Wood density of *Eucalyptus saligna* grown in Hawaiian plantations: effects of silvicultural practices and relation to growth rate

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Summary

We evaluated effects of chemical fertilizer, spacing, and interplanted nitrogen-fixing trees on wood density and diameter growth of 15-year-old *Eucalyptus saligna* trees. The trees were grown in silvicultural trials established on former sugarcane land on the island of Hawaii. Elevation was 480 m, slopes were gentle, and annual rainfall averaged 4600 mm at the trial locations. Breast-high increment core samples were obtained by boring more than 100 dominant and codominant trees. Diameters of individual trees ranged from 16.4 to 45.9 cm, and cross-sectional wood densities from 349 to 496 kg m^{-3}. Silvicultural treatment means for 15-year diameter ranged from 24.2 to 35.6 cm, and means for cross-sectional wood density from 400 to 424 kg m^{-3}. Wider spacing (4 m by 4 m vs. 2 m by 2 m) increased mean diameter by 34% without decreasing, and may have increased, wood density. Level of chemical fertilization did not affect wood density, and mean diameter of trees sampled in the two fertilizer treatments was identical. When compared to chemical fertilization, interplanting of N-fixing *Albizia* trees increased mean diameter by 37% but did not alter wood density. Regression and covariance analyses indicated that growth rate per se (as evidenced by 15-year diameter) had negligible influence on wood density. Pith-to-bark profiles of wood density revealed that trees with rapid growth had more uniform wood density patterns across the radii. We conclude that diameter growth (hence, productivity) can be increased substantially through supplemental nitrogen and increased growing space without decreasing wood density; moreover, wood density may be slightly increased with additional growing space. Moreover, rapid growth - whether associated with improved nutrition or increased growing space - will result in wood with a more uniform density from pith to bark.

Introduction

Eucalyptus saligna is a rapid-growing hardwood planted for fuel and fibre throughout the world. During the past 20 years, silvicultural regimes have been developed for growing this species in Hawaii (Whitesell *et al*. 1992). Tree growth and wood yields in trial plantings have been exceptional (Walters 1980; Whitesell *et al*. 1987; DeBell *et al*. 1997). Several corporations have considered establishing *Eucalyptus* pulpwood plantations on land formerly used to produce sugarcane (Davis 1994), and as of January 2000 about 7000 ha of *Eucalyptus* plantations have been established on the island of Hawaii. The quality and value of pulpwood are affected by several traits; one of the most important traits is wood density (commonly referred to as specific gravity) because it affects pulp yield and other aspects of pulp and papermaking processes.

Knowledge of factors affecting wood density of *E. saligna* is limited and information about the influence of silvicultural practices on wood density or the relationship between growth rate and wood density is particularly sparse. Skolmen (1974) found that wood density of butt logs of 12-year-old trees from Hawaiian plantings averaged 420 kg m^{-3}, and densities within the log increased from pith to bark (and, thus, with age). King (1980) found wood density of 4-year-old coppice sprouts on 23 *E. saligna* stumps ranged from 340 to 520 kg m^{-3}. Most (65%) of the variation in wood density was attributed to differences between the stumps (in essence, stumps were different clones), while the remaining variation occurred among sprouts on an individual stump (i.e., within a clone). On average, there was no correlation between mean growth rate and mean wood density among the clones, but within clones the largest sprouts (hence, the fastest growing shoots) tended to have the highest wood density. Initial assessments of wood density of 10-year-old *Eucalyptus* trees grown in a species mixture trial suggested that trees grown in pure stands had higher density wood than trees grown in mixture with *Albizia falcataria* (L.) Fosberg [= *Paraserianthes falcataria* (L.) Nielson] (DeBell *et al*. 1997).

Work with *Eucalyptus grandis*, a closely related species, has indicated that wood density was generally increased or unaffected by silvicultural treatments that enhanced nutrient availability (Hans and Burley 1972; Donald and Schutz 1977; Bamber *et al*. 1982; Wilkins 1990; Wilkins and Horne 1991; Cromer *et al*. 1996) and/or increased growing space (Wilkins and Kitahara 1991; Malan and Hoon 1992). Most studies of the influence of growth rate on wood density in *E. grandis* have found a negative correlation (Malan 1988, 1991; Schonau 1991), but there are also reports of no correlation (Taylor 1973; Vital and della Lucia 1987; Wilkins 1990; Wilkins and Horne 1991), and suggestions of a positive relationship (Malan and Hoon 1992). In many studies, the relative influences of growth rate per se versus specific effects of silvicultural treatments (such as thinning or fertilizer application), site characteristics, or genotype on wood density are difficult to separate. Given such lack of consistency among reports, it seems likely that effects of silvicultural practices and other factors on wood density may in some instances be independent of effects on growth rate; that is, various silvicultural practices and growing environments may lead to similar growth rates and yet produce different wood densities, or they may produce different growth rates with no alteration in wood densities.

This paper examines the effects of fertilizer, spacing, and interplanted nitrogen-fixing trees on wood density of 15-year-old *Eucalyptus saligna* trees growing on abandoned sugarcane land along the wet, northeastern coast (commonly known as the Hamakua Coast) of Hawaii Island. General relationships of growth rate to wood density are evaluated as are the effects of growth rate on wood density within individual silvicultural treatments. In addition, we examined the trend in wood density across the radius from pith to bark for individual silvicultural treatments.

Materials and methods

Experimental area and silvicultural treatments

Our study was conducted with wood samples collected from trees grown in two research trials established in 1982 near Hakalau (lat. 19º30' N, long. 155º15' W) on lands representative of Hamakua sugarland. Characteristics of the area and the specific trials are described in detail in prior reports (Whitesell *et al*. 1992; DeBell *et al*. 1997). Elevation is 480 m and slopes are gentle, ranging from 0 to 10%. Mean annual rainfall is about 4600 mm and is distributed fairly uniformly throughout the year. The soil series is Akaka silty clay loam (thixotropic isomesic Typic Hydrandept); it is moderately acidic (pH 5.0-6.0), and nitrogen concentration averages about 0.5% in the surface soil.

The two research trials were located on soils derived from lava flows spaced about one kilometre apart, and both were installed as randomized complete block designs with six silvicultural treatments applied in four blocks; position on the gentle slopes was the basis for original blocking. One trial (Kamae) is a spacing study; the other (Chin Chuck) compares growth of pure stands receiving two levels of nitrogen fertilizer, and mixed species plantings based on different proportions of *Eucalyptus* and nitrogen-fixing *Albizia* trees. Trees sampled for the wood density study were selected from throughout three of the four blocks, and three of the six treatments at each location. Blocks were chosen for similarity in mean growth performance for the same treatments; treatments were selected to provide contrasts for assessing the aforementioned effects of silvicultural practices and growth rate on wood density.

The treatments provided three levels of spacing, two fertilizer regimes (low and high), and interplanting of nitrogen-fixing trees (Table 1). Spacing ranged from 2 m by 2 m to 4 m by 4 m. The low fertilizer regime consisted of three applications of 115 g of nitrogen (N), phosphorus (P), and potassium (K) to each seedling at planting and 4 and 8 months later; each application was equivalent to 40 kg N, 18 kg P, and 33 kg K per ha. The high fertilizer regime received, in addition, similar applications at 12, 18, 24 and 36 months plus a broadcast application of N fertilizer equivalent to 130 kg N per ha at 55 months. The interplanting consisted of *Albizia* interplanted among *Eucalyptus* at a ratio of 3:1; the effective spacing among *Eucalyptus* trees was 4 m by 4 m whereas spacing among all trees was 2 m by 2 m.

Table 1. Treatments chosen for sampling at each of two locations

Location	Spacing of *Eucalyptus* trees	Fertilizer regime	Interplanted with *Albizia*
Kamae	2 m by 2 m	High	No
	2.8 m by 2.8 m	High	No
	4 m by 4 m	High	No
Chin Chuck	2 m by 2 m	Low	No
	2 m by 2 m	High	No
	4 m by 4 m	Low	Yes

Tree selection and data collection

We selected for the wood density study six trees from among the dominants and codominants to provide a range in diameter (thus, cumulative growth rate) on each plot; in essence, the sample trees were distributed evenly throughout replicate plots for each treatment. Our sample focused on trees in the upper crown classes because they contained most of the volume and value per unit area. A total of 108 trees was sampled, incorporating a sample of 18 trees from each silvicultural treatment.

Diameter was measured on each sample tree, and increment cores were extracted at breast height and placed in labelled paper straws. After transport to the laboratory, the core samples were oven-dried at 60º C to prevent mould and deterioration.

Eucalyptus saligna is a diffuse-porous hardwood species and does not form distinct annual growth rings at the elevation of the research trials in Hawaii. We therefore were unable to evaluate wood density within individual rings. Instead, we cut the cores into 2-cm segments, determined the volume (based on length measured by vernier caliper and known core diameter) and oven-dry weight of each. A sub-sample of segments was immersed in water under vacuum to bring them to near green condition and volume was determined; the ratio of re-hydrated volume to the previously measured volume of the sub-samples was used to estimate green volume of all segments. Relative wood densities of each segment were then calculated from oven-dry weight and green volume. From these data we calculated mean radial density (= mean increment core density) and mean cross-sectional density at breast height for each tree. The latter value weights each segment in proportion to its contribution to cross-sectional area of the stem; for example, the outer 2-cm segment (ring) contains much more wood than the segment nearest the pith. Cross-sectional density is regarded as more representative of mean tree density but radial (or core) density was also examined in this study because it has been used in many previous wood density studies.

A subsample of the cores - three from each treatment - were cut into 1-cm segments, and the wood density of each segment was determined as above, based on green volume and oven-dry weight. These data were used to examine pith-to-bark trends in wood density.

Data analysis

Initial screening of information collected from 108 sample trees revealed that data associated with 6 of the trees contained some values for either diameter or wood density that were extreme outliers; these trees were dropped from subsequent analyses, leaving 16 to 18 trees for each silvicultural treatment.

Despite the proximity of all sample trees, a preliminary comparison using a t-test was made between two treatments that were essentially identical (2 m by 2 m spacing and high nitrogen fertilizer), except they were established on separate flows (Kamae vs. Chin Chuck). Results confirmed that there were no significant differences between the two locations in diameter or wood density. We therefore combined data from all 102 trees and tested differences between the silvicultural treatments in the wood density and diameter of sample trees via analyses of variance and covariance (using 15-year diameter - a surrogate for cumulative growth rate - as the covariate). Treatment means were adjusted and compared by Bonferroni's method.

To gain greater understanding of interrelationships between wood density, growth rate and silvicultural practices, we used regression techniques with data from selected individual and combined treatments to evaluate the effect of growth rate on wood density, and also to determine whether the relationships varied with silvicultural treatment (i.e., we tested for differences among silvicutural treatments in intercepts and slopes). The latter procedure allowed us to distinguish between effects of silvicultural treatment per se on wood density, and effects that may be associated more closely with enhanced growth.

Wood density values determined for the 1-cm segments were graphed to provide a profile of radial patterns in wood density. The data were smoothed by calculating running medians of three observations (Tukey 1977) and plotting them to compare the radial pattern trends among the silvicultural treatments.

Results and discussion

Comparison of silvicultural treatments

Variance analyses indicated that trees sampled in various spacing and nutritional treatments differed significantly in mean diameter but not in cross-sectional wood density or radial wood density (Table 2). Covariance analyses with 15-year diameter as the covariate for evaluation of wood density traits indicated that the covariate was not significant and had negligible influence on results.

Means for the treatments (Table 2) revealed that tree diameters increased with spacing at Kamae (i.e., 26.5, 31.7 and 35.6 cm in 2 m by 2 m, 2.8 m by 2.8 m, and 4 m by 4 m spacings, respectively). Tree diameters in the low and high chemical fertilizer treatments at Chin Chuck did not differ (24.2 cm). These results, however, reflect diameters of the dominant and codominant trees sampled for wood density and do not represent the mean diameter response of the stand to treatment. Previous reports based on measurement of all trees indicated that high chemical fertilizer produced trees at 4 and 10 years which were larger in diameter than those receiving low fertilizer treatment (DeBell *et al*. 1989, 1997).

Mean values for cross-sectional wood density ranged from 400 kg m^{-3} in the densest spacing to 424 kg m^{-3} in the widest spacing

Table 2. Means, standard errors and results of variance analyses for diameter and wood densities of *Eucalyptus saligna* on Hawaii Island[1]

Treatment	Diameter (cm)		Cross-sectional wood density (kg m^{-3})		Radial wood density (kg m^{-3})	
	Mean	Std error	Mean	Std eror	Mean	Std eror
Kamae 2 m	26.5_{bc}	1.69	400_{a}	8	376_{a}	9
Kamae 2.8 m	31.8_{ab}	1.79	422_{a}	10	395_{a}	10
Kamae 4 m	35.6_{a}	1.21	424_{a}	8	402_{a}	7
Chin Chuck, 2 m, low fert.	24.2_{c}	1.05	402_{a}	6	386_{a}	6
Chin Chuck, 2 m, high fert.	24.2_{c}	1.41	404_{a}	8	382_{a}	8
Chin Chuck, 4 m, Albizia	33.2_{a}	1.76	402_{a}	9	378_{a}	10
Statistical Results						
F (5,96 df)		10.39		1.73		1.38
p-value		0.0001		0.136		0.238
LSD		6.43		35		37

[1]Treatment means followed by the same subscript letter are not significantly different ($p < 0.05$).

at Kamae. This difference was not statistically significant; however, the relatively low p-value (0.136) suggests a slight positive trend in wood density with increased spacing. Mean wood density values for the nutritional treatments show no trend, despite differences in mean diameter between trees fertilized with chemical fertilizer and trees grown in association with N-fixing *Albizia* that approximate those associated with increased spacing. Radial wood density values were about 2 kg m^{-3} lower but showed trends (or lack thereof) with silvicultural treatments similar to those for cross-sectional wood density.

Regression analyses of the relationship of growth rate to wood density

All observations were combined in one general model: cross-sectional wood density ranged from 349 to 496 kg m^{-3} and diameter from 16.4 to 45.9 cm. This provided sufficient sensitivity to identify a statistically significant but minuscule relationship between tree diameter and cross-sectional wood density:

$$\text{Cross-sectional density (kg/m}^3\text{)} = 378.8 + 1.0 \text{ Dbh (cm)}$$

$F(1,100)=5.46$ $p=0.02$ Adj. $R^2=0.04$

It is obvious from these statistical parameters that the relationship is tenuous and accounts for only 4% of the variation in wood density. Moreover, the slope coefficient of 1.0 indicates that the trend has little practical or biological significance. Mean diameter of 15-year-old trees would have to differ by at least 10 cm to result in an average increase of 10 kg m^{-3} in wood density. Mean diameter of the most contrasting treatments in our study differed by 11.4 cm.

The equation for radial wood density as a function of diameter also had a positive slope but it was less steep (0.6) and was not significantly different from zero (p=0.18).

Additional tests indicated that neither intercepts nor slopes of the general relationship between wood density and diameter differed among the six silvicultural treatments. Finally, observations from the three 2 m by 2 m treatments [high fertilizer at Kamae; low and high fertilizer at Chin Chuck (treatments 1, 2, and 3)] were combined in one model. Previous t-tests had established that these treatments did not differ in mean diameter, mean cross-sectional wood density or mean radial wood density, yet the individual trees ranged widely in diameter (16.4 to 39.6 cm) and cross-sectional wood density (349 to 464 kg m^{-3}). This model was not significant; F (1,50)=0.68 and p=0.41. We therefore suspect that the weak positive relationship between wood density and diameter found in the general equation with all data results primarily from inclusion of data from the wide spacing at Kamae. On average, trees in this spacing treatment were large in diameter and also high in wood density, but the two traits were not related within the treatment.

The number and range of values in the observations used in these regression models were sufficient to identify any trends of importance. Although the widest spacing produced much larger trees and slightly higher wood densities than the closest spacing at Kamae, the higher wood density was not related to the increased diameter growth associated with that treatment but may have been influenced by some aspect specific to the growing environment (and attendant physiological effects and conditions) associated with wide spacing. Recall also that *Eucalyptus* trees grown in association with *Albizia* were substantially larger than trees in the other treatments at Chin Chuck and yet were essentially identical in wood density. Thus, all findings in our study indicate that wood density is not related to growth rate in 15-year-old *E. saligna* grown in Hawaii and provide assurance that trees can be grown rapidly without reducing wood density. A recent paper on *E. globulus* also demonstrated a lack of relationship between growth rate and wood density (Raymond and Muneri 2000).

Radial trends in wood density

Examination of pith-to-bark trends in wood density in the sample of 18 trees revealed that, in general, wood density remains constant or decreases slightly in the first few cm (or years) from the pith (Fig. 1). Thereafter, it generally increases with distance from pith at rates that differ somewhat among treatments and with tree size within treatments. In the 2-m by 2-m spacings at Kamae and Chin Chuck, density increased fairly abruptly between 5.0 and 10.0 cm from the pith. In the 2.8-m by 2.8-m spacing at Kamae, this increase was less abrupt and began to occur at about 10.0 cm from the pith. Finally, the increase in wood density tended to be considerably more gradual in the widest tree spacing (4 m by 4 m) at Kamae and in the *Albizia* treatment at Chin Chuck, except for the smallest tree depicted for the 4-m by 4-m spacing at each location. Within each treatment, wood density in trees of smaller diameter began to increase closer to the pith and increased more abruptly than did density in trees of larger diameter. We suspect that such trends are associated with a pattern of increase in wood density with age that is similar in trees of all treatments. Thus, trees that had slow growth at early ages (e.g., trees in close spacings) showed increases in wood density that were close to the pith and rather abrupt. Conversely, when early growth was rapid or generally maintained at similar rates throughout the 15-year period of the study, increases in wood density were more gradual. As a result, wood density appeared more uniform along the pith-to-bark radii in larger, fast-grown trees than in smaller, slow-grown trees. These findings are consistent with recent work on *Eucalyptus grandis* by Malan (1999). Working with samples from 34-year-old espacement trials, he found that widely spaced trees had more uniform wood density across the radial and along the longitudinal axes. Greater uniformity is economically valuable because it provides higher predictability and efficiency in manufacturing processes, and better consistency and commonly higher value in end products (Zobel and van Buijtenen 1989 Malan 1999).

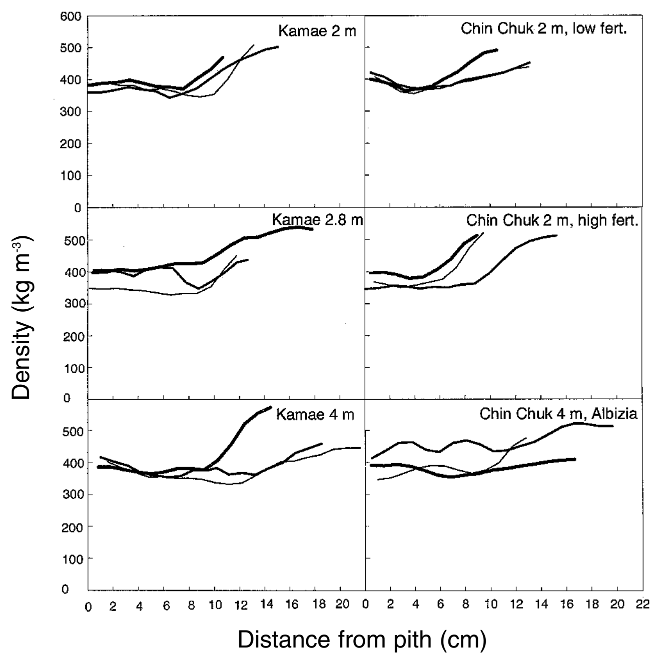

Figure 1. Radial trends in wood density of *Eucalyptus saligna* grown in six silvicultural treatments as related to distance from pith. Each line represents one tree.

Conclusions and implications

The following conclusions apply to young, dominant and codominant *Eucalyptus saligna* trees planted on abandoned sugarcane land along the Hamakua coast of the Island of Hawaii. The results are likely indicative of general trends for this species in other subtropical regions where moisture is abundant and growth is limited by inadequate levels of available soil nitrogen.

1. Supplemental nitrogen – whether provided by chemical fertilizer or N-fixing companion trees - has little effect on wood density of *E. saligna*, irrespective of any enhancement of growth.

2. Wide spacing increased mean tree diameter significantly, and may have slightly increased mean wood density.

3. Wood density of *E. saligna* was, for all practical purposes, unrelated to growth rate.

4. The inherent (presumably age-related) increase in wood density was more gradual (hence, more uniform) along the

pith-to-bark radius of trees that maintained rapid growth rates throughout the short rotation.

Given that 'conventional wisdom' commonly purports that fast-grown trees of many species are likely to have lower wood density, perhaps the greatest significance of this study lies in the assurance that this generality is not true of *E. saligna* in Hawaii. Productivity of short-rotation pulpwood plantations can therefore be enhanced through supplemental nitrogen (chemical or biological) without decreasing wood density. The provision of added growing space (through wide initial spacing and, possibly, subsequent thinning) will increase growth substantially and may increase wood density slightly. And the increased wood produced - whether associated with improved nutrition or increased growing space - will be more uniform, and thus, more economically valuable.

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