6 (0.3)	2.5 (0.1)
Number of branches > 1 cm	PC024A	5 (2)	7 (1)	12 (1)	13 (1)	19 (1)	25 (2)
	WR001B	5 (1)	11 (1)	15 (1)	17 (2)	21 (3)	30 (2)

[#] *At WR001 ten saplings which were additionally sampled beside the regular grid are included in the height class > 8 m.*

are probably explained by the dense intra-specific competition at the CBS coupe and by a continuing seed source from mature trees at the dispersed retention treatment, which allowed ongoing recruitment. The bell-shaped frequency-size distribution for

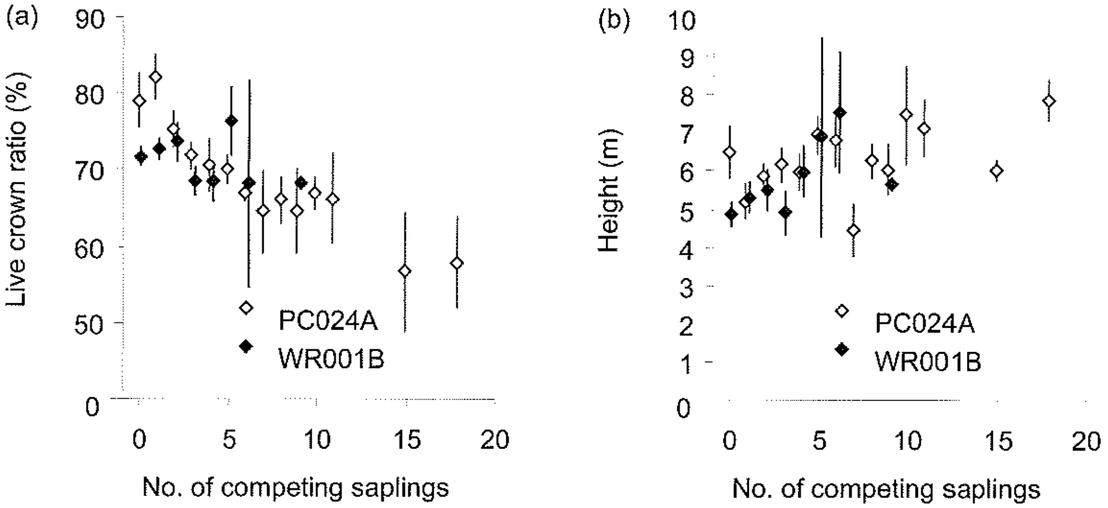

Figure 5. Plot of number of competing saplings and (a) live crown ratio of dominant saplings (proportion of total tree height occupied by the green crown) and (b) height of dominant saplings. Bars show standard errors. Correlation significant for live crown ratio at PC024A ($r^2 = 0.85$, $p < 0.001$). All other correlations are not significant ($p > 0.1$).

the CBS coupe (Figure 1) indicates that an even-aged cohort of saplings is well established by age 5. The frequency-size distribution for the dispersed retention treatment suggests that recruitment has continued over a protracted period. However, branching patterns of dominant *E. obliqua* saplings were similar in both coupes despite the differences in stand density, and moreover did not depend on local densities of eucalypt sapling regeneration. Possible explanations for the lack of difference include the young age of the stands, a possible threshold density for branching responses to density, a high level of competition for light from sedges and shrubs, and, for the dispersed retention coupe, the competition for light from overstorey trees.

Young age of the stands

While very young eucalypt seedlings can bear moderate shade (Ashton and Chinner 1999), older saplings with pendulous foliage are very light-demanding. Saplings grow straight towards the light, enhancing their inherently strong apical growth pattern (Florence 1996). Significant effects of intraspecific competition for light on tree architecture can be expected after canopy closure, when leaf area usually stops increasing in eucalypt forests (Beadle 1997). A low stand density (or removal of trees by thinning) sustains the light environment and retards the effect of canopy closure. At our sites, canopy closure of dense *E. obliqua* regeneration usually starts at age 3 years, and so there had been approximately 3 years for density-related effects to develop in the 5 to 6-year-old stands measured in this work. By age 5-6 the dominant saplings were 3-8 m tall (Figure 1), and the forest may have been too young and too short to develop density-dependent differences in branching, which have been documented for fast-growing eucalypt plantations taller than 10 m (Neilsen and Gerrand 1999). In a thinning trial in young oak *(Quercus petrea)* stands, the effect of stand density on the diameter of the largest branch was obvious only after 5-12 years (Küster 2000). A quicker response can be expected for fast-growing eucalypt species but, even in highly productive *E. nitens* plantations, thinning effects on growth rates were significant for most treatments only 2-4 years after thinning (Medhurst 2000). The *E. obliqua* saplings in PC024A and WR001B may thus have been too young for density-dependent architectural traits to have developed.

Possible threshold density for branching responses to sapling density

Planting density in eucalypt plantations is often about 1000 stems/ha although Schönau and Coetzee (1989) report a range from 400-3000 stems/ha. Plantation spacing trials have mostly investigated densities between 100 and 2000 stems/ha. Investigating density effects in *Eucalyptus nitens* plantations, Neilsen and Gerrand (1999) found a strong decrease in branch size and in number of large branches as density increased from 500 to 1300 stems/ha, while a further increase to 1660 stems/ha had only a minor additional effect. In contrast, green crown height showed a constant increase with tree density (corresponding to a decrease in live crown ratio) throughout the whole density range. These results correspond well with our findings at the high-density coupe PC024A, where local stand density was strongly correlated with live crown ratio but not with branch size. It seems that the influence of density on branch size is strongest at low densities, which is different to the influence of density on live crown ratio which occurs throughout a wide density range. WR001B, however, does not fit this picture as no significant correlation between density and branch size or green height was observed, even though 29% of saplings were single stems with no competing eucalypt within a 16-m^2 circle and another 29% had only one competing eucalypt (a local density of 1250 stems/ha). This indicates that other factors such as competition by non-tree species may play an important role, especially in young stands.

The relevance of eucalypt plantation studies to intraspecific competition in native forests is uncertain. For example, Hastings and Opie (1974), cited in Florence (1996), reported that the merchantable height of dominant *E. regnans* in 15 to 25-year-old stands was little affected by bole branches or stubs, provided that the initial seedling density exceeded 500 stems/ha. Lutze (2003) reports that 10-year-old *E. diversicolor* planted at 1250 and 2500 stems/ha had far more large dead branches below green height than similar-aged seed tree regeneration that had been spaced to the same densities soon after establishment. This suggests that naturally regenerated stands need to reach lower densities than planted stands before branching is affected. It appears that both WR001B and PC024A had densities well above that required to observe density-dependent effects on branching in eucalypt stands regenerated from seed, that is, that the sapling densities present at these coupes allowed all saplings to maintain their apical dominance.

Competition from sedges and shrubs

Shrubs and sedges also compete with eucalypt saplings for light. Especially at WR001B, many of the smaller trees were still subject to a strong competition from a dense sedge and shrub layer, which could have influenced branch development. At PC024A, where most eucalypt saplings had already overgrown the shrub and sedge layer, the live crown ratio was correlated with local stand density. For WR001B no such correlation was present, although the live crown ratio was nearly identical to that of PC024A despite the lower stand density. It is likely that competition for light resulting from the shrub and sedge layer is an important factor in this context. Density-dependent architectural traits might thus develop in both coupes as saplings grow away from the sedge and shrub layers.

Competition from overstorey trees

In Central European forestry, small-scale regeneration methods that retain overstorey trees tend to result in saplings with fewer and smaller branches when compared with open conditions with similar sapling densities (Mayer 1984; Weihs and Klaene 2000). The competition of overstorey trees can replace dense peer competition in regeneration, leading to smaller branches and a more apically dominant growth pattern. A related effect has been reported in Tasmania for blackwood (*Acacia melanoxylon*) when it establishes in small gaps, described as light wells, in selectively logged rainforest (Jennings 1998). The retained trees surrounding the gap induce stronger apical dominance and branch suppression in the establishing understorey blackwood (Jennings *et al.* 2003). Shade effects on crown architecture have also been reported for other rainforest species like myrtle (*Nothofagus cunninghamii*) (King 1998). It is unclear whether, and to what extent, this effect is relevant for shade-intolerant eucalypt species, although eucalypt sapling growth is often reduced up to distances of two tree-crown radii (or about 20 m) from the forest edge (Florence 1996, Incoll 1979, Rotheram 1983). At WR001B tree retention was low with an average of 9 stems/ha being retained. Average distance between the trees was 33 m, which is about two-thirds of tree height. Although the retained trees reduced photosynthetically active radiation (PAR) at noon by only about 20% (under conditions of diffuse sunlight) compared to an open site (Neyland 2003), the retained trees at the coupe edge or within the coupe could have influenced sapling branch development.

Conclusions

At age five years, *E. obliqua* sapling density at the clearfell, burn and sow coupe PC024A was about twice that at the dispersed retention coupe WR001B at age six years. This resulted from a nearly five-fold sapling density difference at establishment (age 1-2 years). Nevertheless, branching patterns were nearly identical in the two coupes, when comparing either the whole sapling population or saplings of similar size, and whether local or total sapling density was used as the measure. Saplings generally showed good apical dominance with small branches. Differences between both coupes were observed in density and distribution of regeneration, and height development. The explanation for the lack of correlation between sapling density and branching patterns remains speculative at this stage. A later re-sampling could indicate whether branch size in both coupes is limited by factors such as the generally moderate to high sapling density or by the additional competition resulting from shrubs and sedges and (in WR001B) from overstorey trees, or whether regeneration of age 5-6 years is too young to develop density-related branching patterns.

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