

Influences of silviculture, genetics and environment on radiata pine corewood properties: results from recent studies and a future direction

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Introduction

Marketing structural wood from radiata pine plantations is limited by the corewood zone of each log, a zone which lacks stiffness and is unstable during drying (Harris and Cown, 1991). While basic density is lower in the corewood zone, the key factor affecting wood properties in this zone is the angle of microfibrils of cellulose within the S2 layer relative to the tracheid axis (Walker & Butterfield 1996). Higher microfibril angle (MFA) is associated with lower stiffness (measured as dynamic modulus of elasticity, MOE) and with greater longitudinal shrinkage during drying (Pentoney 1953). Furthermore, high rates of change in MFA within this zone mean that different parts of boards shrink by different amounts, directly contributing to instability (Walker and Nakada, 1999). The corewood zone has been defined as the first 10 rings from the pith of a radiata pine log, but this is a rough approximation of a zone that varies in properties with silvicultural, climatic and genetic influences. "Outerwood" is wood beyond this zone.

Much has been learned about corewood properties during the last few years, but we do not yet understand the processes that lead to trees growing corewood. We know that corewood grown in warmer regions such as Nelson or Northland tends to be stiffer than that grown in colder climes (Cown *et al.* 1991). We also know that increasing tree stocking tends to improve the corewood; that different genotypes produce different qualities of corewood; and that genotype and stocking tend not to interact in our experiments (i.e.: their effects are additive, see Figure 1) (Lasserre *et al.* 2004, 2005, Waghorn *et al.* 2007). There are several theories about factors that drive corewood formation, but none have been shown to be entirely consistent with experimental results.

This paper reviews the dominant theories explaining corewood formation and outlines two recent NZ experiments designed to examine various hypotheses explaining the formation of wood with high MFA.

Theories of corewood formation

An early view was that ring number from pith, or "cambial age", somehow influences wood properties directly

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(Figure 2), leading to another name for corewood, "juvenile wood" (Cown 1992, Burdon *et al.* 2004). There is nothing physiologically juvenile about corewood, however, because it grows at the tops of physiologically mature trees. While corewood is correlated with ring number because it grows

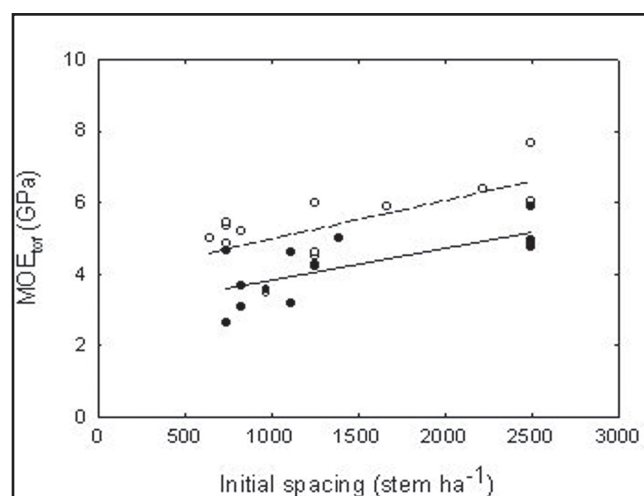


Figure 1 - Relationship between initial spacing and MOE estimated from the speed of sound in standing trees at age 10 for the two most extreme clones (open and closed circles) at Dalethorpe in Canterbury (From Lasserre *et al.* 2004). The velocity of sound in wood is an indicator of stiffness (Harris *et al.* 2003).

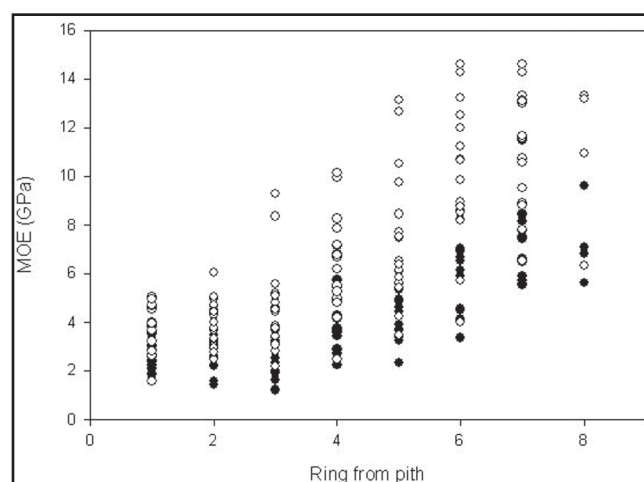


Figure 2 - MOE estimated from Silviscan x-ray diffractometry versus ring number at breast height for clones at the School of Forestry's experiment at Dalethorpe, Canterbury. Open circles are for clones established at 2500 stems/ha and closed circles are for clones established at 833 stems/ha.

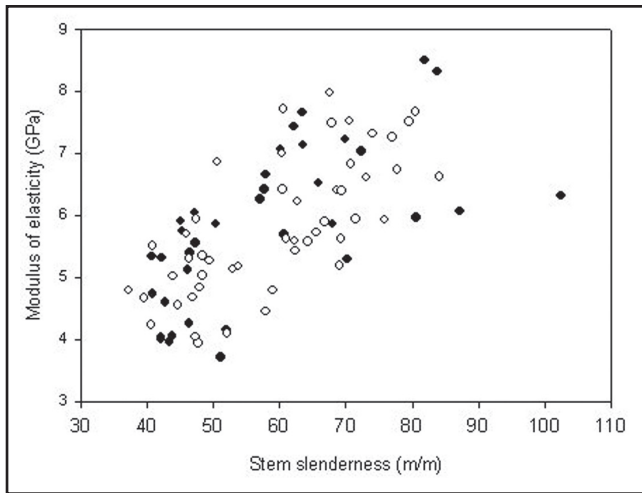


Figure 3 - MOE estimated from acoustic time of flight velocity versus stem slenderness for radiata pine clones at two sites (open and closed circles) planted two years apart but in which trees had almost identical average dimensions at ages 8 and 10 despite differences in age (from Lasserre *et al.* 2008).

near the centre of a log, there is scant evidence that low ring numbers actually cause inferior wood properties, and it is difficult to conceive of a process or an evolutionary rationale that would make ring number a causal factor. Moreover, some evidence directly conflicts with this theory. For instance, Mason & Dzierzon (2007) found other factors were more highly correlated with MFA at a ring level than was ring number.

Radial growth rate has long been regarded in the marketplace as an indicator of wood quality, with merchants often demanding more rings per cm, but evidence supporting this as a causal factor is equivocal. One theory is that higher rates of radial growth are associated with higher rates of anticlinal (lengthwise) cell division, a process that leads to shorter tracheids, and shorter tracheids tend often to have higher MFA (Hirakawa & Fujisawa 1995). Furthermore, Mason & Dzierzon (2007) found that ring width was more consistently related to ring-level wood properties than any other factor in a survey of wood properties within trees on 17 diverse sites in New Zealand. However, if ring width was the sole causal factor, then regions with high radial growth rates such as Nelson and Northland should grow inferior wood (but these regions grow some of our stiffest and most stable corewood), and Lasserre *et al.* (2007) found that trees of identical size but at different ages on two contrasting sites in Canterbury had identical wood properties (Figure 3). We cannot completely rule out ring width as a causal agent, but it may be significant that for any given amount of basal area growth on a tree, rings closer to the pith of a log have to be larger, and we may observe correlations between ring width and wood properties rather than a causal connection. One example of the inconsistency with the radial growth rate theory was found at Dunsandel, south of Christchurch (Figure 4) (Mason 2006, Renard 2008), where a grass competition treatment produced trees with very low radial growth rates but also the slowest acoustic velocity,



Figure 4 - Weed control: 1 m diameter weed-free spots (left), no grass control (centre) and no grass competition in the School of Forestry's clone by competition experiment at Dunsandel. The slowest growing treatment (centre) contained the least stiff stems on average.

compared to more rapidly growing grass-free treatments. A key influence of high stocking is to reduce radial growth rate, however, and so if radial growth rate was a causal factor then this might explain why higher stockings generally lead to stiffer wood in the corewood zone.

Stem slenderness, expressed as height divided by diameter at breast height, has been correlated with stiffness measured at the bases of stems (Figure 3) (Watt *et al.* 2006, Mason 2006, Lasserre *et al.* 2008). The theory, explained by Watt *et al.* (2006), is that tall, slender stems need to be stiffer than short, squat ones in order to avoid buckling. Stems buckle when a uniform vertical load per unit area reaches a critical value and the stem deforms. This theory is corroborated at a regional level; radiata pine grown in Southland, where height growth is slow but basal area growth is high, tends to be of low stiffness compared to other regions such as the Central North Island where trees are more slender. In addition, trees are more slender at higher stockings. Nevertheless, this theory does not explain longitudinal variation in velocity among radiata pines (Figure 5) (Waghorn *et al.* 2007). In addition, clones apparently cannot be correctly assessed for stiffness by measuring their slenderness (Mason unpub. data).

In some parts of the United States corewood is known as "crown" wood, perhaps reflecting the theory of Larson (1962) that proximity to canopy, a source of auxins that influence cambial processes, should promote the growth of wood with corewood properties. Mason (2006) assessed the influence of green pruning on stiffness, finding that after influences of genotype and tree slenderness were accounted for, height of pruning was correlated with velocity measured around breast height in radiata pine trees in Canterbury (Figure 7). While this could corroborate Larson's theory, it may also reflect higher water stress endured in Canterbury by trees with greater amounts of residual canopy. Trees at higher stockings tend to have shorter canopies, and so Larson's theory could be employed to explain the influence of stocking on stiffness.

Another theory to explain patterns of corewood

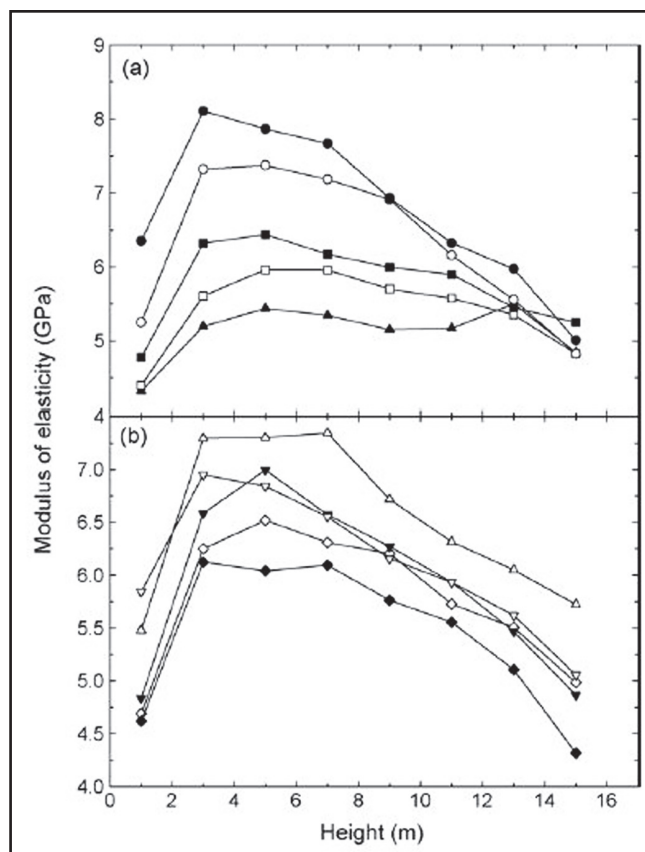


Figure 5 - Relationship between MOE and (a) longitudinal height for trees growing at initial stand densities of 2551 stems ha^{-1} (filled circles), 1457 stems ha^{-1} (open circles), 635 stems ha^{-1} (filled squares), 364 stems ha^{-1} (open squares), and 275 stems ha^{-1} (filled upfacing triangles) and (b) longitudinal height for the 870 breed (open upfacing triangles), three-year-old cuttings (open downfacing triangles), 268 breed (filled downfacing triangles), one-year-old cuttings (open diamonds) and 850 breed (filled diamonds) (from Waghorn et al. 2007).

formation in trees is that the function of corewood is to help a tree avoid cavitation, the entry of air into the water column of a plant. Cavitation can result in the death of the leader of a tree, and so there is good reason for mechanisms to evolve to avoid it. Corewood was found to be less likely to cavitate than outerwood, but was much less efficient at conducting sap than outerwood (Domec & Gartner 2002). As the most negative water potentials occur near the tops of trees, this would explain why corewood grows at the tops of trees. Domec and Gartner (2002) compared mechanical safety (the slenderness hypothesis) with hydraulic safety (avoidance of cavitation) in wood samples taken from several locations within the stems of Douglas fir trees of several ages, finding that the trees were at higher risk of cavitation than of mechanical stem failure (Figure 6). They commented that if tree stems comprised entirely outerwood then catastrophic cavitation would be very common. If we make the assumption that risk of cavitation due to drought stress can promote corewood formation, then this might explain results found at Dunsandel (Mason 2006, Renard

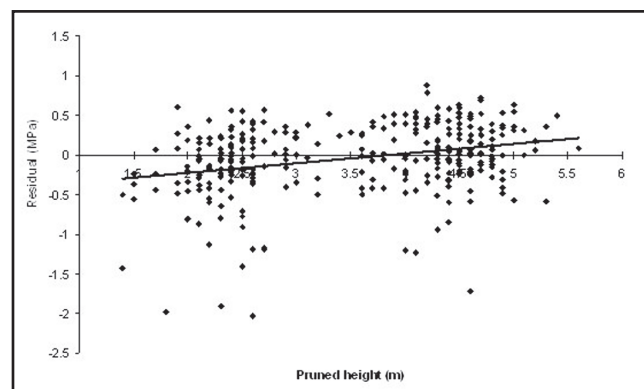


Figure 7 - Residuals of a model of stiffness that includes block and clone plotted against pruned height, for only the pasture control treatments at Dunsandel (From Mason 2006)

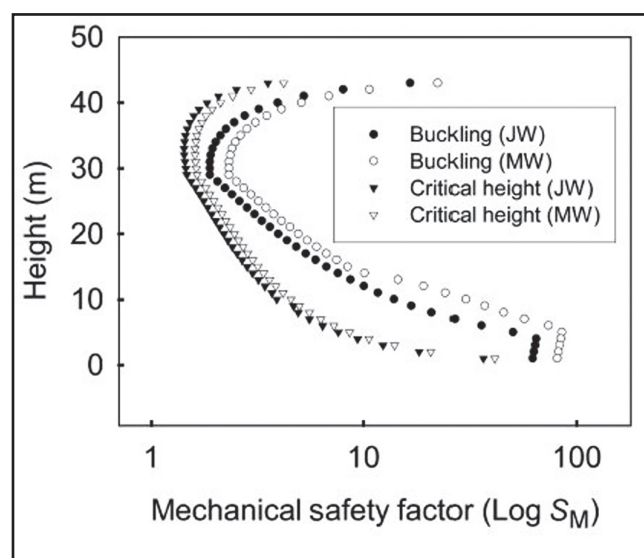
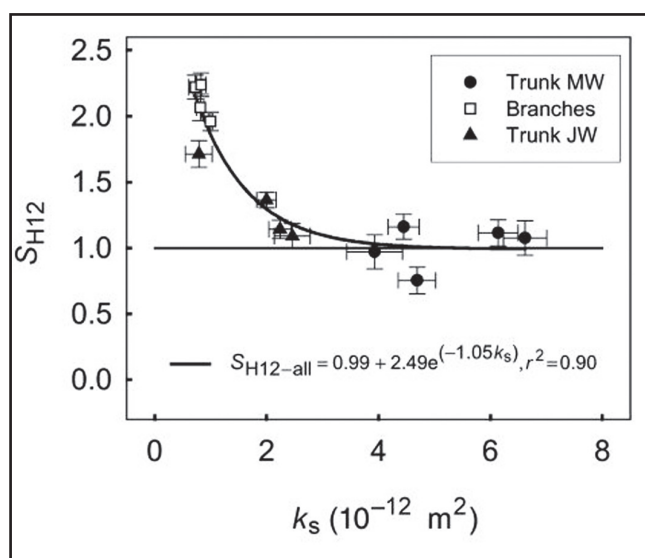


Figure 6 - Hydraulic safety factor (left) versus mechanical safety factor (right) for Douglas fir trees in Oregon, USA, demonstrating that trees were more likely to cavitate than to fail mechanically, thereby favouring the theory of a hydraulic function of corewood/outerwood formation over the slenderness hypothesis (from Domec & Gartner 2002).

Table 1. Mean dynamic modulus of elasticity of trees located at the stand edge, in the one tree height (1H) zone, and in the forest interior (from Bascunan *et al.* 2006).

Stand age (years)	Side of stand	MOE (GPa)			MOE of stand edge trees (GPa)	
		Stand edge	1H zone	Forest interior	SE side (leeward)	NW side (windward)
11	Leeward	4.7	5.2	6.0	4.81*	4.67
	Windward	5.5	5.7	6.1	5.82***	5.18
17	Leeward	8.0	8.4	9.0	8.08 ^{ns}	7.84
	Windward	8.4	8.7	9.1	9.12***	7.71
17 (Whindwhistle)	Leeward	7.3	8.1	9.1	7.49 ^{ns}	7.10
	Windward	7.5	8.2	9.1	7.80	7.11
25	Leeward	10.8	12.1	12.5	10.78 ^{ns}	11.34
	Windward	11.0	10.7	11.5	11.76***	10.30

Significance (as compared to trees at the windward edge) is indicated by the following: *** = $p < 0.001$, ** = $p < 0.01$, * = $p < 0.05$, ns = $p > 0.05$.

2008) and also the fact that wood properties tend to be poor in Canterbury, where drought stress is common. The hydraulic safety hypothesis does not explain the impacts of stocking on corewood formation, however.

Tree sway has also been suggested as a causal mechanism related to stiffness. The theory is that trees subject to high wind loadings need to be less stiff in order to avoid stem failure. Grabianowski *et al.* (2004) and Bascunan *et al.* (2006) both found that trees within several metres of stand edges in Canterbury had lower acoustic velocities than those in the interiors of stands (Table 1). Higher stockings reduce wind loadings per tree, and so this theory might also explain the influence of stocking on corewood development.

Recent results in Canterbury (Sialumba unpub. data) have suggested that fertility might reduce log velocity after apparent influences of slenderness and drought stress have been accounted for, and there are currently no process-level theories that explain this observation.

Influences of regional temperature on wood quality might be explained by differences in climatic variation within years, and models of wood formation therefore need to be linked to stand models that represent this within-year variation.

With so many competing theories and some apparently conflicting results, models of wood properties supplied to managers will be unreliable unless we implement studies directed towards understanding the processes that influence formation of wood that is poor in stiffness and stability. Such understanding will lead to advances in forest production that we cannot yet envisage, but there is also a sound, practical reason why such research should be undertaken. Suppose we provided forest managers with the ring-level models of wood property development created by Mason & Dzierzon (2007) and linked them to growth and yield models so that managers could obtain estimates of the impacts of silvicultural operations on within stem gradients in corewood properties. The models often included ring width as an independent variable, because ring width was most consistently correlated with ring-level wood properties. Such a modeling system would predict that at Dunsandel the best wood should be produced in trees subject to the most weed competition because they grew slowly. Measurements of wood properties at Dunsandel showed that this prediction was entirely wrong; that slower radial growth due to drought stress apparently led to inferior wood properties (Mason 2006, Renard 2008). Understanding processes will lead to more reliable models for forest managers.

Recent experiments

Two experiments have been established just south of Rolleston, Canterbury on land owned by the Selwyn Plantation Board Ltd. (Figure 8). They are designed to examine various hypotheses about formation of wood with high MFA and high gradients in MFA, and have been designed to meet the following research objectives:

1. Test the hypothesis that wind sway is a causal factor influencing MFA distribution that at least partly explains the stocking effect.
2. Test the hypothesis that drought stress produces higher MFA.
3. Test the hypothesis that trees with lower MFA are more likely to cavitate when subjected to drought stress.
4. Test the hypothesis that radial growth rate is a causal factor that explains the influence of stocking on MFA and MFA gradients in stems.
5. Assess the influence of fertility on MFA.
6. Evaluate interactions between genotype and environmental factors as agents affecting patterns of MFA at a ring level.



Figure 8 - An aerial view of the experiments in December 2007

7. Provide a foundation for the development of robust models of ring level wood properties for radiata pine that include ecophysiology ('hybrid' models).

Experiment one occupies most of the 7.5 ha site, and is a randomized complete block with a split-split plot arrangement of factors within the blocks (Figure 2). It was planted in 2005.

Factors in the experiment comprise:

1. Stocking (625, 1250 and 2500 stems/ha)
2. Weed competition (yes/no)
3. Fertilisation (NPKS + trace elements, yes/no)
4. 5 clones with pre-selected wood properties
 - a. Low microfibril angle, high basic density
 - b. Low microfibril angle, low basic density
 - c. High microfibril angle, high basic density
 - d. High microfibril angle, low basic density
 - e. Extremely high microfibril angle, extremely low density
5. Wind sway (yes/no) for clones a and d (Figure 3)



Figure 9 - One tree in each pair has been prevented from swaying in the wind for clone a (left) and b (right)

The experiment is set out in 4 randomised complete blocks, and includes 7200 trees, of which 1360 will be measured. In addition, 384 trees have been restrained from swaying (Figure 9).

Experiment two is a Nelder spacing experiment planted with radiata pine cuttings and *E. nitens* (Figure 10). The pines were planted in 2007 and Eucalypts will be planted in 2008.



Figure 10 - Planted lines in the Nelder experiment

Factors in the second experiment comprise:

1. Stocking (208-40000 stems/ha)
2. Physiological age of pine parents (1 and 5 years)
3. Species (*Pinus radiata* and *Eucalyptus nitens*)
4. Irrigation (yes/no)

Once we understand the reasons why corewood and outerwood differ, we will be able to make robust models that allow managers to simulate patterns of wood development within trees on a range of sites with contrasting silvicultural regimes. These models are likely to represent wood properties at a ring level so that gradients, and likely impacts of gradients in shrinkage on stability of sawn timber, can be estimated. Ring-level properties might be estimated by combining hybrid physiological models of growth and yield with taper equations to represent cambial growth throughout a tree. Growth and yield models combined with taper equations have already been used in the Standpak

modelling system to estimate “juvenile wood” proportions, assuming that juvenile wood is always the first 10 rings from the pith of a tree (West 1997), a representation that we now know to be a broad generalization that doesn’t reflect impacts of silvicultural decisions on wood properties in sufficient detail. Silvicultural stand models with representations of ring level wood properties that reflect well understood influences on these properties should lead to more profitable structural regimes for the forestry sector.

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