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Impacts of tending on attributes of radiata pine trees and stands in New Zealand – a review

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Abstract

Background: Radiata pine (*Pinus radiata* D.Don) has been grown in New Zealand's plantations for more than a century, and silviculturists began by employing Eurocentric ideas about how to manage forest stands. Research and development gradually led to an entirely new approach to silviculture, where volume production was sacrificed to promote value, and high investments in individual trees led to very low stand stockings by international standards.

Methods: The development of pruning and thinning technology was reviewed, highlighting the most important developments, and identifying impacts of tending on tree and stand attributes.

Results: Decision-support systems for planning pruning and heavy, early pre-commercial (waste) thinning became very sophisticated. As ideas changed, however, structural regimes without pruning became more prevalent, and this has necessitated new forms of silvicultural research. Ideas for new areas of tending research in New Zealand are outlined.

Conclusions: A unique approach to tending plantations developed in New Zealand that involves sacrificing volume production to increase the value of an investment in pruned forest stands. Experiments aimed at building decision-support systems for these silvicultural regimes have yielded a great deal of information about impacts of pruning and thinning in stands with relatively open canopies. Recent changes in focus towards growing construction lumber require a greater research focus on factors influencing wood stiffness and stability as well as a clear understanding of the use of higher stocking levels with a variety of genotypes on a range of sites. Stand dynamics and mortality will be more relevant than for pruning regimes, and a variety of new experiments is required.

Keywords: Tending, silviculture, pruning, radiata pine

Introduction

Tending of plantations, including thinning and pruning, can profoundly influence the value of an investment in forests aimed at wood or fibre production (Maclaren & Knowles 1999b). Stand density is an important factor influencing competition between individual plants. This in turn influences branch size (Inglis & Cleland 1982), height to the base of the canopy, diameter growth rate (Waghorn et al. 2007a), rate of stem volume growth (Maclaren & Knowles 1999a), stem taper, carbon sequestration rate (Yallop 2021), the extent to which neighbouring trees compete with each other as they grow, and in gymnosperms wood stiffness (Lasserre et al. 2004), and stability of wood during drying (Cown 1973a). It may also influence rate of heartwood development, a hypothesis that we need to test.

It is important to establish how species respond to different stand densities, stand density management, and pruning. In New Zealand, extensive studies have been conducted investigating the impacts of silvicultural tending regimes on radiata pine (*Pinus radiata* D.Don.), and so this literature review comprises mainly local references to radiata pine management. Former summaries are available from two symposia on pruning

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and thinning of radiata pine (Bunn & Brown 1963; James et al. 1970). The establishment of the “Radiata Pine Project Team” by Dr W.R.J. Sutton in the late 1970s collected many strands of tending research and summarised them in computer software, initially named “SILMOD” then “Standpak” (Whiteside 1990), and now “Forecaster”. Fewer companies are now pruning in New Zealand, and therefore it is important both to document what has been learned from previous studies and to provide a foundation for future research.

In New Zealand both initial stocking and, in pruned crops, final crop stocking in radiata pine plantations gradually diminished over most of the last half century. As more tending investment was made in each tree, managers planted and retained fewer trees thereby increasing growth per tree at the expense of growth per hectare (James 1990). Selection ratios (the ratio of trees planted to those in the final crop) also dropped with improvements in establishment practices and in genetics (Mason 1985; Mason 1992; Trewin & Cullen 1985; Wilcox & Carson 1990). Final crop stocking has been a particularly controversial topic. Not all the research leading to these developments can be included here, but the main contributions that specifically address stocking and pruning will be cited. In recent years large corporate owners of plantations have tended to stop pruning and targeting volume production for structural regimes has led to increases in final crop stocking. This latter trend will lead to different kinds of tending research, and ideas for new tending research are outlined in this review.

Defining stand density

Stand density reflects the extent to which trees use a site. At any given age, density in an un-thinned stand might be expressed as stems per hectare, but measures which relate numbers of stems to average tree size are generally more independent of age and site quality. Reineke (1933) provided a measure of stand density that was independent of age and site quality called “stand density index”, a linear relationship between the logarithm of stems per unit area and the logarithm of mean diameter at breast height over bark (dbh) with functional parameters that varied slightly for different species. This implied a limiting relationship between average size and stocking. A similar assumption was implied by the use of tree area ratio (Chisman & Schumacher 1940), where the area occupied by a given tree in a fully stocked stand was expressed as a quadratic function of dbh.

Relative spacing, the ratio between average distance between trees and average height of the dominant stems, has also been used successfully to represent density but is less universally applicable than stand density index (Beekhuis 1966). Reid (2006) proposed using the mean dbh (cm) divided by basal area/ha (m^2) as a simple measure of competition for eucalypts. In pruned stands, in particular, a constant ratio can gradually increase competition as a stand ages, allowing for rapid dbh growth after pruning the bottom log, but increased competition to create smaller branches as they develop in upper logs. While the logic of such a measure is sound, it imposes assumptions about the desirability of increasing competition between trees with age.

Measures of stand density commonly used in modern growth models are basal area per unit area (the sum of stem cross-sectional areas at breast height, usually derived from measures of dbh), and numbers of stems per unit area, but effects vary as these quantities increase or decrease, hence they cannot be said to be independent of site for a species.

Stand density measurement allowed the production of yield tables sensitive to stand density (MacKinney et al. 1937), known as "variable density" yield tables. MacKinney et al. (1937) also improved on graphical techniques by using least-squares regression to estimate parameters of functionalised yield curves. Variable density yield tables for radiata pine in New Zealand were prepared using graphical techniques by Lewis (1954). These tables and growth and yield modelling techniques subsequently pioneered by Clutter (1963) allowed broad approximations of the consequences of adopting different stand densities. However, stand density has many impacts that are not properly represented by these models, as will be demonstrated in this paper.

Garcia (1984, 1990) and West et al. (1982) used representations of tree canopy as measures of density. In the former case, canopy closure was derived from levels of thinning and pruning of stands assumed to have 100% closure, whilst in the latter, the total length of crown per hectare was directly estimated from tree height, pruned height, and numbers of stems per hectare. These models were built to fill a need for more sensitive characterisation of growth and yield in heavily thinned and pruned stands of radiata pine in New Zealand.

"Stems per hectare" is the measure most often used in radiata pine plantations to control density, and it is important to distinguish between effects of initial stocking, final stocking, selection ratio (the ratio between initial and final crop stocking), and the timing of thinning. Effects of density expressed as stems per hectare vary with other factors such as tree size, site quality, genetics, tending regime, rotation length, and exposure. These and other factors will be covered here. Stand density affects growth rates, mortality, tree form, branching, wood properties, wind stability and weed growth. These outcomes of density management form the outline of this review. I have briefly mentioned a few papers on the topic. These are mentioned because density management practices adopted by a plantation manager will ultimately depend as much on objectives of management and on economic assumptions as on the biological capability of a tree species.

Effects of stand density on growth rates

Foliage

Plant dry matter production is generally a linear function of intercepted radiation (Biscoe & Gallagher 1975; Monteith 1977), but the slope of the relationship varies with environmental conditions. In New Zealand radiata pine plantations intercepted radiation has been shown to increase with increasing amounts of foliage, at least up to a leaf area index (LAI) of 3.5 (Grace et al.

1987). Hunter et al. (1987) found annual radiata pine bole volume increment/ha was linearly related to foliage mass and foliar nitrogen content. At some maximum LAI, the canopy can be considered "closed". For agricultural crops, LAI values greater than 4 were considered to represent a closed canopy (Biscoe & Gallagher 1975). However, for radiata pine aboveground production was found to increase approximately linearly with one-sided LAI values as high as 10, and showed a declining rate of increase up to two-sided LAI values of 20 or more in un-thinned stands (Beets & Pollock 1987). It is, therefore, important to understand the effects of stand density on foliage mass.

Foliage mass of radiata pine was reported to increase with age until an equilibrium level was reached (Madgwick et al. 1977), and the same was reported for Douglas-fir (*Pseudostuga menzeisii* (Mirb.) Franco), with the rate of approach to the maximum greater at higher stand densities (Long & Smith 1984). Not all crops exhibit this pattern of foliage mass with time, however; Switzer et al. (1968) found that in a *Pinus taeda* L. stand foliage increased to a maximum, then declined to a reasonably high equilibrium level, while that of *Betula* spp. increased to a maximum which was also the equilibrium. Kuuluvainen (1991) reported that foliage in a naturally regenerated stand of *Pinus sylvestris* L. increased with time to a maximum, and then declined sharply. Current annual increment of bole volume peaked before the time of maximum foliage. Kuuluvainen (1991) suggested that the decline in foliage and growth was due to competition stress, immobilisation of nutrients, and more mutual shading of trees as stocking diminished. Beets & Pollock (1987) found that radiata pine LAI increased with age to a maximum at age 6 years, and then gradually declined. Mason et al. (2012) obtained direct measurements of one-sided LAI up to 10 for radiata pine.

Madgwick et al. (1977) documented the impact of stocking on foliage mass for radiata pine between the ages of 6 and 22 years (Figure 1). Data were highly variable, but it appears that foliage mass was independent of stand density at densities greater than approximately 500 stems/ha and diminished with decreasing density below this level. This is consistent with the behaviour of the PPM88 growth model (Garcia 1990), where the difference in bole volume growth rate between stands of 100 stems/ha and 200 stems/ha is as great as that between 200 stems/ha and 500 stems/ha. It should be noted that most arguments relating to final crop stocking in pruned radiata pine plantations focus on stand densities below 500 stems/ha, a range in which stocking level should profoundly affect foliage mass/ha, light interception, and therefore productivity.

Canopy depth also varies with stand density (Waghorn et al. 2007b). Radiata pine canopy depth was found to increase by 1.6 m for every 1 m increase in between-tree spacing (Beekhuis 1966). Beekhuis pointed out that the overriding influence on canopy depth in young stands (less than 25 m in mean top height) was height growth, with a 1 m increase in canopy depth for every 3 m increase in height.

Goulding & Inglis (1990) showed that spacing and site quality jointly influenced mean annual increments of radiata pine for spacings between 100 and 400 stems/ha, and site indices at age 20 between 21 and 37 m.

Diameter at breast height and basal area

Using data from 15 Nelder stand density experiments across a range of New Zealand sites, Mason (1992) determined that basal area growth per hectare increased linearly with stand density up to four years of age in young radiata pine plantations across a wide range of stand densities (up to 12000 stems/ha). Individual tree

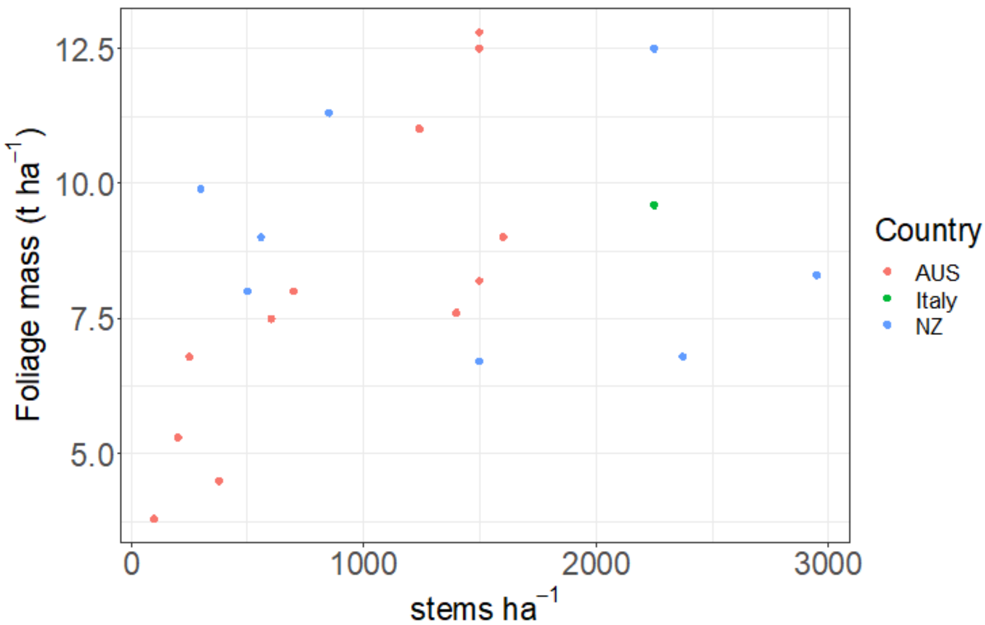

FIGURE 1: Foliage mass/ha for radiata pine between the ages of 6 and 22 years in Kaingaroa Forest, New Zealand, Italy, and Australia (AUS) (Madgwick et al. 1977).

diameter growth was unrelated to stand density for the first 4 years and then diminished with increased stand density during the fifth growing season. An agroforestry experiment at Tikitere, near Rotorua, yielded similar results, where a stocking range of 300-2400 stems/ha did not affect individual tree diameter growth until the fifth growing season (Knowles et al. 1993). Menzies et al. (1989) found the same results except that competition began during the fourth growing season on a very productive farm site at low elevation.

The Tikitere experiment was a very large agroforestry experiment with four replications of four different radiata pine stocking levels in a fully randomised design (Knowles et al. 1993). The third author, Piers Maclaren supplied data which I have analysed with non-linear fixed effects models using a Schumacher (1939) sigmoid equation in yield form for the period after the last thinning at age 8, with plots as random effects and stocking as a continuous variable influencing the asymptote, to show the trends in Figures 2 and 3.

Stocking affects tree dbh growth non-linearly after competition begins (Waghorn et al. 2007b), a fact that is built into many yield tables (Lewis 1954) and growth and yield models (Garcia 1984, 1988, 1990). At Tikitere (Figure 2), final crop stockings from 50 to 400 stems/ha decreased mean dbh at age 26 years from 80 cm to 50 cm, while volume productivity per hectare increased from 200 to 1000 m^3/ha (Knowles et al. 1993). The culmination of current annual increment in basal area was earlier for higher stockings. Mason (1992) also found an earlier culmination for basal area growth at higher stockings in Nelder experiments.

Despite arguments for lower final crop stockings (Maclaren 1995), Whyte & Woollons (1990) reported that, in a thinning experiment in Kaingaroa Forest, late-rotation yields from a stand thinned to 300 stems/ha were so much greater than those of plots at 200 stems/ha, that volumes of the largest 200 trees/ha in the 300 stems/ha plots were almost as great as the entire yield from plots thinned to 200 stems/ha. Some of the earlier arguments for very low final crop stockings (see James (1990) for a summary) may have been motivated by the use of models built using data from only more highly stocked stands, and were therefore based on extrapolations.

Thinning generally results in a small period of growth adjustment immediately following the thinning, with some species growing slightly more than they would have if the same basal area had been reached without thinning owing to a lower initial stocking, and other species, including radiata pine, growing less for a short period after thinning (Methol 2001).

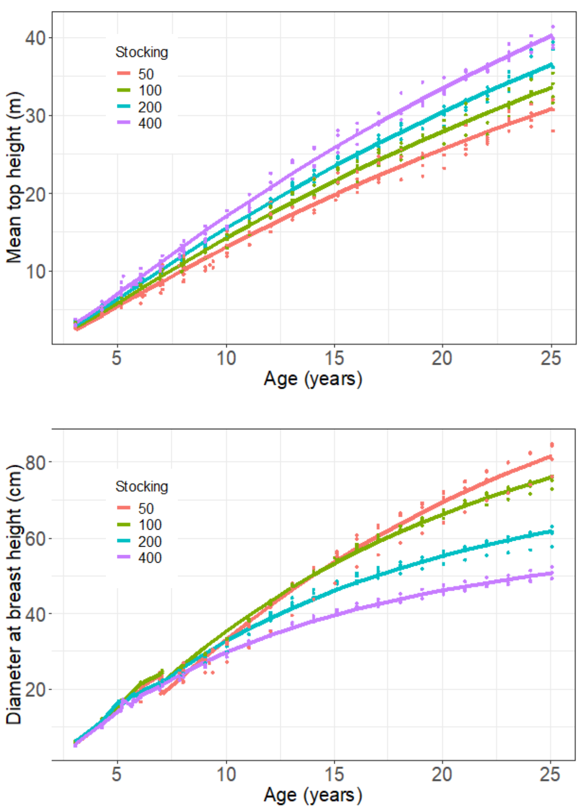

FIGURE 2: Mean top height (m) and dbhob (cm) at Tikitere to age 25 years vs final crop stocking. The Tikitere experiment had consistent selection ratios (Knowles et al. 1993). This graphic was constructed from data supplied by Piers Maclaren, the third author. The effect of stocking was statistically significant for height (P<0.0001) and dbh (P<0.0001).

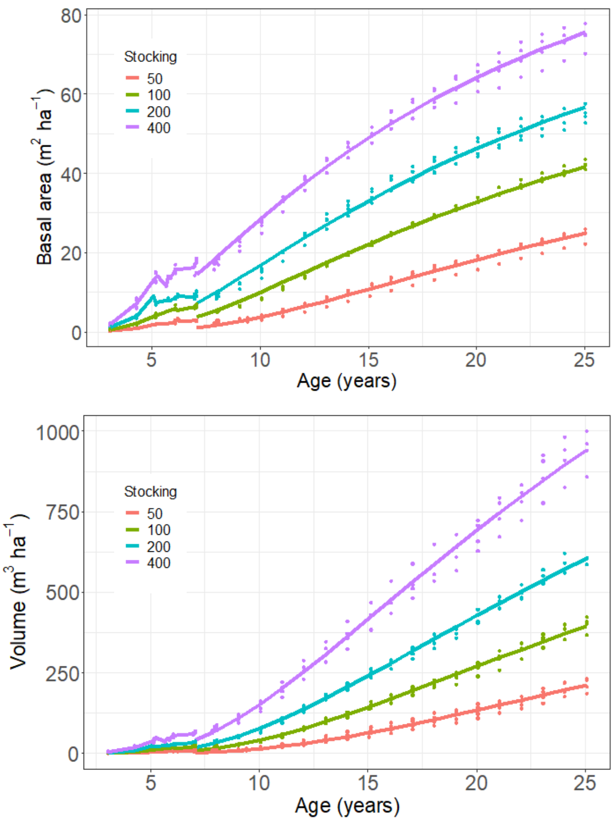

FIGURE 3: Basal area (m^2 ha^{-1}) and stem volume (m^3 ha^{-1}) at Tikitere to age 25, vs final crop stocking. The effect of stocking was statistically significant for both basal area (P<0.0001) and volume (P<0.0001).

Height

Although height growth is much less affected by stocking than diameter growth, several researchers have found that height growth diminishes as stocking diminishes. Menzies et al. (1989) noted an increase in height growth during and after the third growing season with increasing stand density from 200-800 stems/ha. Mason (1992) found a reduction in height growth with decreasing stocking below 2000 stems/ha in Nelder experiments. These effects were apparent by age 3 years, before stocking had affected dbh. Maclaren et al. (1995) studied the effect in older stands and found a 2 m reduction in mean top height for every halving of stocking. They noted that detection of the effect was dependent on a constant selection ratio among thinned stands and postulated that exposure of trees to wind at lower stand densities might explain the phenomenon. An alternative hypothesis is that trees in higher stocked stands may detect infrared radiation from neighbours and respond by accelerating height growth. The results imply that height growth reductions with decreasing stand density are restricted to juvenile stands, but this is an area for future research.

In the Tikitere agroforestry experiment (Figure 2), the mean top height of trees in the 50 stems/ha treatment was almost 10 m less than in the 400 stems/ha treatment at age 26 years (Knowles et al. 1993). Some of the increase in MTH with higher stocking rates is likely to arise from the fact that the largest 100 dbhs/ha represent more extreme portions of size distributions within stands at higher stockings than stands at lower stocking rates.

Selection ratios

A selection ratio is the ratio between numbers of trees planted and numbers of trees left after the final thinning. Varying selection ratios between 1 and 6 did not affect diameter growth of radiata pine at age 19 years (MacLaren & Kimberley 1991). The authors concluded that improved selection of large trees may have counteracted effects of stand density. Subsequent work showed, however that correlations between dbh at young ages (7 years) and dbh at rotation age (32 years) may be very weak (Maclaren 1995). The correlation was poorer where stands had been thinned. These facts suggested that the cost of higher initial stockings may not be justified by the selection of large trees.

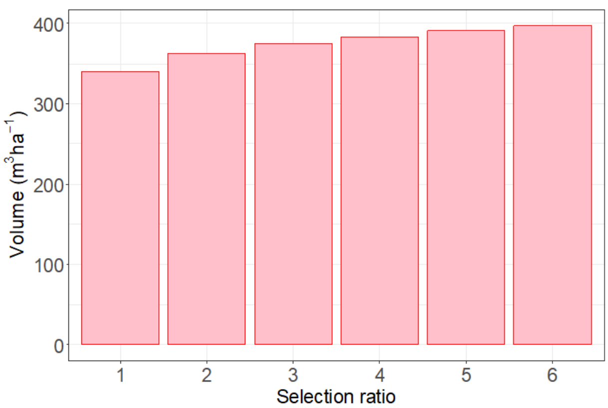

FIGURE 4: Effect of selection ratio on total volume/ha at age 19 years (after Maclaren & Kimberley 1991).

In pruned crops emphasis is generally placed on heavy, early thinning that provides plenty of room for trees selected as crop trees to grow rapidly in diameter. Dominance is apparently a poor basis for selection in young, pruned crops. An even chance of dominants at age 5 years being suppressed by age 12 years was reported by Sutton (1973).

Maclaren & Kimberley (1991) found an increase in height growth with selection ratio that ultimately caused an increase in volume at age 19 years (Figure 4).

Effects of stand density on mortality

The "normal" survival of un-thinned radiata pine as a function of tree height was reported by Penistan (1960). In general, stand density diminishes naturally with increases in mean tree size, and this fact is built into growth and yield models (Beekhuis 1966; Garcia 1988). It should be noted, however, that there was a decline in rates of mortality of radiata pine in the central North Island over 30 years (Klitscher 1987). Control of *Sirex noctilio* and *Dothistroma pini* outbreaks, improved genotypes, and improved management practices were proposed as reasons for the changes in trends, but causes have never been definitively identified.

A geometrical appraisal of growth processes in agricultural crops has led to a "law" of stand density which is actually a hypothesis of a power relationship between numbers of plants per unit area, and average plant mass (Yoda et al. 1963). As explained by Drew & Flewelling (1977), given certain assumptions, mean plant weight should be directly proportional to plants per unit area to the -3/2 power. Assuming a proportionality between mean tree weight and dbh to the 5/2 power, this weight and stand density relationship is equivalent to Reineke's (1933) stand density index.

There is some evidence that the "law" might be applied to New Zealand's radiata pine crops (Drew & Flewelling 1977), but Zeide (1987) pointed out that two necessary assumptions required by the "law" (i.e., complete canopy closure is maintained by the combined action of crown growth and self-thinning, and plants of the same species are always allometrically identical) are usually untenable. The area of gaps in canopies created by mortality might be expected to increase with stand age, and the crown weight:crown length ratios of trees were found to decline with age. Careful analysis of data from long-term permanent sample plots indicated that the hypothesised log-log line was in fact a curve. Reineke's (1933) use of stocking in relation to dbh was found to be more reliable, as dbh was more closely related to crown dimensions than was plant mass. Although Reineke's power constant was found to be -1.605 for 12 of 14 species, it has been found to vary with other species (Zeide 1987).

As a generalised hypothesis, the decline in plant number with increasing average plant size justifies the frequent use of polymorphic mortality functions in stands where between-tree competition is occurring. However, the use of only two parameters, one being the universal -3/2 constant, appears to be an oversimplification of the process. Models of stand growth and yield with higher resolution require more refined representations of allometric relationships and competition.

Reineke's (1933) stand density index (SDI) can be used to guide thinning strategies (Figure 5) if the maximum stand density index for a species is known on the site where it is being established.

Effects of stand density on tree form

Taper

It is well established that trees grown at lower stocking will have greater taper than those grown at higher stocking. For example, at the Tikitere agroforestry experiment, where initial stand densities ranged from 300-2400 stems/ha and final densities from 50 to 400 stems/ha, taper decreased markedly as stand density increased (Knowles et al. 1993). Trees on the edges of shelter belts have been shown to have greater taper than those within shelter belts (Tombleson & Inglis 1986). These effects may be caused by an increase in tree sway at lower stocking (Jacobs 1954), the effect of stocking on height growth mentioned above, and also by a more rapid rise of the canopy level (Beekhuis 1965) at higher stocking. There is a need to fit taper equations to data from these experiments to fully assess the effects of stocking on taper.

If tree sway and reduced height growth are the dominant causes of increased taper with stocking, then reducing initial stocking should increase log taper even for the same final crop stocking. Although increased taper was not explicitly reported, it was implied by the results of a study of selection ratios conducted by Maclaren & Kimberley (1991). The implication is that raising selection ratios and keeping stocking high for a longer period in the rotation may reduce taper even at low final crop stocking, but this topic requires more research.

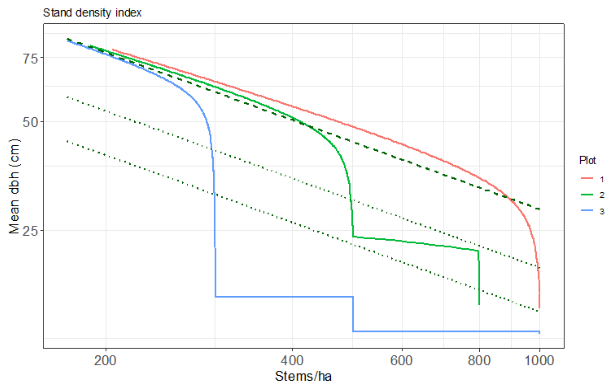

FIGURE 5: A stand density management diagram showing three different thinning regimes for radiata pine, based on output of a growth and yield model. The dotted lines represent the maximum SDI (Reineke 1933) for the species on those sites, 55% of the maximum (SDI=1200), and 35% of the maximum respectively. Above 55% is considered to be the "zone of imminent competition mortality", while the zone between 35% and 55% of maximum SDI is considered to be the "management zone" within which there is full site occupancy but trees still have sufficient space to grow without mortality. The three regimes are typical for an unpruned regime (red), and structural regime (green), and a pruning regime (blue).

Stem quality

Higher selection ratios may allow managers to grow more stems of high quality for any given final crop stocking, but this effect may not be as marked as managers commonly believe. Sutton (1973) found that leader malformation present at age 5 years often disappeared by age 9 years, but that stem malformation was more persistent. Only 38% of leaders malformed at age 3.5 years resulted in multi-leadered trees at age 22 years (Maclaren 1995). Sutton recommended that the order of selection criteria for crop trees in pruned stands be amended to: 1) stem form; 2) leader malformation; and 3) dominance.

Nonetheless, specific tests of selection ratios from 1 to 6 showed that stem form improved markedly with increasing selection ratio (MacLaren & Kimberley 1991). As selection ratio moved from 1 to 6 the percentage of pruned logs that were straight, round, and had no scars moved from 74% to 94% (Figure 6), and from 70% to 90% for unpruned logs. James (1979) had studied the impact of selection ratio and tree breed on the proportion of defective stems in the same experiment. Increasing selection ratio improved the quality of the crop trees, but the rate of improvement slowed with increasing selection ratio. There was a marked improvement changing from a selection ratio of 1 to 2, but much less improvement going from a ratio of 2 to 3.

It should be noted that in the experiment quoted above, researchers selected the crop trees. In practice, thinning contractors usually select crop stems, and they may sometimes pay little heed to stem form. In the area of toppled trees reported by Mason (1985), a return to the site after thinning showed that the contractor had selected large trees but his choice was unrelated to stem form. In such circumstances selection ratio could have minimal impact on final crop quality.

The importance of selection ratio may vary with genotype. Studies by James (1979), Maclaren & Kimberley (1991) and by Wilcox & Carson (1990) showed that improved breeds had more acceptable trees. When evaluating the effects of improved breeds and the consequences of breeding on selection ratio, more emphasis should be placed on stem quality than on leader quality.

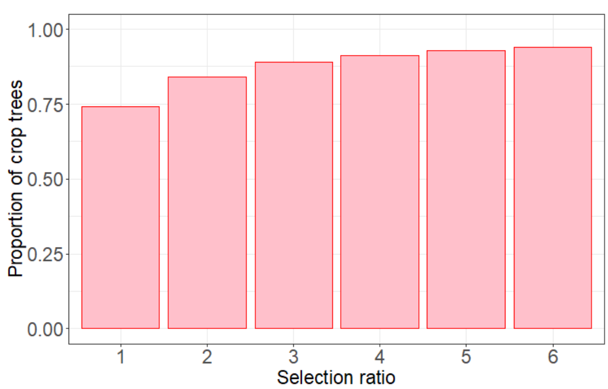

FIGURE 6: Effect of selection ratio on proportion of pruned logs that are straight and round (MacLaren & Kimberley 1991).

Using radiata pine cuttings may also influence choice of selection ratio, with cuttings from aged parents requiring lower selection ratios than seedlings in order to achieve an equivalent quality among crop trees (Menzies et al. 1989).

Effects of stand density on branching

Branch index

Branch index (BIX) is the mean of the largest branch in each of the four quadrants of a log for radiata pine in New Zealand. Strength and stiffness of wood obtained from logs decreases with an increase in BIX (Bier 1986). A model to predict branch index of radiata pine included dbh at age 20 years, the inverse of predominant mean height at final thinning, site index, and log height class. Initial spacing (1370-5100 stems/ha) was not related to BIX (Inglis & Cleland 1982).

However, at the Tikitere agroforestry experiment branch index was strongly correlated with stand density; BIX in the second log decreased from 12.3 to 5.5 cm as stand density increased from 100 stems/ha to 400 stems/ha (Figure 7) (Knowles et al. 1993). Shelterbelts also show strong correlations between stand density and BIX (Tombleson & Inglis 1986). In Inglis & Cleland's (1982) model, dbh at age 20 years reflected stocking, as did the inverse of predominant mean height. A revision of the branch index model included initial stocking, however in a validation of the revised model it was suggested that the model also needed final crop stocking as an independent variable (Tombleson et al. 1990). Departures from the model showed that BIX of the second log decreased with site index and stand density. The revised model included regions and had different coefficients for different 6 m logs up the stem (Kimberley & Knowles 1993).

Branch angle

In a study of branch development of radiata pine, Grace et al. (1998) found a positive correlation between branch diameter in a cluster and branch angle from horizontal at time of harvest. If this correlation applied between stands, then as branches tend to decrease in diameter with stocking (Knowles et al. 1993; Waghorn et al. 2007a), we might expect branches to have a smaller angle at higher stockings. However, unpublished data obtained by the University of Canterbury from an experiment in the Canterbury foothills showed that branch angle increased with stocking for unimproved radiata pine, and that highly improved breeds had lower angles irrespective of stocking in an experiment comparing growth and development of seedlots with growth and form ratings of 1 and 27 at stockings of 2500 stems/ha and 833 stems/ha.

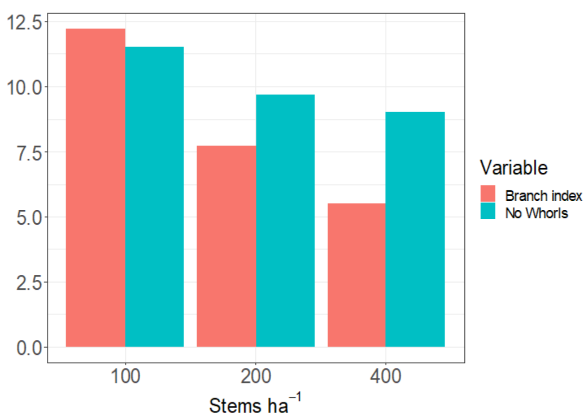

FIGURE 7: Branch index (cm) and number of whorls in the second log vs stocking at the Tikitere agroforestry experiment (Knowles et al. 1993).

Internode index

Studies of the effect of stand density on internode index, the ratio of all branch segments over 60 cm for the total 5.5 m log, have yielded conflicting results. Knowles et al. (1993) found that as final crop stocking increased from 100 to 400 stems/ha whorl numbers decreased and internode index in the second log increased from 0.04 to 0.22. However, Maclaren (1990) reported that internode index was unrelated to stocking between 117 and 383 stems/ha. Grace & Carson (1993) assumed that a measure of stand density was not required in their model that predicted internode length from mean annual rainfall, elevation, and "level of genetic improvement" after examining a few plots that included different stocking levels. Woollons et al. (2002) found that internode index was independent of stand density, across a large dataset that included a range of selection ratios. It is likely that internode index increases with stocking because of increased height growth with stocking, and this effect would only be detectable when selection ratios were held constant as at Tikitere.

Carson et al. (1988) found that internode lengths varied with both genotype and site, and so both factors should be taken into account when manipulating stockings to change internode length. Tombleson et al. (1990) found that internode index increased with site index, but found no clear relationship with final crop stocking.

Implications for pruning

Having larger branches at the beginning of the rotation means that pruning will cost more, and that occlusion of pruned branch stubs may take longer. While these observations are anecdotal, it should be noted that diameter over occlusion is related to diameter over stubs (DOS) (Park 1980), and to the extent that DOS increased with stand density, diameter over occlusion would also increase. With more tapered stems in a lowly stocked stand, more frequent and smaller pruning lifts would be required to maintain the same DOS as in a more highly stocked stand. This would affect the profitability of a clearwood regime.

It is well accepted that for any given species and site there is an optimum final crop stocking for a pruned regime that provides the best return on investment (see below), and that this stocking declines with site quality. Moreover, numbers of lifts, pruning severity and target DOS will also vary with site and final crop stocking.

Branch models
At least two comprehensive branch models have been built for radiata pine in New Zealand. The model of Grace et al. (1999) includes an index that allows branch size to increase as relative spacing increases. Accurate estimates of height growth are critical for this model to predict branch formation accurately.

A different, probabilistic approach to modelling branches was taken by Woollons et al. (2002). This reduces the dependence of the model on estimates of height growth that are notoriously difficult to predict from year to year. Variation in stocking influences branch size through its effect on dbh in this model, and so stocking is not used directly as an independent variable.

Effect of genotype
Implications of effects of stocking on branch size may vary with genotype. Shelbourne (1970) reported that, compared to unimproved radiata pine, the "850" breed of radiata pine had 19% smaller branches in the first log, and 11% smaller branches in the second log. Watt et al. (2000) reported that the "850" breed had 1 cm smaller BIX than the "870" breed, and that this was correlated with smaller internodes for the "850" breed.

Effects of stand density on wood quality

Wood density
Wood density has been found to increase with increasing distance from the pith of a tree in a nationwide survey of wood qualities (Cown et al. 1991). Here, distance was measured in terms of number of growth rings from the pith and was found to be "largely independent" of diameter growth rate.

Density often increases with increasing stocking (Downes et al. 2002; Yang & Hazenberg 1994). At Tikitere, mean-tree wood density decreased from 378 kg/m^3 to 362 kg/m^3 as stocking increased from 100 stems/ha to 400 stems/ha. This was explained by a higher proportion of wood within the first few growth rings at higher stocking.

Wood basic density of radiata pine decreased markedly at lower latitudes and with increasing elevation (Cown et al. 1991). This is a function of temperature, which is very highly correlated with elevation and latitude in New Zealand (Norton 1985). Palmer et al. (2013) found that radiata pine outerwood density increased with mean annual temperature and Kimberley et al. (2015) found that density decreased with ring width, ring number from pith, and also noted lower density in cooler regions. Wood density may be an important issue for structural regimes on lower quality sites, therefore.

Wood stability
Shrinkage of wood is positively correlated with wood density. One might expect higher shrinkage on average, especially from radiata pine corewood, with lower stockings, but whether differences in shrinkage within boards would increase with stand density may depend on the sawing patterns adopted. Microfibril angle (MFA) influences longitudinal shrinkage, and high radial gradients in MFA may account for instability during drying to a far greater extent than gradients in density (Harris & Meylan 1965; Ivkovic et al. 2009; Megraw et al. 1998; Pentoney 1953; Yang et al. 2003). Correlations between density and instability may therefore be spurious.

Stiffness
Along with stability, stiffness, expressed as modulus of elasticity (MOE), is an extremely important wood quality. Little is known about the reasons for variation in stiffness of radiata pine within a tree, but MOE tends to increase with distance from pith and it is hypothesised that decreases in microfibril angle (MFA) with ring number from the pith may explain the phenomenon (Walker & Butterfield 1996). MOE has been found to be more highly correlated with MFA than with density in the corewood zone (Walker & Butterfield 1996). Studies of outerwood in Douglas fir, however, indicate that wood basic density may be more important than MFA in this zone where variation in MFA is much smaller (Lachenbruch et al. 2010).

Wood stiffness is affected by stand density. For example, increasing initial stocking from 833 stems/ha to 2500 stems/ha increased radiata pine MOE in the first 10 growth rings by 40% (Lasserre et al. 2004). This effect was shown to be independent of genotype and site. Genotype and stand density independently influenced distributions of MOE up trees in a Nelder spacing experiment in Canterbury, with MOE being highest in the second 6 m log than in the first, then declining towards the top of a tree (Waghorn et al. 2007b). This longitudinal pattern was more prevalent at higher stockings, and overall stiffness increased with stocking.

Corewood
The inner portion of a radiata pine stem contains wood of lower density, smaller tracheids, higher MFA, higher longitudinal shrinkage, and lower stiffness (Burdon et al. 2004). The corewood zone has been defined as the first 10 rings from the pith of a radiata pine log (Cown 1992), 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. 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 cell wall layer relative to the tracheid axis (Walker & Butterfield 1996). Higher 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 & Nakada 1999).

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 at planting tends to improve the properties of corewood; that different genotypes produce different quantities of corewood (Wu et al. 2008); and that genotype and stocking tend not to interact in our experiments (i.e.: their effects are additive) (Lasserre et al. 2004; Lasserre et al. 2005; Lasserre et al. 2007; Waghorn et al. 2007b). Mean MFA in growth rings has been shown to increase following thinning of radiata pine (Grace & Evans 2012). There are several theories about factors that drive corewood formation, but none have been shown to be entirely consistent with experimental results (Lachenbruch et al. 2010; Mason 2008).

Using an assumption that there was a constant number of corewood rings in all trees, West (1997) examined the impacts of site and silviculture on amount of corewood. Different stockings with constant selection ratios were simulated using the Standpak modelling system (Whiteside 1990), and the exercise suggested that there would be little difference in corewood proportion with changes in stocking. However, using different selection ratios (and initial stockings) to achieve the same final crop stocking would probably result in an increase in corewood proportion with decreasing selection ratio, as early individual tree growth would be more rapid with lower selection ratios. The assumption of a constant number of corewood rings in West's (1997) analysis is almost certainly incorrect (Lasserre et al. 2004; Lasserre et al. 2005). Given that corewood occurs all the way up a tree (Waghorn et al. 2007b), the name "juvenile wood" is not logical either, and causes of the phenomena that make up corewood remain topics for future research.

There is evidence from a Nelder experiment at Rolleston, New Zealand that corewood may not be a major issue for eucalypts, and that relationships between wood quality and stocking may be quite different (Figure 8) from those evident in gymnosperms (Watson 2013). Wood quality of radiata pine was far more influenced by stand density than that of *Eucalyptus nitens* (H.Deane & Maiden) Maiden. We don't know for sure that this is an angiosperm/gymnosperm difference because we have only two species in the Nelder, but it is possible.

Reaction wood

In gymnosperms compression wood has lower cellulose, more lignin, reduced tracheid length, and is undesirable. Toppling of juvenile radiata pine is a common cause of reaction wood in tree stems (Harris 1977; Mason 1985; Mason 1992). For any given toppling rate, lower selection ratios would limit the ability of a manager to thin out previously toppled trees containing large amounts of compression wood. As lower stockings may promote wind damage (Fraser 1964; Somerville 1989), proportions of trees with reaction wood may increase as stocking decreases. "Flexure wood" with higher microfibrial angle, lower density and lower MOE has been postulated as a response to tree sway (Telewski 2016).

Resin pockets

Resin pockets can result in significant value loss in appearance products (Cown 1973b; Cown et al. 2011). In one study, a loss in value of radiata pine veneer bolts of up to 45% was reported (Park & Parker 1982). Causes of resin pockets are unknown, but if, as is sometimes postulated, they result from tree sway, then lowering stocking may increase resin pocket frequency by increasing tree sway (Fraser 1964). They are more prevalent in windy and dry locations (Woollons et al. 2008), which supports the sway hypothesis, but guying to prevent tree sway did not decrease resin pocket frequency in one study (Moore et al. 2014).

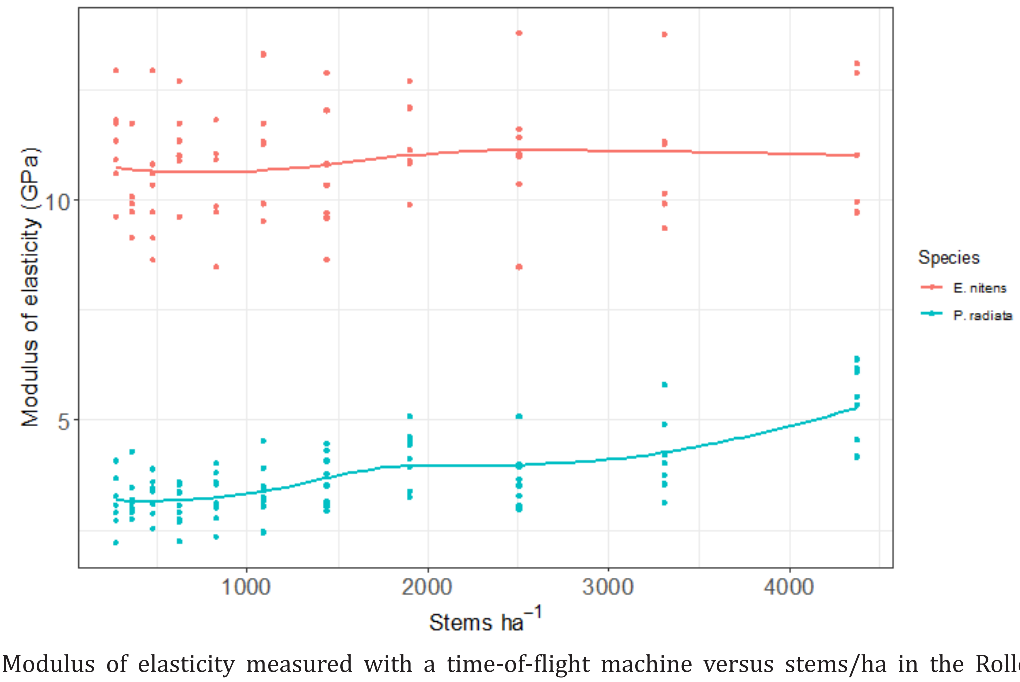

FIGURE 8: Modulus of elasticity measured with a time-of-flight machine versus stems/ha in the Rolleston Nelder experiment at 5 and 6 years of age for *E. nitens* and *P. radiata* respectively (Watson 2013).

Heartwood
Radiata pine does not produce durable heartwood, but heartwood formation may be important for managers for two reasons: a) it has lower moisture content than sapwood and may influence log weight to volume conversions; and b) lower moisture content influences estimates of velocity of sound in logs thereby affecting estimates of MOE based on acoustic testing. Heartwood requires different drying schedules from sapwood, and closed pits generally reduce the chemical preservative uptake of heartwood, relative to sapwood. A survey of wood properties suggested reasonably consistent average numbers of heartwood rings in radiata pine at breast height, but they varied somewhat with region (Cown et al. 1991).

There is little information on the relationship between heartwood formation and stand density in radiata pine, however, a taper and volume model created by Boczniewicz et al. (2022) suggests that a greater proportion of heartwood should form in *Eucalyptus globoidea* Blakely trees at wider spacings, with greater taper. This implication is corroborated by two studies of heartwood formation versus tree density in other eucalypt species (Brito et al. 2019; Gominho & Pereira 2005). Variability in the quantity of heartwood in *Podocarpus totara* trees diminished with dbh, and the proportion of heartwood also increased with dbh in a study of regenerating totara stands in Northland, but heartwood quantities also varied markedly with sites (Steward 2019).

Impacts of stand density on log grade
Two studies have investigated the impact of stand density or selection ratio on volumes of different log grades in radiata pine. Maclaren & Knowles (1999a) did a "MARVL" (Method for Assessment of Recoverable Volume by Log Type) assessment (Deadman & Goulding 1978) of the Tikitere agroforestry experiment at age 21 years and simulated results at older rotation ages. This study examined different final crop stocking levels with identical selection ratios. Results showed that, as expected, far greater volumes were produced at higher stand densities (400 stems/ha). There were greater amounts of pulpwood at lower stand densities (100 stems/ha), but volumes of all other log types increased with stocking. Small-branched saw logs were much more abundant at higher stocking levels. Piece sizes were much greater at lower stocking levels, and it was assumed that lower stocking levels produced higher mean clearwood indices (small end diameter - defect core diameter) (Maclaren & Knowles 1999b). However, across a range of 250-500 stems/ha the volume of the largest 200-300 stems/ha may be little affected by stocking (J. Moore, pers. comm.), as suggested following analysis analysis of a stocking experiment related to final crop stocking in pruned crops (Whyte & Woollons 1990).

Maclaren & Kimberley (1991) conducted a MARVL assessment of the experiment reported by James (1979) that examined alternative selection ratios (1-6) to achieve the same final crop stocking. There was an increase in height growth with increasing stocking, but no increase in diameter growth. This effectively reduced predicted taper, resulting in greater volumes of pruned logs as well as greater volumes overall with higher selection ratios. Increasing selection ratio from 1 to 6 increased pruned volume from 116 m^3/ha to 146 m^3/ha and total standing volume from 340 m^3/ha to 397 m^3/ha. Higher selection ratios also produced a greater proportion of straight logs. As in James' (1979) study, the rate of increase in volume and log straightness slowed with increasing selection ratio.

Effects of stand density on wind damage
Effects of stand density on wind damage have been rarely studied. Anecdotal evidence suggests that while trees can develop resistance to persistent exposure, lower stocked stands are more susceptible to wind damage. A mechanistic model of wind damage in stands indicated that lower stocking led to a higher likelihood of uprooting of *Picea sitchensis* due to greater wind loading on broader canopies (Nicoll et al. 2009). Research supports these hypotheses. For instance, Wind tunnel tests with model trees showed that increasing distance between trees from 25% of height to 40% of height doubled the bending moment experienced by individual trees (Fraser 1964). Moreover, radiata pine trees subjected to sway developed more taper and larger anchoring roots than adjacent trees prevented from swaying (Jacobs 1954). This implies that trees would be more susceptible to wind throw immediately after thinning, an implication that is also supported by anecdotal evidence.

General trends of decreasing wind damage with increasing stockings have also been noted. Somerville (1989), in a review of wind impacts on forests reported that there was generally more damage during storms with lower stockings. At Tikitere wind damage increased with lowered stocking rates. 41% of trees were damaged at 50 stems/ha while only 24% were damaged at 400 stems/ha (Knowles et al. 1993). Cremer et al. (1982) however, found that wind damage was higher in recently thinned stands of radiata pine with more slender trees, at higher stockings prior to thinning.

Impact of stand density on weed growth
Higher stand density may reduce impacts of weeds, but the topic has been rarely studied. Knowles et al. (1999) reported an inverse non-linear relationship between canopy closure and pasture production. Canopy closure was linearly related to basal area for young crops but rose to an asymptote at 60 m^2/ha. Increasing initial stocking would reduce pasture production at a rapid rate according to their models.

The initial growth model for radiata pine (Mason 1992; Mason et al. 1997) when combined with Knowles et al.'s (1999a) model suggests effects of tree competition on pasture productivity could be important by age 3 years on a typical Central North Island site at 200 m elevation.

Rectangularity of initial spacing
Plantation managers typically plant trees at rectangular spacings, with smaller distances among trees within rows than among rows. This reduces costs of site

preparation, planting, and post-planting care and also improves access for mechanised thinning. The effects of rectangularity in spacing on branching have not been fully investigated for radiata pine, but Sutton (1970) noted that rectangularity of initial spacing had no detectable effect on branch size, with rectangularity up to 1.8 x 7.3 m.

Tikitere's twin row treatment, at 100 stems/ha but with distances within pairs as if they were planted at 400 stems/ha can be compared with the more evenly spaced 100 stems/ha treatment. Results at age 25 years showed a reduction in dbh from 75 cm to 69 cm due to rectangularity, and increase in mean top height from 33.1 m to 34.6 m. This equated to a drop in total standing volume from 400 m^3/ha to 368 m^3/ha (Knowles et al. 1993).

Grace (1990) used a process-level model of light interception to evaluate a variety of initial spacing configurations through simulation. Regular (square) spacing produced the highest rates of net photosynthesis in a ten-year-old stand. As rectangularity increased, growth dropped by a small amount (3%). She also found seasonal differences in orientation of rows relative to a north-south direction.

Group planting is an alternative planting configuration that may facilitate selection of crop trees. The idea is to plant the selection ratio number of trees in each group, and then aim to finally select only one tree from each group. Results showed that grouping at time of establishment resulted in less damage during production thinning and production thinning was more economical when compared to more conventional line layouts at time of planting (Terlesk & McConchie 1988).

Financial analyses of alternative stand densities

Choices of planting spacing, selection ratio, and final crop stocking are heavily dependent on objectives of forest owners, product prices, costs, and interest rate assumptions. Maclaren (1990) found that the financially optimum final crop stocking for clearwood regimes of radiata pine varied inversely with interest rate. Moreover, optimum stocking was higher with a higher site index, because higher site indices resulted in larger branches in the second log which can be controlled by higher stocking, and also because high investments in pruning many final crop trees can be justified only on good sites with rapid dbh growth. The optimum stocking increased with rotation length and decreased with an increased price for clear wood. Whiteside et al. (1997) reported that simulations followed by financial analyses showed 250 stems/ha was the most profitable stocking for clearwood regimes, and that 350 stems/ha hectare should be adopted for unpruned regimes, but this assertion is too general, as shown by Maclaren (1990). Maclaren & Kimberley (1991), however, found that choice of selection ratio was highly dependent on interest rate, with high interest rates resulting in low selection ratios.

Regimes for radiata pine changed markedly as people studied the impacts of pruning and thinning strategies on log values at harvest (Figure 9). More than just final crop stocking must be considered when designing a regime. Initial stocking, selection ratio, and timing of thinning operations can affect productivity, tree geometry and wood value. It is also clear that financial factors and assumptions as assessments of risk profoundly affect choice of stocking. For instance, Gadgil (1990) found that wide spacing, pruning, and heavy thinning

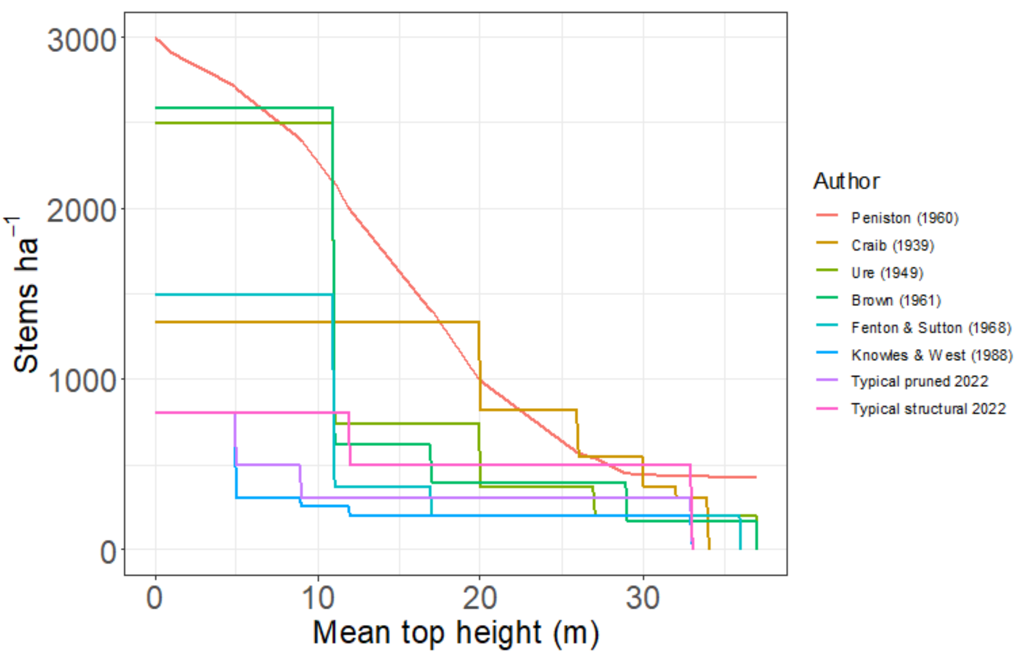

FIGURE 9: Evolution of stand density management for radiata pine in pruned regimes (Brown 1961; Craib 1939; Fenton & Sutton 1968; Knowles & West 1988). This figure was originally conceived by James (1990).

decreased impacts of *Sirex noctilio*, *Dothistroma pini*, and *Cyclaneusma minus*, while potentially increasing exposure to *Armillaria* spp.. Management of stand density, however, is a key to good silviculture, and more research is needed to improve our understanding of its effects.

Pruning for clearwood

Estimating pruned log value

Generally pruned log index (PLI) (Park 1989) is used for valuing pruned logs. This index includes three important factors affecting the proportion of full-length boards sawn from of log that will be clear of knots: (1) overall log size, generally measured by small end diameter; (2) diameter of the defect core, containing knots and pruning scars; and (3) defects in log shape such as sweep. Larger logs generally produce a greater volume of sawn timber per unit volume of round log than small logs, all other things being equal. Rate of conversion from round log to sawtimber is also influenced by sweep and taper, both of which result in more boards that include bark. PLI can be determined from measurements of diameter over stubs, the diameter around pruned branch stubs (DOS), at time of pruning and then measurements of tree dimensions and sweep at time of harvest, or by destructively sampling a small number of trees on a stand prior to harvest (Somerville 1985).

Stubs of branches that are well-pruned, leaving only the tissue around the base of the branch, will occlude as stem diameter increases and the collar tissue grows in from all sides. This is known as occlusion. When the collar tissue meets adjacent tissue in the middle of the branch stub a small amount of bark is encased, and this is known as an occlusion scar. The diameter of the defect core can be measured or predicted if DOS, the lengths of occlusion scars, and variation from straightness of the stem at time of pruning are all known. Generally, diameter over occlusion scars (DOO) is predicted from DOS (Figure 10), which in turn is either measured immediately after pruning or predicted with a model created from measurements (Park 1982). The predictive model generally includes a taper function for small trees.

FIGURE 10: A disc cut at a branch whorl several years after pruning. DOS would be measured around the cut branch stubs shown in the upper half, while radial length of the thin, encased bark extending from pruned branches during occlusion needs to be added to DOS to calculate DOO.

The largest DOS is usually at the base of any given pruned section, or pruning lift, of a tree, and as trees are usually pruned in several lifts, it is important to keep the DOS of each lift even. The largest DOS in a pruned log will determine the contribution of DOO to the defect core size in a pruned log index estimate.

Pruning in several lifts

Pruning of a buttlog is generally done in several lifts because a) we wish to have the a relatively even diameter of defect core in a pruned log, b) tree stems taper, and c) we also wish to retain enough foliage to keep pruned trees vigorously growing (Koehler 1984). Pruning green branches reduces diameter growth during the years immediately following pruning (Figure 11) (Mason & Hayes, in prep). Retaining crown lengths of at least 55% of total height has been recommended as a way to prune with minimal effects on dbh growth of radiata pine (Neilsen & Pinkard 2003). However, foresters routinely prune more heavily than this, and widely quoted rule of thumb is to leave 3-4 m of green crown following pruning of radiata pine in New Zealand irrespective of how far up the tree pruning has extended.

It is likely that pruning of radiata pine in New Zealand routinely impacts quite strongly, but temporarily, on dbh growth. It is generally accompanied by thinning, but thinning is essential to accumulate clearwood rapidly enough to make pruning pay, and selection ratios of 2-3 are usually required so that enough well formed, productive trees are available for the final crop.

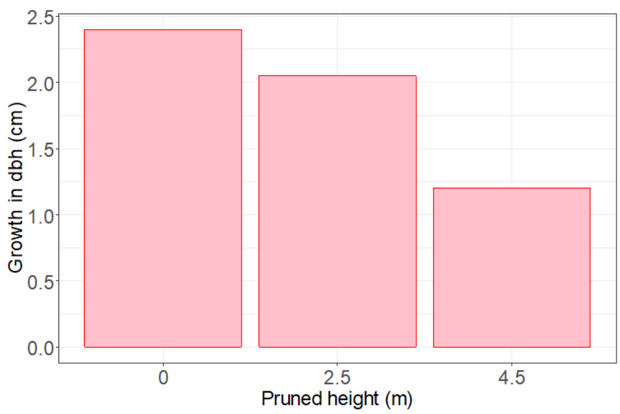

FIGURE 11: Growth in dbh of radiata pine trees during the year after pruning versus pruned height in an experiment at Dunsandel in Canterbury.

Pruning has been shown to change the taper of young radiata pine and *Pinus pinaster* trees and make the bases of the trees more cylindrical, but the changes were temporary and undetectable after a few years (Hevia et al. 2016).

The amount of canopy left on a tree after pruning affects light interception, and therefore the impact of pruning on dbh growth (Bandara et al. 1999; Lange et al. 1987; Sutton & Crowe 1975). However, as trees have tapered stems, leaving more canopy results in a larger DOS in the next lift, given the same delay for the next lift, and DOS size should be consistent between pruning lifts to promote reasonable PLIs while not incurring needless loss in growth (Figure 12).

There are two ways to ensure DOS values remain small, thus limiting the size of the defect core: (1) Leave less canopy so that the diameter at the base of the canopy is small for the next lift, thus reducing diameter growth; or (2) have more and more frequent pruning lifts to reach the desired pruned height (usually 6 m in radiata pine in New Zealand), thereby raising the pruning investment in each tree. As outlined above, stand density also influences dbh growth, and so in order to to grow clearwood rapidly enough to keep ahead of the compounded cost of pruning trees need to be given plenty of growing space. However, as also shown above, below about 500 stems/ha, reducing final crop stocking results in lower volumes at harvest. A secondary consideration is that if stand density is too low then branches in upper logs become too large (particularly on very productive sites), lowering their market value (Maclaren & Knowles 1999a 1999b). Moreover, if stand density is reduced too much too early, or the delay between lifts is too long, pruned branches will be large, increasing the cost of pruning. Large branch stubs also increase the lengths of occlusion scars and DOOs.

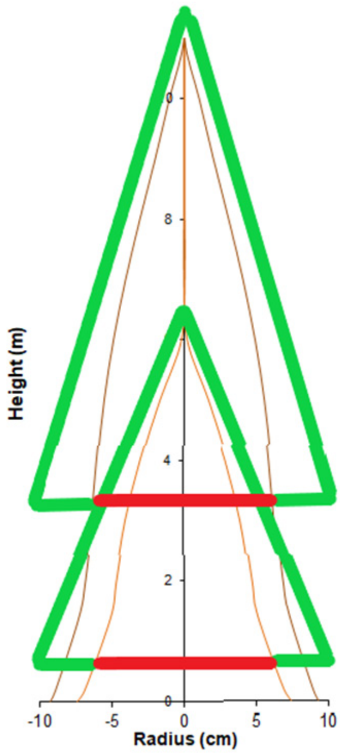

FIGURE 12: An example of good pruning scheduling. The green lines show the canopy just prior to two different times when pruning is undertaken. The brown lines show the stem shapes at those times, and the red lines show the DOS created at each pruning lift. The first pruning lift was to 3.3 m. In this case the two DOS values are identical in extent. Stem radii and heights are not shown to the same scale.

An alternative way to increase total standing volume and the volume of clearwood at harvest is to have longer rotations, which of course means that harvest revenues are more discounted in discounted cash flow analyses and pruning is less likely to pay. This means that there is a balance to be found between canopy remaining after pruning, number of pruning lifts, DOS size, thinning time, thinning intensity, final crop stocking, upper log branch size and rotation length. Silviculturists need to find the combination of these variables that maximises net present value or land expectation value on any given site and for any given species.

In some cases, managers may decide to keep trees pruned to widely different extents in their stands (Figure 13). Groups of trees pruned to roughly the same extent are known as "stand elements", and they will grow at different rates. Modelling these different basal area growth rates is an important part of a decision-support system aimed at assisting with pruning scheduling (West et al. 1982).

Making decisions about silvicultural regimes

In practice decisions about tending and rotation length in pruned regimes are made through simulations on computer once models have been carefully calibrated for any given site (West 1997; Whiteside 1990; Whiteside et al. 1997). The best regimes are usually found by pruning when the target DOS size is reached for each successive lift and when each tree is pruned to a height that results in the same amount of retained canopy length per tree. Repeated simulations with different DOS targets, numbers of lifts, final crop stockings, and rotation lengths followed by discounted cash flow analyses of entire regimes will allow silviculturists to find optimum schedules.

Models required in silvicultural simulators are: (1) plot-level growth and yield simulators of mean top height, basal; area/ha and stocking that are sensitive to site quality as well as pruning and thinning treatments; (2) accompanying models to represent distributions of tree sizes or individual tree lists; (3) compatible taper and volume models for both young and old trees; (4) predictions of DOS and DOO dimensions sensitive to stocking, tree size, and pruned height; (5) branch size distribution models sensitive to stocking and position on the tree; (6) bucking models that can accommodate a range of user-defined log grades; and (7) predictions of pruned log index. Experiments and PSPs aimed at characterising impacts of tending on growth, yield and value of forest stands should be designed to facilitate the creation of the models outlined above.

FIGURE 13: In this stand there are two stand elements, a pruned element, and an unpruned element.

Types of spacing and tending experiments

Nelder designs

Nelder (1962) first developed the idea of a circular spacing experiment with spokes spaced so that spacing increased from the center to the outside to determine the optimum spacing between vegetables. Several Nelder experiments have been established in New Zealand plantations (Sevillano-Marco et al. 2015; Waghorn et al. 2007b), and in 2008 we established a Nelder design spacing experiment at Rolleston containing two species; *E. nitens* and *P. radiata*. (Figure 14).

Nelder designs are very efficient, examining large ranges of stockings in very small areas, but the idea of replication in Nelder designs is problematic. Generally, people analyse them using regressions assuming that

FIGURE 14: A satellite image of the Nelder experiment at Rolleston.

site variation is not important within the experiment. Moreover, when trees grow larger, significant mortality occurs, and then the Nelder rings no longer represent the stockings that they had at time of planting. Thinning is almost never a feature of Nelder designs. To overcome the analytical problem of competition-related mortality, analyses can be conducted using only trees with a full set of neighbours and then the results can be compared with an analysis using all trees.

Nelder designs can be used to investigate impacts of spacing on stem dimensions, branch size, and wood quality (Naylor 2013; Sewell 2009; Watson 2013).

Block stand density experiments

Block stand density experiments take up much larger areas than Nelder designs, can examine fewer stocking levels and are far more costly, but they have four important advantages: (1) true replication is feasible and so statistical analyses can be done without awkward assumptions about site variation; (2) various thinning regimes can be compared; (3) analyses can be conducted until the ends of rotations in large plots with buffer surrounds, so that harvest values can be fully assessed; and (4) they can be used to evaluate pruning and thinning schedules simultaneously.

An experiment with various initial stockings and thinning strategies has been established at Rolleston, near Christchurch in the South Island of New Zealand (Figure 15). This experiment has three different initial planting densities and will eventually have the same final crop stocking in each plot. In addition, the experiment includes weed control, fertiliser application and genetic treatments. Other block stand density experiments, such as the Tikitere agroforestry experiment (Knowles et al. 1993; Maclaren & Knowles 1999a 1999b), have also proven their worth.

Data from permanent sample plots (PSPs) can be used in an attempt to accurately incorporate thinning regimes into model simulations, but these comparisons are often biased because different strategies may be applied to different sites, and it may be very difficult to determine what would happen if those regimes were applied to sites where they were not represented in the PSP database. Impacts of stand density are often inferred in growth and yield models when PSP datasets include a wide range of stand density and thinning treatments. While moderately successful in some circumstances, such analyses are prone to a lack of balance and confounding, and so they are best used when well-designed experiments are available to corroborate effects fitted in models.

FIGURE 15: A satellite view of the Rolleston stocking experiment in October of 2009, just over 4 years after planting.

Discussion

Future tending research needs

New Zealand's plantation forestry companies are increasingly adopting structural silvicultural regimes instead of pruned regimes for radiata pine stands (Mason 2012), and this is influencing our decision-support system and associated tending research requirements.

Our strategy in pruning regimes was to sacrifice volume production in exchange for high value products, leading to regimes with very low stocking by international standards, but this must be tempered by the impacts of very low spacing on branch sizes in the upper logs. Structural regimes generally require far less investment per tree, and key considerations are now wood stiffness, wood stability and volume production, with high financial returns once wood reaches a modulus of elasticity of 8 GPa, the standard required for building timber. Piece size is also important to ensure low logging and transport costs as well as high mill conversion rates. Consequently, some of the key questions are:

1. As both high initial stocking and genotype can improve corewood stiffness and stability, and they do not interact (Lasserre et al. 2004; Lasserre et al. 2005), what combinations of these two factors are best used on a range of sites to maximise value for forest growers?
2. Structural regimes are likely to contain higher stockings than pruned regimes, and so mortality will be a more critical consideration. How does maximum stand density index vary across our sites, and is SDI a good framework in which to design structural regimes?
3. There is evidence that radiata pine stands with lower genetic diversity have lower rates of canopy competition dynamics, resulting in more uniform crops (Sharma et al. 2008), and this would be highly relevant if managers wished to establish stands with minimal or no thinning. What is the best combination of initial stocking and genetic composition for structural regimes that rely on canopy dynamics rather than thinning to achieve large piece sizes at time of harvest on a range of sites?
4. What frequency of defects should we expect in un-thinned stands on a range of sites with a variety of genotypes where canopy dynamics are used instead of thinning to ensure large piece sizes at harvest?
5. Can mechanical tree planting reduce costs of establishment to the point where high initial stockings that improve wood quality become more cost-effective?
6. Can we develop an easily employed structural log index (Mason 2012), similar to PLI so that that market feedback to silviculturalists designing structural regimes is effective?
7. What are the mechanisms influencing the development of corewood (Mason 2008) in radiata pine, and how should we intervene to improve corewood properties?
8. If wood quality can be sufficiently improved, can extraction thinning be employed profitably in structural regimes?
9. Can tending of radiata pine be improved to the point where it will not be replaced with other species, such as naturally durable eucalypts (Millen et al. 2018), that produce inherently better wood quality, or are those other species the best solution?

Suggested tending experiment strategy

Growth and yield models can be built with standard permanent sample plots (PSPs) located in forests managed in conventional ways, but they are more secure if they are informed by analyses from designed experiments. Designed experiments enable us to push the boundaries of current silvicultural strategies and ensure that if management strategies change we can make decisions without extrapolation. Relying solely on PSPs results in models that are well parameterised for prevailing management practices but which may be badly biased when alternative strategies are modelled. However, PSPs have the advantage that we can cover a wide range of site types relatively efficiently. If we also use hybrid models (Mason et al. 2011; Rachid-Casnati et al. 2020) then these models are likely to be more secure in modelling alternative silvicultural strategies so long as impacts of such strategies on radiation use efficiency are known.

The first pillar of a tending strategy should therefore be to measure permanent sample plots across as wide a range of site and management types as possible. Many PSPs already exist, but new PSPs are required to cover the full range of silvicultural regimes, genotypes and site types.

Silvicultural strategies are likely to vary with site type, and so ideally we should have silvicultural experiments across a range of sites as well, but the cost of this would mount very quickly. The cheapest form of stand density experiment is a Nelder design. These have the advantage of taking up about a hectare each and providing a very wide range of stockings. They can be used to explore impacts of stand density on external stem dimensions, branching, mortality and acoustically or electrically determined wood properties. They are useless for determining impacts of thinning and alternative pruning strategies, however.

The second pillar of a tending research strategy should be to establish a range of Nelder experiments across site types. Each one should include a meteorological station. Data from past Nelder experiments should be fully analysed prior to establishing new ones. Designed plot-based experiments allow us to examine impacts of pruning and thinning, and can also be designed to allow destructive harvesting for biomass and wood quality assessment at a range of ages. They allow us to compare a limited range of most likely silvicultural strategies across a limited number of sites and species, because they are expensive.

The third pillar of a tending research strategy should therefore be to establish designed tending experiments, across a range of sites containing a variety of silvicultural strategies. These experiments should include meteorological stations, soil moisture monitoring, and plenty of provision for destructive harvesting of trees so that we can explore *why* things happen rather than just *what* happens. Data from older designed experiments could be included in future analyses, but we lack experiments for new silvicultural approaches, particularly with improved breeds in unpruned crops.

Conclusions

A unique approach to tending plantations developed in New Zealand that involves sacrificing volume production to increase the value of an investment in pruned forest stands. Experiments aimed at building decision-support systems for these silvicultural regimes have yielded a great deal of information about impacts of pruning and thinning in stands with relatively open canopies. Recent changes in focus towards growing construction lumber require a greater research focus on factors influencing wood stiffness and stability as well as a clear understanding of the use of higher stockings with a variety of genotypes on a range of sites. Stand dynamics and mortality will be more relevant than for pruning regimes, and a variety of new experiments is required.

Competing interests

The author declares he has no competing interests.

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