Spacing affects stem form, early growth and branching in young whitewood (*Endospermum medullosum*) plantations in Vanuatu

K. GLENCROSS[1], J.D. NICHOLS[1], J.C. GRANT[1], M. SETHY[2] and R.G.B. SMITH[1]

[1]*Forest Research Centre, School of Environment, Science and Engineering, Southern Cross University, Lismore NSW Australia*
[2]*Department of Forests Vanuatu, Luganville, Santo, Vanuatu*

Email: kevin.glencross@scu.edu.au

SUMMARY

This paper investigates the early growth response, branching and stem quality of *Endospermum medullosum* (whitewood) at different spacings. Whitewood plantings were established at stockings of 400–833 trees per hectare and early growth, tree stem quality and branching were quantified up to age 3 years. Growth, number of live branches and branch size were negatively correlated with stocking. The stocking of trees of acceptable quality had high spatial variation. Initial spacing in whitewood plantations can be used to manipulate branch size, crown rise and stem size; all of which are important for development of pruning and thinning regimes to produce high quality logs. If unimproved whitewood stock is used, to ensure that there are 300 stems per hectare of acceptable quality to produce sawlogs, more than 600 trees per hectare should be established at planting.

Keywords: Plantation establishment, stocking, canopy development, pruning, wood quality

L'espacement affecte la forme des troncs, la croissance de départ et les branches dans les plantations de jeune bois blanc (*Endospermun medullosum*) à Vanuatu

K. GLENCROSS, J.D. NICHOLS, J.C. GRANT, M. SETHY et R.G.B. SMITH

Cet article étudie la réponse de la croissance de départ, de la qualité des branches et des troncs de l'Endospermum Medullosum (bois blanc) à différents espacements. Les plantations de bois blanc avaient été établies en populations de 400–833 arbres par hectare, et la croissance de départ, la qualité du développement des branches et des troncs étaient quantifiés jusqu'à l'âge de trois ans. La croissance, le nombre de branches en vie et leur taille révélaient une corrélation négative avec la population. La plantation d'arbres de qualité acceptable connaissait une variation spatiale importante. L'espacement initial dans les plantations de bois blanc peut être utilisé pour manipuler la taille des branches, la pousse de la cime et la taille des troncs, lesquels sont tous importants pour le développement de régimes d'élagage et de coupe pour produire des bûches de bonne qualité. Si une source de bois blanc non amélioré est utilisée, il faudrait établir 600 arbres par hectare lors de la plantation initiale pour obtenir 300 individus par hectare d'une qualité acceptable pour la production de bois de coupe.

El espaciamiento afecta a la forma del tallo, el crecimiento inicial y la ramificación en plantaciones jóvenes de madera blanca (*Endospermum medullosum*) en Vanuatu

K. GLENCROSS, J.D. NICHOLS, J.C. GRANT, M. SETHY y R.G.B. SMITH

Este artículo investiga el crecimiento inicial, la ramificación y la calidad del tallo de *Endospermum medullosum* (madera blanca) bajo diferentes espaciamientos. Se establecieron plantaciones de madera blanca en densidades de 400 a 833 árboles por hectárea y se midió el crecimiento inicial, la calidad del tallo y la ramificación hasta los tres años de edad. Se encontró una correlación negativa entre la densidad de plantación y el crecimiento, el número de ramas vivas y el tamaño de las ramas. Se observó una gran variación espacial en la densidad de plantación de árboles con una calidad aceptable. En plantaciones de madera blanca se puede utilizar el espaciamiento inicial para manipular el tamaño de las ramas, la altura de la copa y el tamaño del tallo, siendo todas estas características importantes en el régimen de podas y raleos para producir trozas de alta calidad. Si se utilizan plántulas no mejoradas de madera blanca, es necesario establecer inicialmente más de 600 árboles por hectárea, para asegurar la obtención de 300 fustes por hectárea de calidad aceptable para madera de aserrío.

INTRODUCTION

Whitewood (*Endospermum medullosum*) from natural forests in Vanuatu is highly regarded as a furniture and internal joinery timber; it machines and works well, making it suitable for many purposes including mouldings, boards, veneer and plywood manufacture (Viranamangga *et al.* 2012). The natural forest resource in Vanuatu is severely depleted and replacement with plantations has begun to ensure future wood supply (Viji *et al.* 2001), however trees grown in plantations differ from native forests in many ways (West 2006). The development of high value plantations in the tropics has a long tradition with species such as teak and mahogany (Mayhew and Newton 1998, Bhat 2000, Jagels 2006), however the use of native species is often limited by a lack of silvicultural information (Condit *et al.* 1993). Introduced plantation species have been tried in Vanuatu, but have struggled due to cyclones and forest health issues (Thompson 2011). In comparison, whitewood has shown excellent plantation potential with rapid growth, tolerance to cyclone damage and brown root rot (*Phellinus noxious*) in Vanuatu (Thompson 2006).

Log size, stem shape and internal defects are influenced by stand management of plantations; primarily spacing, pruning and thinning. Log size is determined by tree diameter growth, which is controlled by tree density (Ola-Adams 1990). Initial spacing is therefore important for early growth and thinning important to maintain or increase growth later in the rotation (Kanninen *et al.* 2004). However, there are trade-offs. Even though the result is slower early growth, higher initial stockings are commonly used for several important purposes: to rapidly capture the site by suppressing weed competition (Evans and Turnbull 2004); to increase the number of trees with high quality stem shape available to select for pruning; and to restrict branch growth and therefore increase wood quality outcomes from pruning.

Stand management silvicultural prescriptions are in various stages of development for many tropical species (James and del Lungo 2005, Evans and Turnbull 2004, Kanninen *et al.* 2004, Jagels 2006). The need to define silvicultural prescriptions is most pronounced for plantations of new species (Glencross and Nichols 2005, Smith and Brennan 2006, Vanclay 2010, Nichols and Vanclay 2012), such as whitewood, where little is known about the growth, wood properties and future markets for plantation grown trees. Perez and Kanninen (2005) also point out that it is difficult to make comparisons of management regimes and growth responses to silvicultural practices and site conditions to other regions. Therefore, when undertaking a plantation program it is important to base silvicultural decisions on local data and species, rather than relying on general principles from other species and other regions.

Spacing, thinning and wood quality have a role in wind firmness (Grant *et al.* (2012) describes the wind environment of Espiritu Santo Island). Lower height to diameter ratios and higher strength characteristics (correlated with wood density) confer greater resistance to breakage and uprooting (Read *et al.* 2011, Cremer 1982, Gardiner *et al.* 2008). The main influence on individual tree growth of higher stocking is restricting diameter growth. Therefore at higher stocking, height to DBH ratios are increased, reducing mechanical strength and increasing risk of stem damage. In natural forest trees in New Caledonia, height: diameter ratios ranged from 44–72 for angiosperms and 72–85 in two conifer species (Read *et al.* 2011). However it is not clear if this will be sufficient in the wind environment of Vanuatu and with the wood mechanical properties of whitewood. Stands are also more susceptible to wind damage after thinning as stands are opened up (Gardiner *et al.* 2008).

Investors and growers often struggle to develop sufficient log value from plantation-grown trees to justify the required investment, particularly for large saw-log regimes which require long rotations (Brown and Beadle 2008). Log value is largely determined by the quantity and pricing of the products that may be recovered after conversion, minus the costs of growing, harvesting and processing (Cassidy *et al.* 2012). Internal defects are often very different in trees grown in plantations to those in natural forest (Jagels 2006). Studies of the wood quality of new plantation species often report poor wood quality due to inappropriate silviculture resulting in significant downgrading of timber, especially because of knots and other branch related defects (Forrester *et al.* 2010). Pruning is undertaken to enhance wood value; however, pruning is a costly and challenging silvicultural intervention and decisions can have an affect on growth and economic returns to growers (Montagu *et al.* 2003). Branching characteristics will inform the timing and height to which branches are removed. Pruning is often undertaken in the first 5 years of growth in highly productive plantations (West 2006).

For forest growers the total wood value realised is largely determined by log size, stem shape (stem form) and the distribution of internal defects (Montagu *et al.* 2003, Palmer 2010, Todoroki 2003). Our objective was to examine the influence of spacing on the growth, stem quality and branching characteristic of whitewood grown in silvicultural experimental trials across Espiritu Santo Island, Vanuatu (Santo). The implications of stand management as it affects wood quality and product value are discussed.

METHODS

Silviculture trials were established at 5 different locations on Espiritu Santo Island, Vanuatu. A spacing trial was established initially in 1995 at Loro, and a series of spacing and thinning trials and demonstration plots in 2007–9 across the Island. Details of the trials planted in 2007–9 and treatments at each site are contained in Table 1.

Early growth was measured as tree diameter at breast height (DBH).

Tree selection for pruning and thinning

Stem form was assessed at Victor and Kelsai at age 4 years on the basis of straightness, and the degree of defects in the merchantable section of the stem (0–6 m), which generally

TABLE 1 *Site and trial details*

Trial	**Victor**	**Kelsai**	**Jubilee Farm**	**Lorum**	**Loro [1].**
Location	Central Santo	Shark Bay	Luganville	Shark Bay	Shark Bay
Plant Date	Feb 2008	Mar 2008	Apr 2008	Oct 2008	1995
Previous land use	Garden	Garden	Coconut, garden	Bush	
Area (spacing)	0.5	2 × 1 ha	0.5	2.5	1.5
Spacings - m	4 × 3, 4 × 6	8 × 3; 6 × 3	8 × 6	4 × 3; 4 × 4; 8 × 3.	2 × 4; 2 × 6; 2 × 8; 2 × 10; 4 × 4; 4 × 6; 4 × 8; 4 × 10; 6 × 6; 6 × 8; 6 × 10.
Replications	6	0	0	8	2
Treatments	Unthinned Thinned to 415 tph at age 2.8.	(8 × 3) garden for 2 years		To be thinned	Variable plot size
Design	RCB			RCB	RCB
Measurements	DBH, branch, stem quality	DBH, branch, stem quality	DBH	DBH, Ht age 1, 2, 3	DBh, Ht age 2,4,9.

1. planted by QFRI staff 1995 (Walker *et al*. 1996).

resulted from the presence of large branches or bends in the stem. Trees were classified into one of three groups:

Crop trees: were the straightest, free of defects and suitable for pruning;

Minor defect trees: minor stem deviations, minor deformities on trunk, largest branch <50 mm diameter, lean <5% but were deemed as merchantable. These could be pruned but would result in lower quality products (the cost of pruning is less likely to be recouped).

Cull trees: had a major defect in the lower section of the stem (ramicorns, double leaders, very large branches >50 mm, severe stem deviations, broken tops) and were considered unmerchantable.

The questions of interest were; the total number and spatial variation of crop or merchantable trees available for pruning at each stocking, and the proportion of trees in each stem classes at both stockings. The optimum number of trees for final harvest in a solid wood regime on high quality sites to ensure full utilisation of the site while maintaining growth rates and is generally considered to be about 200–400 trees per hectare (West 2006). Therefore 200 trees per hectare was used as an indication of adequate stocking. A total of 732 trees were assessed in two stockings and three spacings (Victors: 4 × 3, Kelsai: 6 × 4, 8 × 3).

Canopy development

All branches in the lower 4 m of the stem (3 m at Lorum) were assessed as being dead or alive. Branch diameter was measured at a point just past (20 mm) the branch collar swelling (Table 2). Approximately 30 sample trees in each stand were selected across the range of diameter classes within each stand (spacing). Measure trees were surrounded by buffers at least 6 m wide from plantation edges or any change in spacing. Plot sizes in experimental trials ranged from 480 m^2 in 4 × 3 m treatments to 700 m^2 in the 8 × 3 m plots.

Data analysis

Differences in mean plot DBH between the four spacing and thinning treatments at Kelsai and Victor were analysed for each measure date separately using ANOVA in SPSS. The effect of growth and spacing at Loro was modelled by fitting linear or logarithmic regressions in Excel with DBH as the dependent variable and stocking as the independent variable. A model was fitted for each age separately. The model chosen was that with the greatest correlation coefficient (model selection and residuals were checked using visual inspection of plots). Differences in the frequency of trees in the three

TABLE 2 *Branch data collection sites*

Site	**Age years**	**n trees**	**Stocking trees/ha**	**Spacing m × m**	**Average DBHcm**
Jubilee Farm	3.1	30	208	8 × 6	18.5
Victor	3.3	33	417	4 × 6	18.0
Kelsai	3.8	34	417	8 × 3	17.6
Kelsai	3.8	32	556	6 × 3	16.3
Lorum	2.8	33	625	8 × 2	13.0
Victor	3.4	25	833	4 × 3	16.5

classes between the two different spacings at 417 stocking at Kelsai and the 833 stocking at Victors were analysed using chi-squared tests. Relationships between DBH, maximum branch size, branch size and number of live branches and stocking were modelled using linear regression in Excel and plots were also checked visually. Initial stocking was used as the independent variable for mean branch size per tree and number of live branches. DBH was the independent variable against maximum branch size.

RESULTS

Growth

The spacing trial at Loro showed no effect of spacing on DBH at age 2 years (Figure 1). The difference in DBH between lowest and highest stocking was less than a centimetre. At this early stage, a linear regression with slope approaching zero being the best fit ($r^2 = 0.085$) for DBH across spacing treatments. By age 4 years the best fit model was logarithmic ($r^2 = 0.52$). The difference in DBH between stockings of 1250 and 625 tph was only 0.35 cm compared to 3.32 cm between 166 and 625 tph. By age 8 the non-linear suppressive effect of higher stocking on DBH was apparent across all stockings and best represented by a logarithmic regression ($r^2 = 0.55$), the difference between 1250 and 625 compared to 625 and 166 were 5.9 and 8.3 cm respectively (Figure 1). Different rectangularities appeared to have no discernable effect on DBH growth. In the only stocking with square and rectangular spacing treatments (625 tph; 4 m × 4 m, 8 m × 2 m), the rectangular spacing had smaller mean DBH than the square spacing at all ages. Other similar stockings with varied rectangularities showed similar results.

The results from the trials planted in 2008 showed a similar growth trend to the Loro spacing trial planted in 1995. At Lorum, survival and growth were unaffected by spacing up to age 3 years (data not shown). At Victors and Kelsai, there was a significant difference in DBH growth between spacing treatments at age 4 years (Figure 2, ANOVA: $F_{3,25}$ 9.803. $p<0.001$). The thinned treatment at Kelsai (6 × 4) and the wider spacing at Victor (8 × 3) were significantly greater than the other two treatments at 4.3 years age.

Tree selection for pruning and thinning

The number of defect-free trees suitable for pruning and producing high quality final crop trees was highly variable (Table 3). There were on average in each spacing treatment between 40 and 65% of trees without defect per plot. However, spatial variation was considerable; ranging from 24 to 75% in individual plots. This has implications for site occupancy. Defect free final crop trees were as low as 100/ha in one plot.

The overall proportion of trees within each of the classes was significantly different between the two spacings (both 417 trees per hectare) at Kelsai ($p<0.001$), but was not significantly different between 833 trees per hectare at Victors and the 6 × 4 spacing at Kelsai ($p=0.49$). The proportion of unmerchantable trees was significantly lower in the thinned stand at Victors ($p<0.05$) compared to the unthinned, however when the cull trees were excluded from the analysis the proportion of minor defect trees was not significantly different.

Canopy development

The maximum branch diameter per tree was positively correlated with tree DBH ($r^2 = 0.35$. Figure 3). Maximum

FIGURE 1 *DBH at various spacings at the Loro spacing trial. Each point represents the mean of two replicate plots, spacings are listed in Table 1. Series are measurement ages; the trees were planted in 1995 and measured at age 2.1, 3.1, 4.1, and 8.7 years*

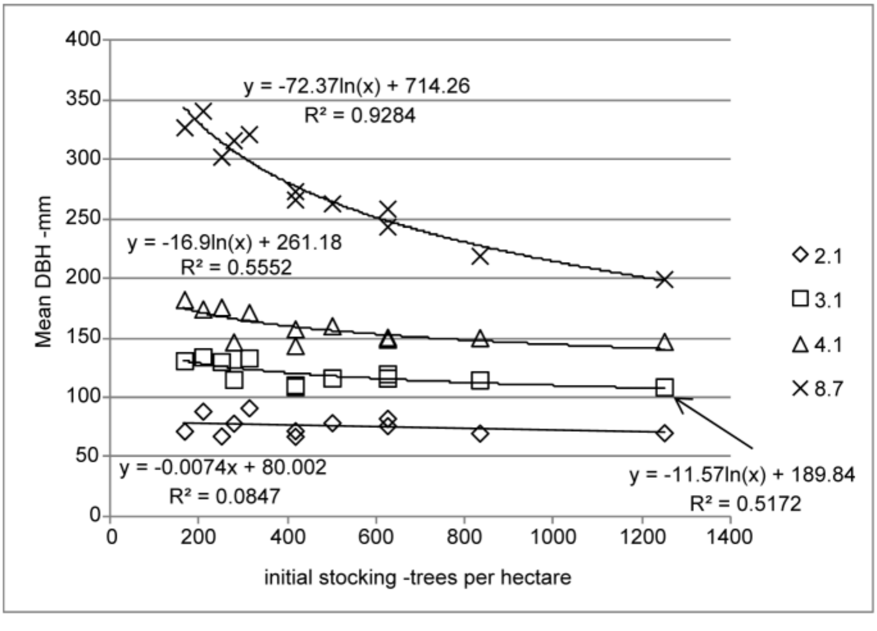


FIGURE 2 *DBH growth of two spacings at Victor and Kelsai sites. were significantly different between spacings by age 4. Error bars are standard error of the mean*

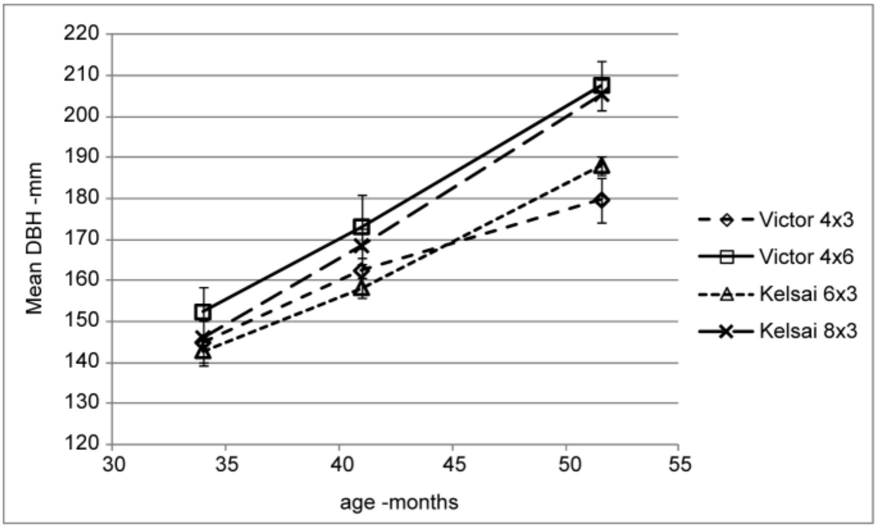
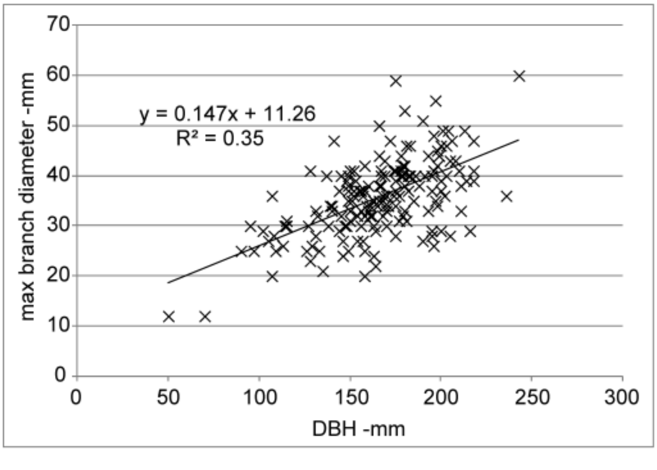


TABLE 3 *Mean number of merchantable trees per hectare without defect in 29 plots planted at two stockings*

Intial stocking - trees /ha		417	833
Spacing - m		6x4	4x3
Defect free trees	Minimum	101	235
	Mean	237	354
	Maximum	336	563
Defect free plus Minor defect	Minimum	277	641
	Mean	394	743
	Maximum	416	790

diameters ranged from 25 mm in trees of 100 mm diameter to 50 mm for trees of 250 mm DBH. Mean branch diameter (Figure 4) and the number of live branches (Figure 5) were negatively correlated to initial stocking ($r^2 = 0.78$, $r^2 = 0.54$ respectively). Lower stockings produced larger mean branch diameter, maximum branch diameter and larger numbers of live branches. The average branch diameters were only below 25 mm at 625 and 833 stockings. Maximum branch diameter was closely correlated to the mean diameters and is above 25 mm for all stockings.

FIGURE 3 *The relationship between maximum branch diameter and diameter at beast height (DBH at 1.3 m height)*



DISCUSSION

Growth rate and the characteristics of the canopy will influence key decisions about stand management, including weed control, pruning and thinning. Understanding those growth characteristics for a given species will help forest growers make informed decisions about the timing and intensity of silvicultural interventions, anticipate operational requirements and better predict production costs. The growth, stem quality and branching characteristic of whitewood grown in

FIGURE 4 *Average branch diameter at 3 sites and five stocking rates. Sample site details are contained in Table 2*

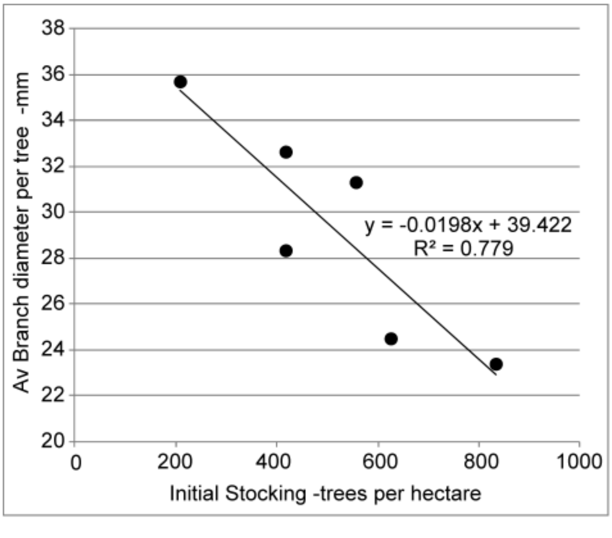
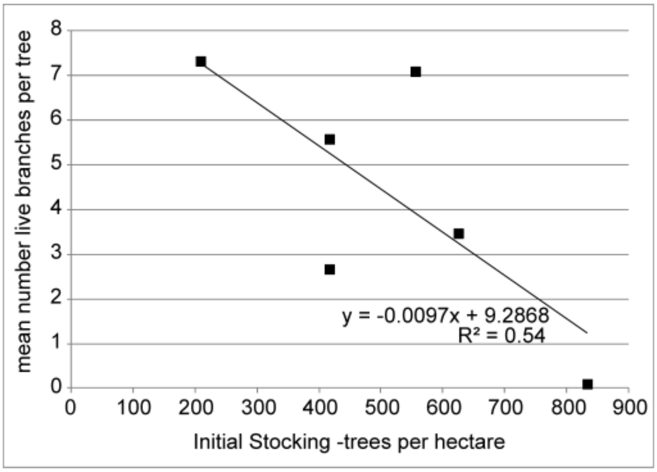


FIGURE 5 *Mean number of live branches per tree related to stocking. Sample site details are contained in Table 2*



silvicultural experimental trials and demonstration plots across Espiritu Santo, Vanuatu indicate that the species has many favourable plantation traits; including early rapid growth and a tendency to form smaller branches at higher stocking rates (over 500 trees per hectare). Whitewood planted at higher stocking has shown a capacity to initiate branch death and branch shedding. The implications of these traits are that forest growers may use spacing and thinning to produce positive effects on log size, defect levels (knot size) and therefore wood quality.

In many solid wood plantation programs, growers plant over 1000 trees per hectare to ensure rapid site capture and sufficient crop trees of the desired form. In Vanuatu, the planting of over 600 trees per hectare has been seen as overstocking; where woodlots and plantations are generally planted at < 500 trees per hectare (Grant *et al.* 2012). A survey of landholders showed that even lower stockings may be preferred in future (Aru *et al.* 2012).

Growth

The early growth of whitewood was affected by stocking. The competition and subsequent reduction in DBH growth was related to initial stocking and was consistent across several trials on Santo. At Loro the curves fitted to DBH growth showed a pattern of increasing effect of stocking with age (Figure 1). At age 2 the curve is linear and horizontal and DBH is unaffected by stocking. By age 3 stockings below approximately 300 trees/ha have slightly greater DBH than those greater than 400 trees/ha, which are largely unaffected by the stocking. By age 8 the DBH is affected by all stockings.

Similar results were found in trials at Kelsia and Victor (Figure 2). At initial stockings from 417 to 833 the early growth was unaffected by stocking until after age 3, when mean DBH started to decline in stands with 555 and 833 trees per hectare compared to stand with 417. At age 4.3 years the DBH of stands stocked at 417 and those thinned from 833 to 417 were significantly greater than higher stocked stands. Stem diameters did not differ significantly in stands with 55 and 833 stems/ha at age 4.3 years.

When whitewood is established at stockings less than 400 trees/ha accelerated growth can be achieved after approximately age 3. For stands established at stockings between 417 to 833 trees/ha thinning after age 4 will significantly increase growth, however the pruning regime will be very important (see below). Once pruning has been undertaken thinning is needed to maximise the growth on the pruned trees. As with initial spacing, thinning can influence wood properties and tree shape by increasing branch size and increasing stem taper (Pinkard and Neilsen 2003).

Stem quality

Tree stem quality was found to be highly spatially variable (Table 3). 200 trees/ha is used as the lower end of an acceptable number to ensure full utilisation of the site. Of 23 plots with initial stocking of 417, 6 (25% of the trial) had less than 200 crop trees. When minor defect trees were included, all plots had sufficient trees, however while these trees are prunable, they will produce a lower quality log product. However, with an initial stocking of 833, all plots had over 200 crop trees.

High spatial variation in stem quality suggests that higher stocking may be need to be used to mitigate the risks of poor stem quality, particularly within a stand specifically managed for sawlogs. The markets for final and intermediate products will also have a bearing on the timing and economic incentives for activities like thinning and pruning. If a commercial thinning event is possible, then growers will be more likely to plant densely and undertake thinning (Viranamangga *et al.* 2012). The proportion of stems of a higher quality (crop trees) was not significantly different between the lower stocking at Kelsai and the higher stocking at Victors. Similar results were found in subtropical eucalypts (Smith and Brennan 2006), where the proportion of quality crop trees in the stand was consistent between stockings. The conclusion drawn was that high enough initial stocking and a pre-commercial thin should be used to increase stand quality, especially in unimproved genetic material. The comparison of the stand quality between thinned and unthinned stands at Victor showed there were no unmerchantable stems retained after thinning, however the proportion of minor defect trees remained comparable. This is due to the need to maintain spacing within the stand and therefore some trees with minor defect need to be retained.

The proportion of minor defect trees was significantly lower in the 8 × 3 m spacing at Kelsai. It seems unlikely the minor difference in rectangularity of spacing was causal. The main difference in management was the planting of gardens between the rows in the 8 × 3 m spacing block but not in the 6 × 4. Tending gardens around the planted trees does eliminate weed problems, especially merremia, which causes many form problems when vine stalks deform trees stems. It should be noted the measures were only on one site, there was considerable variation, and the stands had very small numbers of un-merchantable stems. The use of gardening also has other potential benefits for plantation systems in terms of establishment cost (Grant *et al.* 2012, Smith *et al.* 2012).

Canopy Development

While stand level stem form can be improved by selection, branch development is more influenced by the availability of light as a result of spacing (Alcorn *et al.* 2007). The production of large branches needs to be controlled by spacing and pruning as large branches are slower to occlude, are more difficult to prune and can result in large downgrade of timber quality.

Branching in whitewood was controlled by stocking with larger branches developing at lower stockings (Figure 4). There is also a consistent relationship between maximum branch diameter and DBH (Figure 3). If stocking is used to control branch diameter it will restrict DBH growth. This can be managed in two ways. Branches can be pruned before growth is effected and the stand then thinned, or stands can be allowed to develop with growth effected (reduced DBH increment) and thinned after self-pruning has occurred. The loss of growth before a clear bole has formed reduces the size of the defect core, making the log more valuable. The increased value must be evaluated against the slower growth and resulting longer time to attain a final crop.

Pruning

Canopy dynamics strongly influence the quality and quantity of wood produced (Montagu *et al.* 2003, Jagels 2006). The quantity of high quality wood produced can be increased through the manipulation of the canopy by pruning and thinning. Pruning branches restricts the proportion of branch related defect wood in the core of the stem and facilitates the production of clear wood with no reduction in growth rate, provided no more than 50 percent of the leaf area is removed (Montagu *et al.* 2003, Forrester *et al.* 2010). There is therefore a trade-off between pruning and loss of growth due to removal of leaf area.

The object of pruning is to minimise the diameter of the defect core which is determined by the diameter after all branches have occluded termed the diameter over occlusion. The whorled growth habit of whitewood will result in very large diameters over occlusion at lower whorls if branches are allowed to develop at low stockings. However young trees can have a large investment in leaf area on the first whorl if branches are allowed to develop. The distribution of leaf area will be important for the scheduling of pruning. If large proportion of leaf area is contained in the first whorl, pruning may reduce growth such that trees are affected by competition.

The optimal time to prune depends on the leaf area development of the stand. The LAI generally increases until neighbouring canopies meet and the canopy closes, following which the LAI reaches equilibrium or gradually declines (Beadle and Long 1985, Cromer *et al.* 1993). After canopy closure the lower canopy is shaded and eventually its leaves are unable to maintain a positive carbon balance. This results in leaf and branch death. Dead branches can lead to numerous defects, including knots, decay and in some eucalypts kino-trace defect (Wardlaw and Neilsen1999); however branches can occlude without defect in many other species (Smith *et al.* 2006, Evans and Turnbull 2004, O'Hara 2007). The timing of pruning will depend on the development of branches and if necessary stocking can be used to control branch development in whitewood.

More work is needed to determine the effect of various pruning regimes on growth in young trees and to devise pruning schedules that optimise growth and defect core diameter. Where whitewood is planted at low stockings pruning will be required.

Self-pruning

Whitewood is efficient at self-pruning (Thompson 2006, Viranamangga *et al.* 2012). Trees that received only minimal pruning and early tending had clear boles and harvestable and merchantable timber by age 15 harvest (Viranamangga *et al.* 2012). In some species lower canopy branches remain alive to a greater extent than others (Alcorn *et al.* 2007), and some species retain dead branches more than others (Evans and Turnbull 2004, Montagu *et al.* 2003). Whitewood branch death appears to be influenced by higher stocking (Figure 5) and smaller branches would be expected to occlude more rapidly than larger. Subtropical eucalypts exhibit a range of canopy dynamics (Alcorn *et al.* 2008), however for four species with a range of behaviours, dead branches occluded at the same rate whether they were pruned or not (Smith *et al.* 2006). The clear boles and observations indicate that whitewood branches will self-prune (Thompson 2006). There were also a number of large trees that had self-pruned (no branches on the lower stem) that were omitted from the branch size analysis. The important implication is that if the canopy can be forced to rise then self-pruning will occur more rapidly, minimising the diameter of the defect core (Smith *et al.* 2010). The canopy behaviour of whitewood will determine the optimum management regime, although the difference in log quality between pruned and unpruned trees is as yet unclear.

Thinning

If higher stocking is used for many of the reasons discussed above, then it will be necessary to thin the stand. Thinning will be a particularly important part of many silvicultural regimes designed to produce sawlogs in the shortest possible time (West 2006). Thinning generally aims to remove the less valuable trees and redistribute the site resources to the most valuable crop trees in a stand to increase value rather than volume (Long *et al.* 2004, Cassidy *et al.* 2012). In the non-commercially thinned site at Victors, by age four, the retained trees had increased diameter growth comparable to plots planted at low initial stocking at Kelsai (Figure 2). The value of higher stocking and a non-commerical thin needs to be evaluated based on the reduced risks and increased stand quality compared to lower stocking.

As happened at Victors, thinning often results in increased individual tree size. Thus the aim of an optimal thinning regime is to balance the need for individual growth and therefore stand value, whilst not under-utilising the site resources, reducing wood quality or foregoing volume production (Smith and Brennan 2006). However, productivity and value of thinned and pruned stands may vary greatly depending on the age and intensity of thinning and the conditions of the site (Medhurst *et al.* 2001).

Costs and the absence of markets for thinnings are disincentives for thinning (Evans and Turnbull 2004, Smith and Brennan 2006), even though lack of thinning in fast-growing plantations leads to lower individual tree growth and therefore plantation value (Medhurst *et al.* 2001, Cassidy *et al.* 2012). Thinning costs need to be justified by the higher value product mix at the end of a shorter rotation returning a significantly higher net value (Nolan *et al.* 2005).

An optimal thinning regime in whitewood will depend on markets for thinning and for final products. Both of these are not known, although markets for natural forest whitewood do exist (Viranamangga *et al.* 2012). Market uncertainty is not uncommon in solid wood sawlog regimes due to the long time frames (Smith and Brennan 2006, Kanninen *et al.* 2004), however large high quality pruned logs offer the greatest flexibility in terms of products and the lowest conversion costs for processors, and therefore higher returns and least market risk for growers (Montagu *et al.* 2003, Donnelly *et al.* 2003). In the absence of a market for small roundwood, a noncommerical thinning will return greater value at the end of rotation, removing low quality and low value trees, reallocating site resources to higher quality pruned trees and therefore bringing forward final harvest. It is possible to produce high quality logs using several different stand management regimes which may suit different grower situations such as agroforestry or industrial-scale plantings. The important factor is the supply of resource of consistent quality.

CONCLUSIONS

Spacing in whitewood plantations will influence growth and canopy characteristics that are crucial in solid wood production. Our results show higher stocking (closer initial spacing) results in:

- less rapid early diameter growth;
- greater availability of sufficient high quality trees for pruning and intermediate thinning crops;
- restricted branch growth, increasing the time available for pruning and therefore minimising branch related defects.

Lower stocking (wider initial spacing) results in:

- maximises individual tree diameter growth and therefore log size and value, minimising the time to thinning and final harvest;
- larger branches and longer holding of live branches lower on the stem,
- reduced planting costs.

Maximum and average branch diameter and the number of live branches were all negatively correlated with stocking. Therefore, if whitewood is grown at lower stockings, such as in agro-forestry systems, special care must be taken to ensure timely pruning is undertaken to prevent large branches developing. The number of trees with acceptable stem quality for pruning was positively correlated to stocking but was highly variable between plots. If whitewood is planted at higher stockings, to maximise the production of high quality products and ensure full utilisation of the site, thinning will be required. If planted at low stockings, pruning will be required in the first three years to reduce the presence of large branches in the merchantable part of the stem.

ACKNOWLEDGEMENTS

This research was funded by the Australian Centre for International Agricultural Research (ACIAR) grant FST 2005/089. The authors would like to express sincere gratitude to all the people who contributed their time, information and efforts to this study.

REFERENCES

ALCORN, P.J., PYTTEL, P., BAUHUS, J., SMITH, R.G.B., THOMAS, D.S., JAMES, R.N. and NICOTRA, A.B. 2007. Effects of initial planting density on branch development in 4-year-old plantation grown *Eucalyptus pilularis* and *Eucalyptus cloeziana* trees. *Forest Ecology and Management* **252**: 41–51.

ALCORN, P.J., BAUHUS, J., THOMAS, D.S., JAMES, R.N., SMITH, R.G.B. and NICOTRA, A.B. 2008. Photosynthetic response to green crown pruning in young plantation-grown *Eucalyptus pilularis* and *E. cloeziana*. *Forest Ecology and Management* **255**: 3827–3838.

ARU, R., NICHOLS, J.D., GRANT, J., LEYS, A., GLENCROSS, K., SETHY, M., CONVERY, K. and VIRANAMANGGA, R. 2012. Constraints to whitewood (*Endospermum medullosum)* plantation development on Santo Island, Vanuatu. *International Forestry Review* **14**(4): 414–423.

BEADLE, C.L. and LONG, S.P. 1985. Photosynthesis- is it limiting to biomass production. *Biomass* **8**(2): 119–168.

BHAT, K.M. 2000. Timber quality of teak from managed tropical plantations with special reference to Indian plantations. *Bois et Forets des Tropiques* **263**(1): 6–15.

BROWN, A.G. and BEADLE, C.L. 2008. Plantation Eucalypts for High-Value Timber: Enhancing investment through research and development Publication No. 08/ Project No. CVF-2A. Canberra, RIRDC Joint Venture Agroforestry Program.

CASSIDY, M., PALMER, G., GLENCROSS, K, NICHOLS, J.D, AND SMITH, R.G.B. 2012. Stocking and intensity of thinning affect log size and value in *Eucalyptus pilularis*. *Forest Ecology and Management* **264**: 220–227.

CONDIT, R., HUBBELL, S.P., FOSTER, R.B. 1993. Identifying fast-growing native trees from the neotropics using data from a large, permanent census plot. *Forest Ecology and Management* **62**: 123–143.

CREMER, K.W., BOROUGH, C.J., MCKINNELL, F.H. and CARTER, P.R. 1982. Effects of stocking and thinning on wind damage in plantations. *New Zealand Journal of Forestry Science* **12**: 244–268.

CROMER, R.N., CAMERON, D.M., RANCE, S.J., RYAN, P.A. and BROWN, M. 1993. Response to nutrients in *Eucalyptus grandis* 1. biomass accumulation. *Forest Ecology and Management* **62**(1–4): 211–230.

DONNELLY, R., FLYNN, B. and SHIELD, E. 2003. The Global Eucalyptus Wood Products Industry: A Progress Report on Acheiving Higher Value Utilization. Washington, Robert Flynn & Associates.

EVANS, J. and TURNBULL, J.W. 2004. Plantation forestry in the tropics: the role, silviculture and use of planted forests for industrial, social, environmental and agroforestry. third ed. Oxford University Press, Oxford.

FORRESTER, D.I., MEDHURST, J.L., WOOD, M., BEADLE, C.L., VALENCIA, J.C. 2010. Growth and physiological responses to silviculture for producing solid-wood products from Eucalyptus plantations: an Australian perspective. *Forest Ecology and Management* **259**: 1819–1835.

GARDINER, B., BYRNE, K., HALE, S., KAMIMURA, K., MITCHELL, S.J., PELTOLA, H. and RUEL, J.-C. 2008. A review of mechanistic modelling of wind damage risk to forests. *Forestry* **81**(3): 447–463.

GLENCROSS, K. and NICHOLS, J.D. 2005. Growth performance and review of wood quality concerns for rainforest timber species in subtropical eastern Australia. *Reforestation in the Tropics and Subtropics of Australia using rainforest tree species* P.D. Erskine, D. Lamb and M. Bristow. Canberra, Joint Venture Agroforestry Program, Rural Industries Research and Development Corporation. 101–113.

GRANT, J., GLENCROSS, K., NICHOLS, J.D., PALMER, G., SETHY, M. and VANCLAY, J. 2012. Silvicultural implications arising from a simple simulation model for *Enospermum medullosum* in Vanuatu. *International Forestry Review* **14**(4): 452–462.

JAGELS, R. 2006. *Management of wood properties in planted forests: a paradigm for global forest production*. Working Paper FP/36/E FAO, Rome, Italy.

JAMES, R.N. and DEL LUNGO 2005. *The potential for fast-growing commerical forest plantations to supply high value roundwood*. Planted Forests and Trees Working Papers. Working paper FP/33 Rome, FAO Rome. 46 p.

KANNINEN, M., PEREZ, D., MONTERO, M. and VIQUEZ, E. 2004. Intensity and timing of first thinning of *Tectona grandis* plantations in Costa Rica: results of a thinning trial. *Forest Ecology and Managament* **203**: 89–99.

LONG, J.N., DEAN, T.J., ROBERTS, S.D. 2004. Linkages between silviculture and ecology: examination of several important conceptual models. *Forest Ecology and Management* **200**: 249–261.

MAYHEW, J.E. and NEWTON, A.C. 1998. *The Silviculture of Mahogany*. CABI Publishing.

MEDHURST, J.L., BEADLE, C.L. and NEILSEN, W.A. 2001. Early-age and later-age thinning affects growth, dominance, and intraspecific competition in Eucalyptus nitensplantations. *Canadian Journal of Forest Research* **31**: 187–197.

MONTAGU, K.D., KEARNEY, D.E. and SMITH, R.G.B. 2003. The biology and silviculture of pruning planted eucalypts for clear wood production – a review. *Forest Ecology and Management* **179**: 1–13.

NICHOLS, J.D. and VANCLAY, J.K. 2012. Domestication of native rainforest tree species for plantations: a review. *International Forestry Review* **14**(4): 402–413.

NOLAN, G., WASHUSEN, R., JENNINGS, S., GREAVES, B., PARSONS, M. 2005. *Eucalypt Plantations for Solid Wood Products in Australia – A Review*. Forest and Wood Products Research and Development Corporation. Canberra.

O'HARA, K.L. 2007. Pruning wounds and occlusion: A long-standing conundrum in forestry. *Journal of Forestry* **105**(3): 131–138.

OLA-ADAMS, B.A. 1990. Influence of spacing on growth and yield of *Tectona grandis* Linn f (teak) and *Terminalia superba* Engl. & Diels (Afara). *Journal of Tropical Forest Science* **2**(3): 180–186.

PALMER, G. 2010. Conversion modelling: simulating tree stems. PhD thesis, Southern Cross University, Lismore, NSW. http://epubs.scu.edu.au/cgi/viewcontent.cgi?article=1127&context=theses.

PEREZ, D. and KANNINEN, M. 2005. Stand growth scenarios for Tectona grandis plantations in Costa Rica. *Forest Ecology and Management* **210**: 425–441.

PINKARD, E.A. and NEILSEN, W.A. 2003. Crown and stand characteristics of *Eucalyptus nitens* in response to initial spacing: implications for thinning. *Forest Ecology and Management* **172**: 215–227.

READ, J., EVANS, R., SANSON, G.D., KERR, S. and JAFFRE, T. 2011. Wood properties and trunk allometry of co-ocurring rainforest canopy trees in a cyclone-prone environment. *American Journal of Botany* **98**(11): 1762–1772.

SMITH, R.G.B., BRENNAN, P. 2006. First thinning in sub-tropical eucalypt plantationsgrown for high-value solid-wood products: a review. *Australian Forestry* **69**: 305–312.

SMITH, R.G.B., NICHOLS, J.D., SETHY, M., GRANT, J. and GLENCROSS, K. 2012. A review of site-preparation, fertilizer and weeding practices for tropical plantation species with recommendations for whitewood (*Endospermum medullosum*) in Vanuatu. *International Forestry Review* **14**(4): 433–441.

SMITH, R G.B., DINGLE, J. KEARNEY, D. and MONATGU, K. 2006. Branch occlusion after pruning in four contrasting sub-tropical Eucalypt species. *Journal of Tropical Forest Science* **18**(2): 117–123.

SMITH, R.G.B., HARDING, K.J., ZBONAK, A. and THOMAS, D.S. 2010. Wood properties and knot occlusion of plantation grown *Eucalyptus dunnii* and *Corymbia citriodora subsp variegata* in a pruning and thinning experiment. *Wood Structure and Properties* **10**: 41–47.

THOMSON, L. 2011. SPRIG: Its implementation and impact on forest genetic resources in the Pacific. *Pacific workshop regional training, State of the world's forest genetic resources* www.fao.org/forestry/27930-0e968573609608b1bf9ef0a37cd4eb41e.pdf.

THOMSON, L.A.J. 2006. *Endospermum medullosum* (whitewood), ver. 2.1. In ELEVITCH, C.R. (ed.) Species profiles for Pacific Island agroforestry. Holualoa, Hawaii: Permanent Agriculture Resources.

TODOROKI, C.L. 2003. Importance of maintaining defect cores. *New Zealand Journal of Forestry Science* **33**: 25–34.

VANCLAY, J.K. 2010. Robust relationships for simple plantation growth models basedon sparse data. *Forest Ecology and Management* **259**: 1050–1054.

VIJI, I., SMITH, A. SETHY, M. and THOMSON, L.A.J. 2001. Assessment of whitewood (*Endospermum*) family trial in Vanuatu. *Pacific Islands Forests and Trees* **4**: 8–9.

VIRANAMANGGA, R., PALMER, G. and GLENCROSS, K. 2012. Plantation-grown whitewood timber in Vanuatu: Challenges and opportunities for export and domestic use. *International Forestry Review* **14**(4): 486–491.

WALKER, S., HAINES, R. and ARU, R. 1996. Melcoffee hardwood plantation project in Vanuatu: current status and future directions. Pacific Islands Forests and Trees newsletter 4/96, South Pacific Forestry Development Program, Suva, Fiji. (4 pp.)

WARDLAW, T.J. and NEILSEN, W.A. 1999. Decay and other defects associated with pruned branches of Eucalyptus nitens. *Tasforests* **11**: 49–57.

WEST, P.W. 2006. Growing Plantation Forests. Springer-Verlag, Berlin.