Selection and breeding for wood quality A new approach

Luis Apiolaza, Shakti Chauhan, Michael Hayes, Ryogo Nakada, Monika Sharma and John Walker

Early selection by age two for wood quality attributes is possible provided the trees are tilted to separate normal wood from reaction wood. Experimental results for *Pinus radiata* and *Eucalyptus globulus* and *E. regnans* are presented in this paper.

Introduction

Most plantations in temperate regions are softwoods which are generally harvested when aged between 25 and 60 years. The age at harvest is influenced by tree growth, with average productivity varying from 10 cubic metres per hectare per year in high latitudes to 25 cubic metres per hectare per year in warmer climates.

Fast growth and early harvesting have brought with them unforseen problems regarding wood quality of softwoods, as exemplified by Macdonald and Hubert (2002). They noted that low-value pallets, packaging and fencing accounts for two-thirds of all production from United Kingdom sitka spruce. Huang et al (2003) have noted similar poor performance in other species and advocated the use of acoustics to screen for candidate trees with superior wood properties.

There are three reasons for this phenomenon of poor wood quality –

- The large natural variability in the unimproved population
- The steep wood quality gradient immediately adjacent to the pith improving out towards the bark
- The economic drive towards short rotations resulting in a large proportion of low quality wood from the first 10 growth rings.

By convention for pine, the first 10 rings are characterised as corewood with the wood beyond that described as outerwood. Under this convention Cown (1992) noted that half the merchantable wood from a 25-year radiata pine stand in New Zealand is corewood.

Density and stiffness

For over 50 years breeders have focused on selecting straight, vigorous and healthy trees marketed as growth and form (GF), which has resulted in trees being harvested earlier. A recent Radiata Pine Breeding Company estimate puts the percentage gain in recoverable volume at 25 per cent in deploying GF23 as opposed to GF2, with a further 10 per cent being attainable by 2017 (FOA, 2012). Unfortunately little attention was paid to wood quality, except to seek a modest increase in wood density.

Density was chosen because it was easy to measure and was an index of quality to which all end-users could relate (Bamber & Burley 1983; Zobel & van Buijtenen 1989). The sawmiller was persuaded that denser wood was stiffer and stronger while the pulp mill operator obtained more pulp per cubic metre of wood. However, if mass was all that is involved then, as Ashby and Jones (1986) point out, the effect of density should be linear and along-the-grain wood properties should increase by 50 per cent. This mirrors the same increase in density from pith to bark, for example, from 330 to 500 kilograms per cubic metre.

However, the principal controlling agent of wood quality is the winding angle of the cellulose microfibrils within the plant cell walls (MFA), which was first measured by X-ray diffraction in the 1930s. The gradual decrease in MFA with distance from the pith had been well characterised by the 1960s (Preston 1974).

Cave (1968) measured a corresponding four-fold increase in axial cell wall stiffness as the microfibril angle decreased from 40°, typical in a seedling, to 10° found in the outerwood of 30-year-old radiata pine. This far exceeds any contribution by density that usually increases by around 50 per cent in going from pith to cambium in a 25-year-old pine.

For hardwoods, there is no corewood problem. Instead there is a suite of unrelated problems such as brittleheart, growth stress, collapse, slow drying, and for high-valued woods early heartwood formation, colour and durability.

Mass screening of seedlings and trees for wood quality only became practical in the last 10 years through the use of much faster X-ray diffractometers and cheap surrogate technologies such as acoustics (Bucur 1995, Lindström et al 2002) that track changes in MFA indirectly.

In this article we make the case for very early selections before age two for wood quality using examples from several sets of data. In turn, this allows for the selection and deployment of genotypes which eliminate the corewood problem for many softwoods. In effect, this is treating a slow-growing plantation forest like an agricultural crop.

Experiments and results

SilviScan data of *P. radiata* and *E. globulus*

In two separate studies, 10 millimetre increment cores were taken from 480 trees of *P. radiata* in New Zealand, part of the Radiata Pine Breeding Company research programme (Dungey et al 2006). They were also

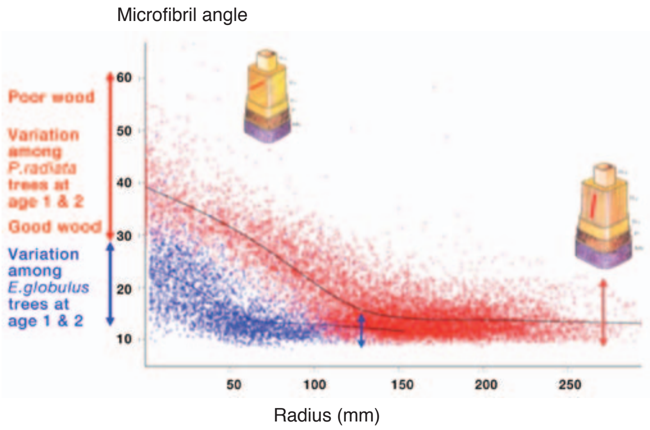

Figure 1: Very early selection will significantly improve wood quality as the microfibril angle is very variable

taken from 188 trees of *Eucalyptus globulus* in Tasmania, part of the Sustainable Production Forestry research programme (Apiolaza et al 2005). X-ray diffraction and other measurements were undertaken by SilviScan at CSIRO in Melbourne.

The trees were selected from one trial in each of the two genetic improvement programmes at age 30 years (*P. radiata*) and 15 years (*E. globulus*). The data is superimposed on one another as shown in Figure 1 above.

Amberley field trials of three-year-old *P. radiata* families

In September 2007, a total of 49 families each with 48 replicates were planted on flat land at Amberley, Canterbury. They were divided into four adjacent sections, with 12 replicates each. Trees were tilted after 12 months to induce compression wood on the underside of the stem and opposite wood on the upper side during subsequent growth. The tested material was genetically improved in relation to growth, form and disease resistance but there is no reason to believe that it is noticeably different to the original 'wild' unimproved species with regard to intrinsic wood quality.

Here we summarise the results of destructive sampling of two sections in July 2010. A 200-millimetre bolt was taken at the base of each stem. This was then ripped and faced on three sides to yield two 'with-cambium' samples only 100 millimetres along the grain, one of compression wood and one of opposite wood. Measurements included basic density, longitudinal and volumetric shrinkage and dry modulus of elasticity – all oven dried at 35° C to five per cent moisture content to minimise thermal degradation of hemicelluloses as some specimens were needed for chemical analysis.

The data has been analysed by families for phenotypic and genetic variation (Sharma, unpublished). Figure 2 compares mean longitudinal shrinkage and dry modulus of elasticity of all 49 families and longitudinal shrinkage and dry modulus of elasticity of individuals from the best and worst families.

Procedures were applied which remove the

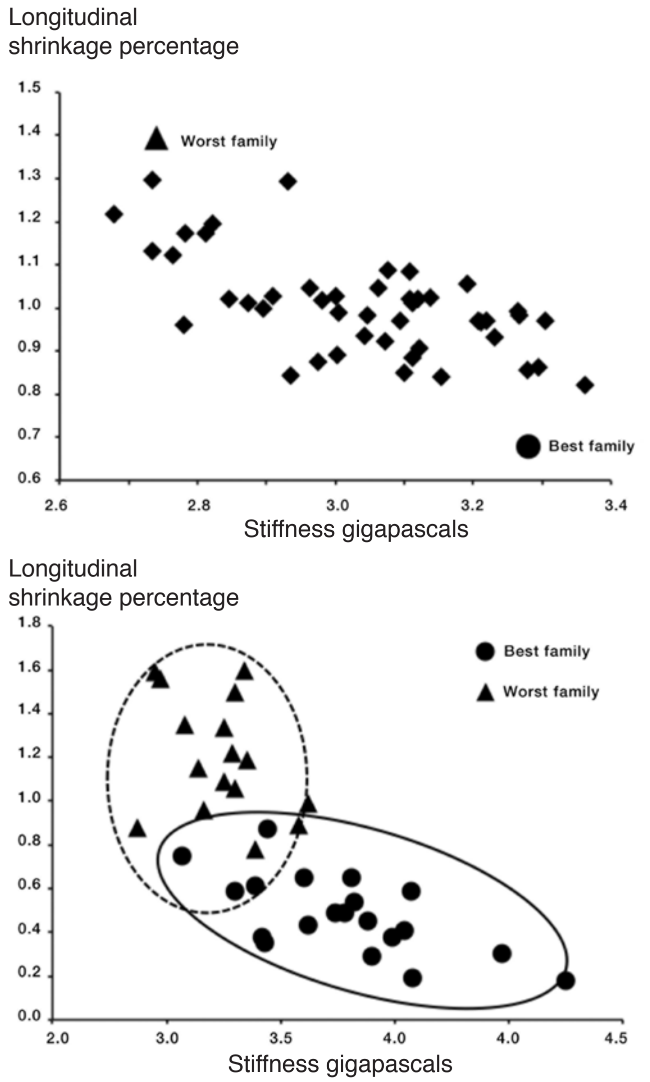

Figure 2a and 2b: Phenotypic variation (a) mean value for each family and (b) for individuals within the best and worst families. after oven drying at only 35°C to a mean moisture content of about five per cent.

environmental effects in such a trial and so highlight the genetic component. Figure 3 compares basic density, longitudinal shrinkage and modulus of elasticity of opposite wood for the 64 parents involved in crosses within the Amberley trial.

Compression wood is significantly denser, displays greater longitudinal but reduced volumetric shrinkage than opposite wood and it has broadly comparable stiffness as shown in Table 1. Compression wood stiffness increases linearly with its basic density. Compression wood data is not discussed further, as there is no intention to select for compression wood properties.

Harewood trial of 10-month-old *E. regnans*

In September 2009, a total of 100 *E. regnans* of unknown parentage were planted in 100 litre bags of fertilised potting mix and trickle irrigated. The trees were tilted after three months and harvested in August 2010. Destructive sampling and testing procedures were the same at those for *P. radiata* at Amberley. In

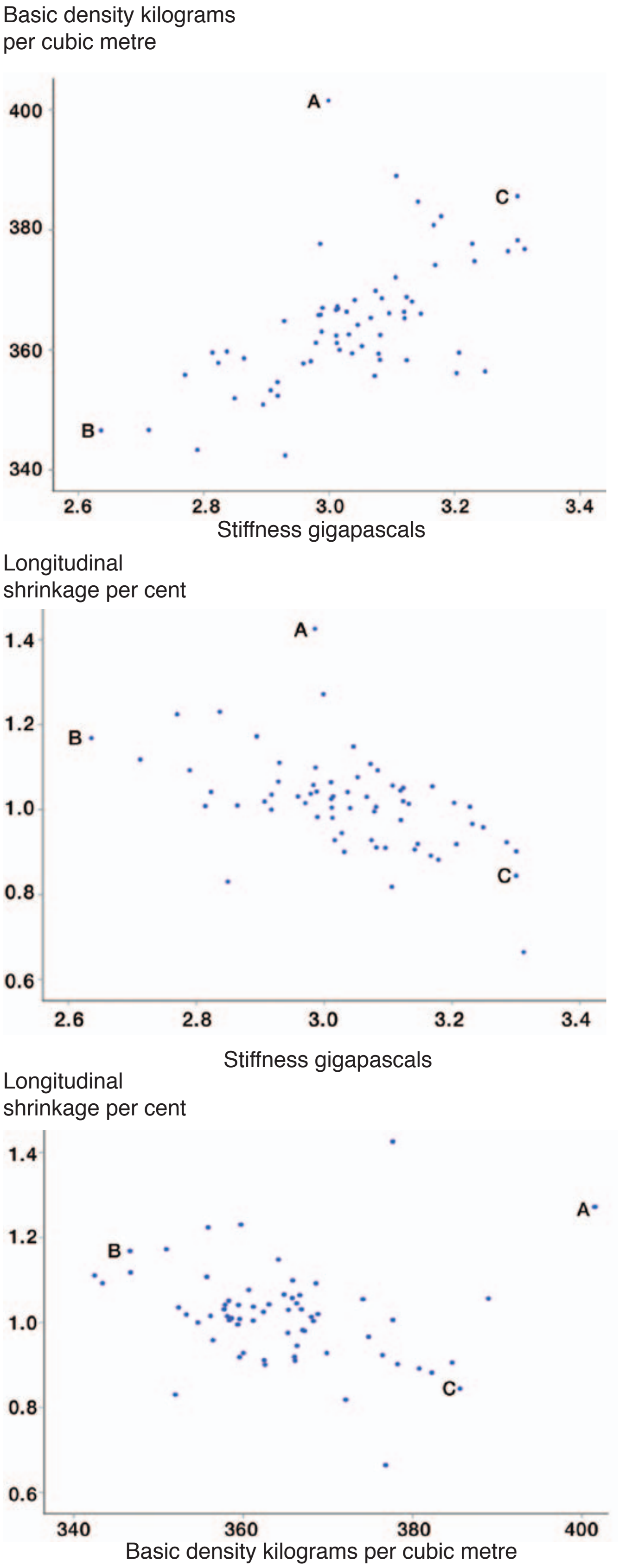

Figure 3: The genetic contribution of individual parents can be extracted from the Amberley study. Parent A displays the highest basic density but has only average stiffness and high longitudinal shrinkage. Parent B should be rejected on all counts. Parent C has good density, stiffness and low longitudinal shrinkage and is an obvious candidate for tree breeding.

Table 1. Wood properties in opposite and compression wood

	Compression wood		Opposite wood	
	Mean	CV per cent	Mean	CV per cent
Basic density kg per cubic metre	544	10.4	363	7.1
Dry dynamic modulus of elasticity GPa	3.4	10.5	2.99	12.4
Longitudinal shrinkage per cent	3.34	19.3	1.02	29.2
Volumetric shrinkage per cent	7.99	12.7	12.83	17.7

addition, longitudinal growth strains in whole stem were determined by the log-splitting method described by Chauhan and Entwistle (2010). Table 2 summarises the properties of the tension wood and opposite wood.

Table 2. Wood properties in opposite and tension wood of *E. regnans* and longitudinal growth strain in the green stem wood, after Chauhan & Walker 2011

	Opposite wood		Tension wood	
	Mean	CV per cent	Mean	CV per cent
Green moisture content per cent	182	8.28	113	7.76
Green density kg per cubic metre	1088	1.78	1154	1.76
Basic density kg per cubic metre	388	6.58	542	5.13
Green acoustic velocity km per second	1.72	10.40	3.13	6.68
Dynamic modulus of elasticity GPa	3.25	21.25	11.36	13.52
Longitudinal shrinkage per cent	0.76	28.86	0.78	24.28
Volumetric shrinkage per cent	18.13	8.19	37.28	19.63
	Whole stem wood			
	Mean	CV per cent	Min	Max
Longitudinal growth strain (με)	1412	38.41	708	2319

Discussion

Regarding the SilviScan data, there are three significant observations for tree breeders –

- For both species there is a large range in values among individual trees of the same age, or distance from the pith and sufficient variability is a main criterion for tree breeding
- There is a general trend of lower microfibril angle, and so of improved wood properties with age, or distance from the pith, for individual trees.
- The data for the hardwood *E. globulus* lies below the data for the softwood *P. radiata*. This has

been observed by others, but they reported on small sample numbers. For example, *P. radiata* (Donaldson 1992), *P. taeda* (Ying et al 1994), *E. nitens* (Evans et al 2000) and poplar clones (Fang et al 2006).

Following from the third observation, if foresters wish to grow trees for solid wood on short rotations, such as under 15 years, then this can best be done using hardwoods. Figure 1 implies that the corewood in the best of softwoods is only as good as wood of the same age in the worst of the hardwoods. Both will have comparable MFAs.

We can attribute the divergence between softwoods and hardwoods to the different strategies against environmental disturbance. Softwoods generate compression wood, with MFAs of 40º to 50º, wherever the stem leans in response to snow, wind or phytotropism, whereas hardwoods develop tension wood, with MFAs of 5º to 10º.

Early selection for wood quality in softwoods

One general remark is in order. All softwood timber containing wood with a microfibril angle of 35° or more and stiffness of 7 GPa or less is undesirable, for structural purposes with inadequate stiffness and strength and appearance purposes being unstable and liable to distort (Huang et al 2003). The price differential between low-grade material which is found predominately in corewood and utilitarian grades for framing and dressing is greater than that between utilitarian grades and premium grades for engineering and finishing.

Australia grows pine on longer rotations so MGP12 is their premium grade and MGP10 their utility grade. In New Zealand MGP10 is the premium grade and MGP8 our utility grade. Moore (2012) makes the crucial observation that our timber is inherently MGP8, such that segregating two grades to produce some MGP10 results in disproportionately less MGP8 and so more low-value low-grade wood.

As a result, more is to be gained by improving stiffness in corewood than improving density in outerwood. Tree breeders should not delay selection, nor should they be too concerned with age-age correlations.

Table 3. Approximate prices in Australian dollars for structural timber for premium, framing and utility grades

Product		Price per cubic metre	Premium - discount
Premium grade	MGP12	$475	$45 – 11 per cent
Utility grade	MGP10	$430	
Low-grade	Pallets and boxes	$220	$210 – 49 per cent

Tree breeders, with experience selecting for tree form and volume, prefer to make selections for such attributes at between a quarter and a third of the rotation age, around eight to 10 years. They delay selection in order to increase the accuracy of their prediction for merchantable volume at the end of the rotation, which reflects directly on the value of sawlogs and pulpwood. However, for wood quality it is desirable to make selections by age two. For softwoods the MFA ranges between 50° and 30° in the first two rings from the pith.

This, in turn, would account for a two-fold or more range in axial stiffness (Cave 1968) resulting in an air-dry stiffness values of two to six GPa for corewood assuming a basic density of 320-360 kilograms per cubic metre. Rapid screening by age two using acoustics would eliminate troublesome material with MFAs of 35° or more (Huang et al 2003). It should be possible to make a one-off selection of a new deployment population with an initial MFA of 30° by screening within the current breeding population of fast growth, good form trees.

The MFA data for the 480 increment cores in the Radiata Pine Breeding Company data shows a universal trend with distance from the pith and with increasing ring number, namely that the MFA declines with age. The decline may be very gradual or abrupt. Eventually, at some distance from the pith, the MFAs of all trees fall to around 10º to 20°. On average, the trees having low initial MFAs arrive there sooner and on average have lower MFAs whatever the distance from the pith or whatever the ring number. In other words, if you select a population having low initial MFAs, that advantage will be retained throughout the life of those trees.

Figure 2a plots the average longitudinal stiffness and dry modulus of elasticity for the opposite wood found in the all tree families at the Amberley trial. Figure 2(b) plots the individual tree data for all trees in the best and worst families. Stiffness values may appear absurdly low, but very young pines have high MFAs and form little latewood.

Figure 3 displays the derived basic density, shrinkage and dry modulus of elasticity for the 64 seed orchard parents involved in the various crosses that generated the 49 families – a parent could be mother or father. Three examples are noted.

Under traditional breeding, Parent A would be highly desired as it displays the highest basic density (ρ). Unfortunately it also had one of the highest longitudinal shrinkages, so is likely to warp on drying, and only an average modulus of elasticity (E). Presenting the data in terms of specific or relative stiffness E/ρ, a practice used to take account of the performance by weight of steel and aluminium in aircraft or where comparing two different polymer foams, means that the comparison between parents is now focused on the stiffness of the cell wall itself (Ashby and Jones 1986).

Strictly cell wall stiffness, $E_{cell\ wall}$, is $E_{wood.}\ \rho_{cell\ wall}/\rho_{wood}$, where $\rho_{cell\ wall}$ is about 1500 kg per cubic metre. Now Parent A is the worst performing of all parents with the lowest E/ρ. This implies a very high microfibril angle, and explains the excessive longitudinal shrinkage.

Historically, such a high-density parent would have been highly prized within a broad population of high-density parents.

Parent B is an obvious candidate for elimination displaying the lowest dry modulus of elasticity, a high longitudinal shrinkage and a low basic density. Its lowest stiffness is matched to a degree by the low basic density, such that E/ρ is actually comparable to that for Parent A. Finally, Parent C is an ideal candidate for selection, with a high stiffness, a high basic density within the top 10 per cent of all parents and an exceptionally low longitudinal shrinkage.

A new population for deployment with initial MFAs around 30° would eliminate the corewood problem. That this can be done by very early selection before age two is a transformational opportunity. A focus on MFA, or in practice on specific or relative stiffness E/ρ for softwoods, allows breeders to retain one of their desirable characteristics in relation to most hardwoods, which is their low density.

Density is a measure of the quantity of matter while shrinkage, warp, acoustic velocity and specific stiffness are measures of the quality of matter. There are many end uses which prefer light, moderately stiff softwoods to heavy, super-strong hardwoods.

The high density and modulus of elasticity of compression compared to opposite wood as in table 1 explain why selection by age two should be made on leaning stems in which compression wood is isolated to the underside and pure opposite wood forms on the upper side of the leaning stem. In a straight tree the two tissue types are intermixed and measured wood properties are a hybrid value and there lies the confusion.

A high basic density in a straight stem can arise from the presence of some compression wood which is undesirable rather than from high-density opposite/normal wood tissue which is desirable. In the worst case, high density and stiffness might be entirely due to an excess of compression wood. Straight trees are the exception. For example –

- When grown in the nursery under intense competition the stems are rarely straight
- When planted in the field or trial the seedlings are rarely planted vertically
- Wind, snow-loading or phytotropism can tilt the growing stem.

The reticence of tree breeders to select for wood quality at an early age is understandable. Tilting the stem to separate opposite wood from compression wood obviates this difficulty.

Any shortening rotation age of radiata pine comes up against the limitations of an increasing volume of low quality corewood. Today we have tools and technologies which permit rapid assessment of main properties by age two. We would not delay selection beyond that age as handling physically larger trees slows the operation and does not improve the quality of the data.

Therefore there is the opportunity to select early and so greatly ameliorate the corewood problem. The potential intrinsic qualities of an elite breed of radiata pine – less contrast between earlywood and latewood, a light colour, modest stiffness and excellent stability– are those of an excellent utilitarian timber, with little waste but little which is truly excellent (Moore, 2012).

Hardwoods for high-quality timber on a short rotation

Table 2 summarises the properties of one-year-old *E. regnans* grown in irrigated 100 litre planter bags at Harewood, Christchurch. Two points need emphasising. First, there are significant variations in wood properties which will admit significant tree improvement. Second, this table summarises individual values for tension wood and opposite wood properties.

Hardwoods do not have a corewood problem although they may display growth stress (Wilcox 1992), which is noticeable when opening the log on the headrig. They can display brittleheart. Wood quality selection in hardwoods centres on a suite of problems which differ from those for softwoods, such as collapse, growth stresses and tension wood, and for certain hardwoods it would be desirable to achieve early heartwood formation and lower basic density of under 600 kilograms per cubic metre.

With regard to MFA there is limited evidence that suggests that you should be selecting for seedlings with a modest MFA of 18° to 25° because high growth stresses in young trees are associated with low MFAs (Okuyama et al 1994). That the MFAs of hardwoods lie below those of softwoods in the early years implies that, where foresters plan to produce premium sawn timber from short-rotation plantations, they should focus on hardwoods such as eucalypt and poplar.

With a leaning stem, desired values for wood properties such as density, moderate shrinkage and stiffness are apparent in the first year's wood such that selection of eucalypts at age one has been demonstrated (Chauhan & Walker 2011). In a straight stem, tension and opposite wood co-mingle so high density and high stiffness might be as much due to more tension wood in the cross-section as to superior properties of the opposite wood. More critically for eucalypts, early selection should target low growth stress and low volumetric shrinkage.

At the same time, market analysis demonstrates that there are opportunities for short-rotation hardwoods. This is especially for highly-coloured, naturally-durable eucalypts yielding both ground-contact poles and sawlogs which contrast with utilitarian products from many fast-grown softwoods (Millen 2009).

Conclusion

Very early selection for wood quality marks a profound break with traditional tree-breeding strategies. We redefine the quality problem as improving corewood, arbitrarily defined as the first 10 growth rings. This permits us to ignore age-age correlations with harvest age and focus on very early performance.

In addition we have avoided dealing with unpredictable quantity and distribution of reaction wood by leaning the trees and separately analysing the properties of normal and reaction wood. This approach is applicable to both hardwoods and softwoods, although the selection targets would be different. Smaller MFA will redress the corewood problem in softwoods and reduced growth stress and volumetric shrinkage or collapse in some hardwoods.

Acknowledgements

This work was funded by the Foundation for Research Science and Technology and by our industry partners in that programme. We acknowledge data from the Radiata Pine Breeding Company and the CRC for Sustainable Production Forestry in developing Figure 1.

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Luis Apiolaza, Monika Sharma and John Walker are at the School of Forestry, University of Canterbury. Shakti Chauhan is based at the Institute of Wood Science and Technology, Bangalore, India. Michael Hayes is at the Department of Electrical and Computer Engineering, University of Canterbury and Ryogo Nakada at the Forest Tree Breeding Center, Ibaraki, Japan.