

Can use of clones improve wood quality?

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Improving Wood

Radiata pine, while by far the most common plantation conifer grown in the southern hemisphere, has certain limitations in terms of product performance in some regions. This is particularly the case for products requiring high stiffness (Ivkovic *et al.* 2007), but is equally applicable to appearance products (Beauregard *et al.*, 1999). This has major implications for growing export-oriented plantations.

Climate and soil have a strong and unavoidable influence on both crop growth rates and their average wood properties (Fig. 1), and often make structural products challenging to produce commercially. High natural genetic variability is expressed in mature radiata pine on all sites.

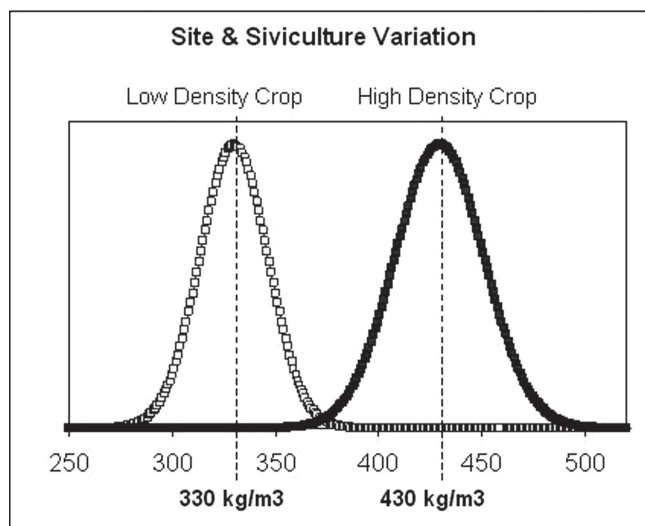


Figure 1. Large environmental influence on stem-average wood density of mature radiata pine in New Zealand (Source: D. Cown) CV 5%.

Wood density has been the most intensively studied wood property within New Zealand and elsewhere because of its measurability, and its positive financial impact on material properties as strength (MOR), stiffness (MOE), hardness, machinability and nail withdrawal (Cown, 1974a) and pulp and paper properties.

Consequently many studies examined the genetics of wood density of radiata pine (Bannister & Vine, 1981; Burdon & Bannister, 1973; Burdon & Low, 1992; Burdon *et al.*, 1992; Donaldson *et al.*, 1995; Shelbourne *et al.*, 1997; Matheson *et al.*, 1997; Cown & Ball, 2001). Density is a highly heritable trait, averaging 63% (from 238 estimates) versus 23% for DBH growth (from 228 estimates) (Wu *et al.* 2007). Density's high heritability has been known for over four decades (e.g. Dadswell *et al.* 1961; Burdon and Harris

1973; Burdon, 1992). Given reasonable selection pressure, family breeders can achieve mild density gains of about 10 kg/m³, and perhaps to 20 kg/m³, a level similar to observed density losses in seed orchard seedlots bred for exceptionally fast growth (S. Kumar, 2007 *pers. comm.*). The New Zealand Radiata Pine Breeding Company (RPBC) lists 20 kg/m³ gain as the density improvement target of their current FRST funding (years 2005-2010).

Long-term coniferous breeding programmes have all used volume growth and stem form as primary selection criteria. They have typically treated wood quality traits such as wood density or grain spirality as secondary or tertiary selection traits (Ridoutt, *et al.*, 1998; Gapare *et al.*, 2006) despite the high heritabilities of most wood properties in part because high density is adversely correlated to fast growth (e.g. Lindström, 1996; Kumar, 2004; Dungey 2006). Fast growth resulting from silvicultural practices like aggressive stand thinning has also led to reduction in density and stiffness (Cown, 1973; Cown and McConchie, 1981).

Wood quality studies have consistently shown mild adverse growth-quality relationships (Cown, 1992; Cown, 2006; Sorensson, 2007). Breeding for high wood density, while attractive in concept, has been avoided due to perceived unacceptable growth losses.

According to both early and recent theorists (e.g. Libby and Rauter, 1984; Carson, 1986; Kumar, 2006), clonal pines should offer growers and processors a number of significant advantages over traditional seed-orchard stock form progeny-tested parents:

1. Shorter timelag to bring new genetic products to market, i.e. to commercial forest deployment
2. Capture of useful non-additive gene effects, as well as the additive gene effects that are accumulated over generations of breeding
3. Better crop customisation possible from greater performance diversity and stricter control of traits
4. Greater uniformity amongst final-crop trees (quality consistency)

Clones capture additive gene effects plus two types of non-additive gene effects (dominance, epistasis), and together this gene diversity accounts for how some clones behave uniquely, and sometimes in ways that interest commercial foresters. Clonal uniformity of good or improved clones deployed in monoclonal stands or block has been reported several times, most recently in doctoral work by Rajesh Sharma at the University of Canterbury. The rule of thumb for clonal improvement seems to be that clonal gains for most traits are double that expected from family forestry; e.g. for DBH growth (Dean *et al.*, 2006; Baltunis *et al.*, in press). High clonal gain results arise in two ways, utilisation of non-additive gene effects (e.g. by the

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ratio of H^2 to H^2) and increased statistical precision of data from cloned (vegetatively propagated) individuals (Dean *et al.*, 2006). Clonal density improvements of at least 30 kg/m³ or more are expected, and these are not surprising given its large genetic variation (Fig. 1).

Three density studies are summarised below that help highlight improvements in density and stiffness expected from family and clonal selection:

1. Densitometric ring-by-ring analyses of ten different age-22 half-sib families across geographically-contrasting sites revealed strong and consistent family differences in both average wood density and radial patterns of variation in density (Cown and Ball, 2001). The spread in family means was large, ranging from 50 kg/m³ in the corewood (growth rings 1 to 10 from the pith - historically called "juvenile wood" by many authors) to 100 kg/m³ at bark. Higher density was associated with higher latewood percentages, giving a wood texture similar to structural timbers such as the Southern yellow pines.
2. Study of 40 stems of ten clones at a single site indicated strong broad-sense heritabilities for average density and within-stem patterns of variation at age 27 years (Cown *et al.*, 2002). In the inner 10 wood rings, clonal mean corewood volume varied from 39% to 61% on average. Average wood density also varied markedly between clones (354 to 438 kg/m³). Using a technical definition for corewood (proportion of the stem of average basic density under 400 kg/m³ - Cown, 1992), the corewood zone occupied from 5 to 13 growth rings between clones, or from 15 to 64% of stem volume. This study concluded that clonal selection could dramatically improve wood qualities of radiata pine.
3. Fifty-four stems of 27 radiata pine clones were tested destructively for density and stiffness from over 2000 wood samples (Sorensson *et al.*, 2004). Clonal means of "whole-tree" stiffness in clearwood of these age-10 trees ranged from 4.7 to 8.6 GPa. "Whole-tree" density (13.5% M.C.) varied from 357 to 438 kg/m³. Density explained about 40% of the variation in wood stiffness, as it has in other studies (Mishiro *et al.*, 1986; Walford, 1991; Cown *et al.*, 1999). Clonal (individual-tree) heritabilities (H^2) were high and comparable for both density and stiffness, 79% and 77% respectively. Simulated clonal selection determined that selection for high stiffness would favourably reduce by several years the age when trees first produced structural-quality clear specimens, and would do so very reliably. In the worst-case scenario (lower 95% confidence limit), stiffness was still improved two tree-to-tree standard deviations above the average.

Somatic Embryogenesis Varieties

Clonal forestry of pines is practised commercially in such countries as Chile, the USA and New Zealand

(Sorensson and Shelbourne, 2005). Annual commercial deployments of clonal pines are scheduled to reach 50 to 70 million trees in the year 2008 worldwide, with the bulk of this in the US South (Pait, 2006; Sorensson, 2006). Clonal pines propagated through the somatic embryogenesis process are marketed as "varieties", and offer advantages over other types of clonal pines because their tissues are cryo-stored in order to halt the physiological aging that affects other clonal material.

Large-scale clonal testing of *P. radiata* began over 40 years ago in New Zealand (Shelbourne, 1991). Early conclusions about clonal forestry were mixed - many successes but also some failures. Some clonal trials suffered from variable or poor nursery stock quality, and led to inferior establishment and survival. When clones were deployed as "aged" materials, either generated by cuttings from older field trees, old mother plants in stoolbeds, or old tissue cultures, this sometimes led to ca. 10% reductions in DBH growth (though less in height). Some unstable clones were detected, i.e. ones that grew slower in rank than expected on new sites, referred to as GxE (genotype x environment) interaction (Carson, 1991; Concheyro, 1998). Since clones propagated solely by tissue culture (organogenesis) could not be commercially repropagated to a full juvenile state after lengthy field testing, their commercial lifespan was less than five years.

Commercial clonal development began in earnest in NZ in the late 1980s and early 1990s with Fletcher Challenge Forests and Carter Holt Harvey (amalgamated as Horizon2, and now ArborGen Australasia), and CellFor (now Forest-Genetics CellFor). In contrast to organogenic clonal trials, which had to be selected for production at age 5 to control ageing risks, NZ's clonal developers all work exclusively with cryo-stored SE varieties now. Cryo-storage enables field testing to be continued to any tree age, although age 8 remains the standard age of assessment, as with ordinary seedling forestry. Re-testing of top-rated varieties onto new sites and regimes is now possible, and in trial designs that can accommodate permanent sample plots for growth modelling. Clonal responses to site are observed by trialling them at each of several contrasting sites, e.g. volcanic ash soils versus phosphorus-deficient clays. These practices minimise risk.

Screening trials contain hundreds of candidate varieties, derived from many unrelated parents, such as top 2nd and 3rd-generation parents from breeding programmes like the RPBC and STBA (Southern Tree Breeding Association). Genetic analyses of clones are done in concert with progeny datasets in mammoth ASReml runs (B. Baltunis *et al.*, in press.), with the practical result that clonal performance can be compared directly to family products on the 0 to 30+ performance scale they are marketed under. Varieties are screened for twice as many traits as are progenies, and can at any time be characterised intensively for further traits of possible interest such as resinous defects, clear lengths distributions, large branch size, or warp propensity.

As clonal genetics has become standardised, developers have responded by proportionately increasing their efforts to reduce clonal treestock cost and improve yield and quality. Improvements are visible and measurable: better treestock juvenility, more fibrous root systems, better mycorrhizal infection, and better field survivals that tend to match or exceed that of bareroot seedling controls.

ArborGen is the largest clonal developer in NZ, and its nurseries produce over half of all radiata pine sold in NZ, or over 300 million pines worldwide annually. Its varietal pine costs have dropped from over a dollar per plant to about eighty-five cents. CellFor also sells SE varieties in NZ, and has backing from CellFor (Vancouver). About half of the larger forestry companies in NZ deploy varieties commercially to their estates.

Some of the SE varietal stands and trials are now eight or more years old, and are thus being critically measured to estimate realisable gains to forest. Projects are ongoing to determine investments returns from future stumpage sales. TIMOs (Timber Investment Management Organisations) like Global Forest Products and Hancock Forest Management are exploring how improvements in crop value from varietal stands can be recognised in their annual forest re-valuations.

Eliminate value-destroyers from forest

A special benefit of clones is the identification of "correlation breakers", a loose term referring to any clone that exhibits strong simultaneous improvements in adversely related traits like growth and density (Libby & Rauter, 1984; Carson, 1986). Their overall adverse relationship ($r = -0.22$ - weak, but practically significant for breeders) is evident amongst 668 top NZ radiata parents (Fig. 2), as well as a small experimental clonal population (Fig. 3). Clones can be selected which grow appreciably faster and have higher density than the CP and OP seedling controls. The frequency is low in this data, only 1.5% (1 of 68 experimental clones), but it should be pointed out, that ArborGen's varietal database is already twenty times larger, and will continue to increase in size. It also involves a wider array of parents and pedigrees. Thus one may reasonably assume that clonal developers can expect to find many such selections.

Forest growers are well aware that producing crops with well-defined and consistent quality is of more value to a wood processor. Wood processors prefer well-defined and consistently higher quality feedstocks, and this interest is reflected practically in investments in log segregation. Log segregation has one goal - culling unacceptable quality logs. It follows that an attractive target for genetic improvement is to eliminate unacceptable stems from the crop entirely, or at least from the larger final-crop stems.

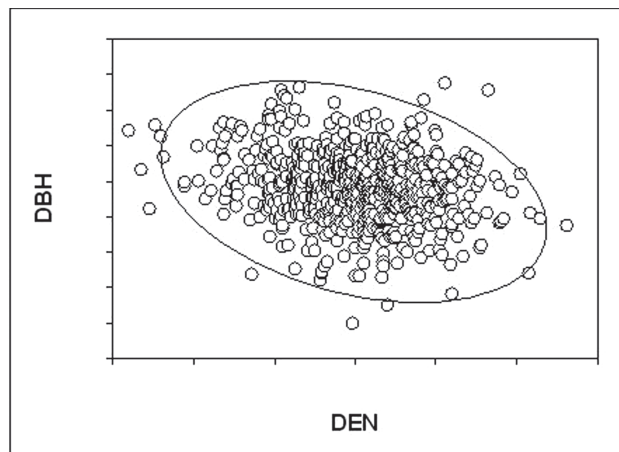


Figure 2. Scatterplot of breeding values for DBH and density of 668 top NZ parents. (Reproduced without scale with permission from RPBC).

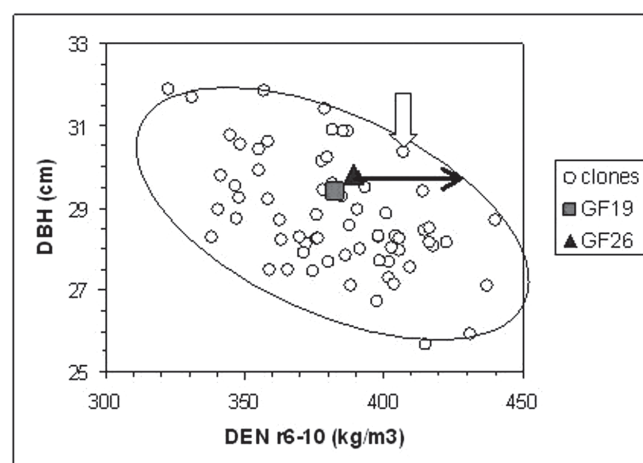


Figure 3. Scatterplot of age-12 DBH and rings 6-10 basic density of final-crop GF26 seedlings and 68 random clones. Black arrow ca. 40 kg/m³; white arrow identifies a "correlation breaker" (study of the authors, unpublished)

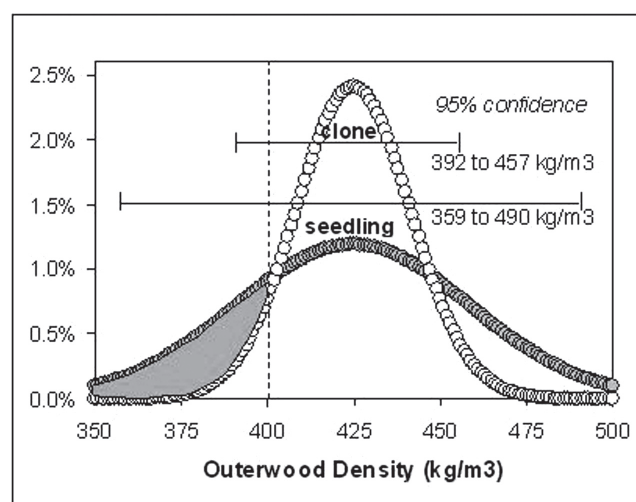


Figure 4. Clonal uniformity for density removes about 16% of low-density final crop stems (defined as density below 400 kg/m³ coloured zone) on average. Study of the authors of age-12 radiata pine clones versus seedling controls; CV% 3.9% for clone & 7.9% seedling.

Even in the absence of genetic gain for secondary traits like density, clones will create more value for a forest owner than planting seedlots, because of clonal uniformity (Fig. 4). Clones (e.g., deployed normally as mosaics of monoclonal) occupy the top rung of the genetic 'Uniformity Ladder' (Sorensson 2002). It is this same quality consistency the horticultural industry has taken advantage of by planting clonally propagated fruit trees like apples and avocados. That seedlings are variable is to be expected, because the genetic recombination that occurs during sexual reproduction is designed to ensure that siblings are sufficiently different from each other that at least one of them will survive.

Discussion

A common response of the NZ forest industry to crop-quality challenges is to invest in segregation technologies like log sonics. Unfortunately, the number of manageable log grades defined by size and quality is considerably less than that required to meet market complexity demands. This causes published log grades to be overly simple for practical reasons.

This does not mean that additional log qualities are not of keen interest. Processors should pay less when quality is insufficient, or sometimes refuse to purchase such logs even under large discounts. But equally, wood processors do create a better return from a feed of high quality logs and consequently should (and several wood processors do) pay forest owners more for high quality logs (Anderson, 2004; Young, 2004; Drummond, 2004), and this attitude is reflected in shipments of logs to mills from distant forests. Higher quality logs offer a wider than normal range of market applications, a "future market flexibility" of particular interest to some growers.

Stiffness is an important wood property that is limiting in radiata pine grown in certain regions of several countries. Admittedly, it was exacerbated in NZ by aggressive thinning regimes that encouraged early rapid stem growth and



Figure 5. Clonal pith-in board from ex-pasture site proof tested as joist to structural stiffness, and photo in forest of example tree of clone 194001.

Clone 194001

Clone 194-001 was installed in ex-farm and forest trials in 1995. Twenty final crop stems of clone 194001 were cored at Tarawera Cpt. 45, 10 trees from each of two reps of 36-tree monoclonal plots. For comparison, 30 commercial final crop seedling trees were also tested - 15 trees each adjacent to the clonal plots. The ensis WQ lab assessed basic density (rings 6 to 10).

Clonal density was 31 kg/m³ (7.8%) greater than seedling (427 kg/m³ vs 396 kg/m³), even though clonal DBH was also 5.2% greater (283 mm vs 269 mm). No significant compression wood was observed in any trees. Using ADEN v2 software³, mature wood density at ring 20 of the clone was predicted to be 522 kg/m³, with a probability of 99.9% of exceeding a subjectively chosen density threshold of 475 kg/m³. Clonal gain for mature wood density over seedling was estimated to be 36 kg/m³ (7.4%). Clone 194001 also showed strong clonal uniformity, averaging 42% more uniform in wood density than seedling (CV of 4.2% vs 7.2%). All clonal results were significantly different from seedling.

led to shortened rotation ages causing predictable wood quality losses (Sorensson *et al.*, 1997). Nevertheless, there is substantial evidence that, even under aggressive forest management, family and particularly clonal selection can sharply improve wood qualities like stiffness of fast-growing radiata pine. ArborGen has varieties in production that are rated 5 to 7 points higher than top CP for both growth (DBH) and density on the standard 0 to 30+ performance scale.

Because most SE varietal forests and trials are still young, the direct evidence of realisable gain from varieties is still emerging. It was beyond the scope of this paper to critically review such evidence, so we decided to critically test a known high stiffness clone (Richardson, 2002) that Fletcher Challenge Forests had put into limited production in the 1990s (box, Fig. 5). Knotty framing lumber (90 x 45mm) of unexpectedly high stiffness had been produced from young trees grown in both ex-pasture and forest, the latter averaging MSG10 in boards prepared and proof tested by the Kawerau drymill.

Silviculture is and should be the "front line of attack" against quality challenges facing NZ's radiata resource (i.e. control of branching). However, because better stiffness is achieved via conservative practices (higher stockings and longer rotations, which achieve quality in part by slowing down individual tree growth and reducing average log size), silviculture must also be viewed in tandem with the realistic opportunities afforded from modern genetics.

Clonal developers find their best clients to be those companies who have already taken pains to understand the

³ Proprietary to ArborGen, written by M. Kimberley, based on SilviScan of 75 age-18 clones at two sites).

market needs and optimise stocking, thinning, pruning and rotation age. It is such companies who thus are most aware of the critical challenges to crop quality left unresolved, and who tend to become particularly vocal advocates of varietal forestry.

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References

- Anderson, B. (2004). Logs to lumber value chain - a sawmill/forest owner's perspective. Pp. 125-128 in "Profitable Wood Processing", Proceedings of NZ Institute of Forestry Annual Conference, Gisborne, 19-20 April 2004.
- Baltunis, B.S.; Wu, H.W.; Dungey, H.S.; Mullin, T.J.; Brawner, J.T. (in press): Comparisons of genetic parameters and clonal value predictions from varietal trials and seedling base population trials of radiata pine. *Tree Genetics and Genomes* (submitted)
- Bannister, M.H. and Vine, M.H. (1981). An early progeny trial in *Pinus radiata*. 4. Wood density. *New Zealand Journal of Forestry Science* 11(3): 221-243.
- Beauregard, R.; Gazo, R.; Kimberley, M.O.; Turner, J.; Mitchell, S.; Shelbourne, A. (1999). Clonal variation in the quality of radiata pine random width boards. *Wood and Fiber Science* 31(3): 222-234.
- Burdon, R.D. 1992: Genetic survey of *Pinus radiata*. 9: General discussion and implications for genetic management. *New Zealand Journal of Forestry* 22: 274-298.
- Burdon, R.D. and Bannister, M.H. (1973). Provenances of *Pinus radiata*: their early performance and silvicultural potential. *New Zealand Journal of Forestry* 18: 217-232.
- Burdon, R.D. and Harris, J.M. (1973). Wood density in radiata pine clones on four different sites. *New Zealand Journal of Forestry Science* 3(3): 286-303.
- Burdon, R.D. and Low, C.B. (1992). Genetic survey of *Pinus radiata*. 6: Wood properties: Variation, heritabilities, and interrelationships with other traits. *New Zealand Journal of Forestry Science* 22(2/3): 228-245.
- Burdon, R.D.; Young, G.D. and Cown, D.J. (1992). Evaluation of wood properties in highly select *Pinus radiata* progenies and preliminary estimates of genetic parameters. Pp. 168-169 in Proceedings IUFRO All-Division 5 Conference, Nancy, France, Wood Quality Group 5.01.
- Carson, M.J. (1986). Advantages of clonal forestry for *Pinus radiata* - real or imagined? *New Zealand Journal of Forestry Science* 16(3): 403-415.
- Carson, S.D. 1991: Genotype x environment interaction and optimal number of progeny test site for improving *Pinus radiata* in New Zealand. *New Zealand Journal of Forestry Science* 21(1):32-49.
- Concheyro, S.C. (1998). Evaluation of the 1986-1987 radiata pine clonal trials at Forest Research, New Zealand. Master of Applied Science Thesis, Massey University, New Zealand.
- Cown, D.J. (1973): Effects of severe thinning and pruning treatments on the intrinsic properties of young radiata pine. *New Zealand Journal of Forestry Science* 3 (3): 379-389.
- Cown, D.J. (1974a). Wood density of radiata pine: its variations and manipulation. *New Zealand Journal of Forestry Science* 19(1): 84-92.
- Cown, D.J. (1974b): Comparison of the effects of two thinning regimes on some wood properties of radiata pine. *New Zealand Journal of Forestry Science* 4 (3): 540-551.
- Cown, D.J. (1992). Corewood - should we be concerned? *New Zealand Journal of Forestry Science* 22(1): 87-95.
- Cown, D.J. (2006). Understanding and managing wood quality for improving product value in New Zealand. *New Zealand Journal of Forestry Science* 35(2/3): 205-220.
- Cown, D.J. and Ball, R.D. (2001). Wood densitometry of 10 *Pinus radiata* families at seven contrasting sites: Influence of tree age, site, and genotype. *New Zealand Journal of Forestry Science* 31(1): 88-100.
- Cown, D.J.; Hebert, J.; Ball, R. 1999: Modelling radiata pine lumber characteristics. Part 1: Mechanical Properties of Small Clears. *New Zealand Journal of Forestry Science* 29(2): 203 -213.
- Cown, D.J. and McConchie, D.L. (1981). Effects of thinning and fertiliser application on wood properties of *Pinus radiata*. *New Zealand Journal of Forestry Science* 11(2): 79-91.
- Cown, D.J., McConchie, D.L. and Young, G.Y. (1991). Radiata pine wood properties survey. FRI Bulletin No. 50. New Zealand Ministry of Forestry.
- Cown, D.J., McKinley, R.B., and Ball, R.D. (2002). Wood density variation in 10 mature *Pinus radiata* clones. *New Zealand Journal of Forestry Science* 32(1): 48-69.
- Dadswell, H.E.; Fielding, J.M.; Nicholls, J.W.P. and Brown, A.G. (1961). Tree-to-tree variations and the gross heritability of wood characteristics of *Pinus radiata*. Forestry and Timber Bureau, Leaflet 77.
- Dean, C.A., Cotterill, P., Burdon, R.D. 2006: Early selection of radiata pine. 1. Trends over time of additive and dominance genetic variances and covariances of growth traits. *Silvae Genetica* 55: 182-199.
- Donaldson, L.A.; Evans, R.; Cown, D.J. and Lausberg, M.J.F. (1995). Clonal variation of wood density variables in *Pinus radiata*. *New Zealand Journal of Forestry Science* 25(2): 175-188.
- Dungey, H. (2006). The genetic value of clones for growth, form and sonic velocity properties in *Pinus radiata* in the North Island of New Zealand. In 13th Australasian Plant Breeding Conference 18-21 April 2006, Breeding for success: Diversity in action, Christchurch, New Zealand April 2006. p110.
- Drummond, S. (2004). Wood quality, veneer needs. Pp. 33-40 in "Profitable Wood Processing", Proceedings of NZIOF Annual Conference, Gisborne, 19-20 April 2004.

- Dungey, H.S.; Matheson, A.C.; Kain, D. and Evans, R. (2006). Genetics of wood stiffness and its component traits in *Pinus radiata*. *Canadian Journal of Forest Research* 36: 1165-1178.
- Gapare, W.J.; Wu, H.X. and Albarquez, A. (2006). Genetic control of the time of transition from juvenile to mature wood in *Pinus radiata*. *Annals of Forest Science* 63: 871-878.
- Ivkovic, M.; Wu, H.X., Spencer, D. and McRae, T.A. (2007). Modelling the effects of stem sweep, branch size and wood stiffness of radiata pine on structural timber production. *Australian Forestry* 70(3): 173-184.
- Kumar, S. (2004) Genetic parameter estimates for wood stiffness, strength, internal checking, and resin bleeding for radiata pine. *Canadian Journal of Forest Research* 34: 2601-2610.
- Kumar, S.. (2006): Correlation between clonal means and open-pollinated seedling progeny means and its implications for radiata breeding strategy. *Canadian Journal of Forest Research* 36: 1968-1975.
- Libby, W.J. and Rauter, R.M. (1984). Advantages of clonal forestry. *The Forestry Chronicle* 60(3): 145-149.
- Lindström, H. (1996). Basic density of Norway spruce. Part II. Predicted by stem taper, mean growth ring width, and factors related to crown development. *Wood and Fiber Science* 28: 240 - 251.
- Matheson, A.C.; Spencer, D.J.; Nyakuengama, J.G.; Yang, J. and Evans, R. (1997). Breeding for wood properties in radiata pine. Pp. 169-179 in "IUFRO '97 Genetics of Radiata Pine" (eds. Burdon, R.D.; Moore, J.M.) *Proceedings of NZ FRI - IUFRO Conference* 1-4.
- Mishiro, A., Cown, D.J. and Walford, G.B. (1986). A further examination of the clearwood properties of radiata pine grown in New Zealand. *FRI Bulletin* No. 104, 23 pp. Forest Research Institute, Rotorua, New Zealand
- Murphy, G.E.; Marshall, H.; Conradie, I. 2003. Market complexity and its effect on variables that gauge the economics of harvesting production. *New Zealand Journal of Forestry Science* 33(2): 281-292.
- Pait, J. (2006). Trait valuation in varietal forestry (June 26-29 2006), IFG Conference, Jacksonville, FL. (conference. ifas.ufl.edu/IEG40/presentations.html)
- Richardson, M. (2002). Delivering the dream. *NZ Forest Industries*, August 2002, p. 15.
- Ridoutt, B.G.; Sorensson, C.T. and Lausberg, M.J.F. (1998). Wood properties of twenty highly ranked radiata pine seed production parents selected for growth and form. *Wood and Fiber Science* 30(2): 128-137.
- Shelbourne, C.J.A. (1991). Clonal testing of *Pinus radiata* in New Zealand. In *Proceedings FRI/NZP Forests Ltd Clonal Forestry Workshop*. *FRI Bulletin* 160. New Zealand Ministry of Forestry.
- Shelbourne, C.J.A.; Evans, R.; Kibblewhite, R.P. and Low, C. (1997). Inheritance of tracheid transverse dimensions and wood density in radiata pine. *Appita* 50(1): 47-50.
- Sorensson, C.T. (2002). Reflections on radiata pine genetic improvement by a clonal forester. *NZ Journal of Forestry* 47(3): 29-31.
- Sorensson, C.T. (2006). Varietal pines boom in the US South. *New Zealand Journal of Forestry*, August 2006: 34-40.
- Sorensson, C.T. (2007). Improving the relevancy of wood quality breeding in softwoods. In *Proceedings 2007 Australasian Forest Genetics Conference (AFGC) Breeding for Wood Quality*, 11-14 April 2007, Hobart, Tasmania, Australia. 25 pp. Australasian Forestry Research Working Group 1 (Genetics) <http://www.cdesign.com.au/afgc2007/>
- Sorensson, C.T. and Shelbourne, C.J.A. (2005). Clonal forestry. Chapter 5-7, 4th edition of NZ Institute of Forestry "Forestry Handbook", pp. 92-96. NZIF, New Zealand (nzif@paradise.net.nz).
- Sorensson, C.T., Cown, D.J., Ridoutt, B.D. and X. Tian. (1997). The significance of wood quality in tree breeding: a case study of radiata pine in New Zealand. Pp. IV 35-44 in *Timber Management Toward Wood Quality and End-Product Value* (eds. S.Y. Zhang, R. Gosselin, G. Chauret). *Proceedings of the CTIA/IUFRO International Wood Quality Workshop*, 18-22 Aug. 1997. Quebec City, Canada.
- Sorensson, C.T.; Nepveu, G. and Kimberley, M.O. (2004). Intra- and inter-tree modelling of wood stiffness of clears of age-10 radiata pine clones, and simulated response of stiffness to increased genetic selection intensity. Pp. 104-117 in *Connection between Forest Resources and Wood Quality: Modelling Approaches and Simulation Software* (G. Nepveu, ed.), *Proc. IUFRO Conf. S.01-04 Harrison Hot Springs*, 10-15 Sept. 2002, British Colombia, Canada.
- Walford, G.B. (1991). Mechanical properties. Pp. 8-17 in "Properties and Uses of New Zealand Radiata Pine" (ed. J.A. Kininmonth and L.J. Whitehouse). Ministry of Forestry, Forest Research Inst., Rotorua, New Zealand.
- Wu, H.W.; Ivkovich, M.; Gapare, W.G.; Matheson, A.C.; Baltunis, B.; Powell, M.B.; McRae, T.A. 2007. Breeding for wood quality and profits in radiata pine: A review of genetic parameters and strategies. P 22 in "Australasian Forest Genetics Conference: Breeding for Wood Quality" *Program Book*, 11-14 April 2007, Hobart Tasmania.
- Young, D.L. (2004). Profitable wood processing - sawn timber needs. Pp. 41-46 in "Profitable Wood Processing", *Proceedings of NZIOF Annual Conference*, Gisborne, 19-20 April 2004.