# WOOD DENSITY OF RADIATA PINE: EFFECT OF NITROGEN SUPPLY

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## FOREST & FARM PLANTATION MANAGEMENT COOPERATIVE

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# EXECUTIVE SUMMARY

## WOOD DENSITY OF RADIATA PINE: EFFECT OF NITROGEN SUPPLY

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## ABSTRACT

In a comparison of 27 year old *Pinus radiata* D.Don on a nitrogen deficient coastal dune and growing with or without lupin plus fertiliser, mean wood density, earlywood density, and latewood density in individual annual growth rings were significantly lower in treated compared to control stands. Latewood percent showed a similar pattern of variation in relation to treatment and tree age when the ring was laid down. Wood density and late wood percent increased radially from pith to bark, both increasing more rapidly in unfertilised compared to fertilised trees. Mean density, earlywood density, and latewood percent were significantly related to tree nitrogen status, as reflected by foliar analysis undertaken in the year rings were laid down, and ring age. Other foliar nutrients tested (P, K, Ca, Mg, B, Mn, Zn, Cu) did not appear to influence wood density when analysed in the presence of N.

Wood density was high at this trial site by NZ standards, even in fertilised stands, which can be explained at least partly by the low foliar N levels at Woodhill Forest. These exceeded 1.2% only in stands younger than 5 years old. Thereafter, foliar N decreased to approximately 1.2% in fertilised stands receiving 100kg N/ha of fertiliser annually for 10 years, and 0.8% in unfertilised controls. Foliar N levels on recent sands typically fall in the range of 0.9 - 1.2% at Woodhill Forest, compared to 1.2 - >1.5% in most other soil types in NZ. Effective rainfall at Woodhill also tends to be lower than other forest growing areas in New Zealand. At Woodhill, low rainfall during autumn/winter/spring was associated with high latewood percentage and hence high ring mean density, while low summer rainfall had the opposite effects.

**Keywords:** Wood Density Prediction, Foliar Nitrogen, Wood Quality, Carbon Sequestration

# INTRODUCTION

In New Zealand, *Pinus radiata* D. Don has historically been established on unimproved land previously under native forest and shrub, however, the downturn in pastoral sheep and cattle farming over the last 30 years has seen an increasing trend towards reafforestation of pastureland. Stem volume production is typically around 20% higher on ex-pasture sites relative to normal forest sites, owing to the high soil fertility developed while under pasture management (eg Beets & Brownlie 1987). The wood properties of ex-pasture stands are receiving increased attention as these plantations reach maturity (McConchie 1997). Initial results show that outer wood density is 5 to 10% lower than expected. The area of the *P. radiata* plantation estate in New Zealand is increasing at approximately 50 thousand ha per year (ANON 1999), with a large proportion of new planting occurring on sites previously under pasture. Systems to predict wood density will need to be improved to allow accurate forecasting of fibre yield from this new resource. In addition, plantations established since 1990 are classified as Kyoto Forests for which accurate methods to predict carbon sequestration are necessary, particularly for Carbon Trading purposes.

New Zealand has been classified into three wood density regions, based primarily on mean annual air temperature (Cown et al. 1991). Considerable variation in wood density occurs within each wood density region, which could be related to site fertility, among other factors. For example, it has been shown that the application of fertiliser (containing a mixture of N and P) in a trial growing on a nitrogen and phosphorus deficient site near Nelson reduced wood density by 50 $kg/m^3$ or more (Cown & McConchie 1981). This fertiliser effect was consistent with previously reported studies, which showed that volume responses were associated with a reduction in latewood percent, and hence mean density immediately after treatment, especially if fertilisation was undertaken in conjunction with thinning. The reduction in wood density persisted for only one or two years and was considered to be of little technological significance (Cown & McConchie 1981). However, the effect of site fertility on wood density could be more important than hitherto realised.

At most forest sites foliar N is significantly elevated for one or two years following fertilisation before returning to control levels, however, foliar N remains high throughout the rotation when trees are established on improved pasture. Direct evidence linking tree N status to wood density was obtained at the Biology of Forest Growth (BFG) research site in Australia (Benson et al., 1992), which included experimental treatments that significantly altered foliar nitrogen levels in radiata pine. Analysis of wood density cores from the BFG trial showed that wood density was significantly related to the nitrogen status of foliage produced in the year the growth ring was formed (Beets 1997). Furthermore, while it is generally reported that wood density decreases with increasing growth rate, at the BFG site irrigation increased growth rate both with and without nutrient additions, however wood density increased using water alone, but decreased using water containing nutrients in solution. These contrasting responses in wood density following growth stimulation through irrigation were associated with a reduction in foliar N status using water alone, but an increase in foliar N status using nutrient solution (Beets 1997). Variation in wood density decreased

following cessation of experimental treatments at the BFG site, following the pattern for foliar N, though possible effects of nutrients other than N could not be examined (Beets 1997, Crane and Banks 1992, Thompson and Wheeler 1992). Tree age and rainfall also appeared to be important at the BFG site, but not growth rate *per se*. Given the limitations of the BFG wood density study, it was considered desirable to further test whether wood density was related to tree nutritional status using independent data.

In this paper we present new wood density data from increment cores obtained immediately prior to harvesting of a fertiliser trial at Woodhill Forest in New Zealand. This trial was selected because growth, water use, and nutrition data had been collected since inception of the experimental treatments (Jackson et al., 1983a; Jackson, et al., 1983b; Gadgil et al., 1984, Baker et al., 1986; Beets & Madgwick 1987), allowing a more complete analysis of factors influencing wood density.

The objectives of this paper are to:
1) Test if wood density and latewood percent of individual annual rings is related to foliar nitrogen status measured in the year the rings were laid down;
2) Assess if nutrients other than N influence wood density at this site;
3) Examine whether seasonal differences in rainfall influence wood density and latewood percent.


# METHODS

## Site description and experimental treatments

Woodhill Forest is located 50km north of Auckland on recent sands. Volume production is sub-normal but large responses to nitrogenous fertilisers have been obtained (Jackson et al., 1983a), coupled with increases in foliar N (Gadgil et al., 1984). The trial was located on a large dune after normal sand stabilisation procedures were followed. This involved planting marram grass, topdressing with "Nitromoncal" in 1965, and over-sowing with tree lupins in the following year. In 1968 the lupins were crushed and <u>Pinus radiata</u> seedling planted at 2.4 x 1.8m spacing.

Eight treatment plots were established (each 0.566ha in area) in a randomised block design. These comprised four nutritional treatments designated "Control, C" (lupins excluded, no fertiliser applied), "Lupin, L" (lupins allowed to grow, no fertiliser applied, "Fertiliser, F" (lupins excluded, fertiliser applied), and "lupin + Fertiliser, LF" (lupins allowed to grow, fertiliser applied), each with two replicates. The fertiliser regime was designed to provide a balanced supply of nutrients, and was applied biennially for a ten year period from August 1968 until August 1978. The amount and timing of fertiliser additions and the foliar nutrient status of trees in each of the treatment plots are given in Gadgil et al. (1984). The fertiliser regime was successful in maintaining treatment differences in tree nitrogen status, without inducing other nutrient imbalances in the trees.

Rainfall data were collected immediately adjacent to the trial (Jackson et al., 1983b). Annual rainfall totals averaging 1260mm (ranging between 920 and 1550mm). Least rainfall occurred in summer months (15% of total), which was also the most variable season of year (range is 100 to 350mm), with a coefficient of variation of 40%, compared to Autumn, Winter, and Spring with a coefficient of variation of approximately 20%.

**Foliar analysis**

Foliar N was measured on an individual plot basis from age 6 to 13 years, and at ages 15 and 20 years. Other nutrients (P, K, Ca, Mg, B, Mn, Zn, Cu) were analysed at ages 11, 12, 13, 15, and 20. Analysis methods, treatment means, and results of statistical analysis for stands up to 15 years were reported previously, including some earlier data analysed by block (Gadgil et. al., 1984; Baker et. al., 1986). The age 20 data have not been reported previously. In summary, foliar N was initially in the high range (>1.5% N) but decreased to approximately 1.2% by age 6, when significant treatment differences had emerged. From age 6 years, foliar N in unfertilised controls decreased to 0.8%, while fertiliser maintained foliar N at around 1.3% in the LF treatment. After fertilisation ceased at age 10, foliar N gradually declined to approximately 1.1% by age 20 in LF treatment, and is likely to have declined further thereafter. Zn was significantly lower in fertilised stands in all years measured up to and including age 15, after which no treatment differences were found for any nutrient. For other elements, statistically significant treatment effects were observed in some years for P, B, K, Mg, and Mn, but were not consistent over time. Consequently, because N was rarely correlated with other elements, the statistical analysis of N effects on wood density was not confounded by variation in other elements (apart from Zn). Foliar concentrations of all nutrients except N were considered satisfactory for normal growth. Foliar N was in the marginal range in stands receiving annual fertiliser additions, and deficient in unfertilised control stands.

**Method for X-ray densitometry**

A pith to bark increment core (10mm in diameter) was taken from trees in the unthinned C and LF plots in 1995 when the stand was 27 years old. A total of 12 intact cores were available from the C treatments and 8 from the LF treatment. The sample size is therefore small, however, the mean ring density was not different in the C and LF treatments prior to onset of nutritional differences, which became apparent after stand age 5 years. Furthermore, the radial pattern of wood properties within experimental treatments was of primary interest.

Radial strips with a thickness of 5mm were cut from 10mm increment cores removed at breast height (1.4m). The strips were resin-extracted using methanol in a Soxhlet extractor for 72 hours and then stored for 1 month in constant 50% relative humidity. They were then accurately machined to a tangential thickness of 1.5mm, and reconditioned to 50% relative humidity for several days prior to scanning. The X-ray densitometry analysis involved passing the machined samples between a radioactive source (Fe[55]) and a scintillation counter which measures the penetration of X-rays through the wood sample, which is related to the wood density. Each pith-to-bark sample was scanned using a step interval of 0.3mm. For this experiment, the density threshold between earlywood and latewood was set at 500kg/m$^3$. This value has been the standard for both radiata pine and Douglas-fir in New Zealand and Canada (Cown and Clement, 1983; Jozsa *et al.* 1989). Using this value, the earlywood and latewood widths are similar to those determined visually. Ring width, earlywood width, latewood width, latewood %, ring density, earlywood density, latewood density, minimum density, maximum density, density range (maximum density - minimum density) and density uniformity (latewood density - earlywood density) were determined.

## Data analysis

The individual tree growth ring data (earlywood density, latewood density, mean ring density, latewood percent) were averaged on a plot basis by ring age, because foliar N (Gadgil et al., 1984) had been determined on a plot basis from age 6 at this trial. The annual ring density data were merged, by year, with the foliar nutrient concentration data (measured in February) and wood density was examined in relation to the N (and other nutrients) status of the stands at the time the growth rings were laid down. The latter data were analysed using regression methods (SAS GLM procedure), to test for the effects of nutritional status, tree age, and rainfall on density and latewood percent.

## RESULTS

### Nitrogen status and age effects

Mean density of individual growth rings increased from approximately $320kg/m^3$ at age 2 to approximately $600kg/m^3$ by age 15, and thereafter remained approximately constant up to age 25 years (Fig. 1). Mean density was initially similar in all plots, but diverged from stand age 4 to 5 years to give a maximum treatment difference of approximately $100kg/m^3$ by age 8. The initial rapid increase in density in control plots relative to fertilised plots coincided with a reduction in foliar N concentration from approximately 1.5% initially (when no treatment effects were evident) to deficient levels (averaging approximately 0.8%) in control plots after stand age 6 years (Gadgil et al., 1984). In contrast, the LF treatment showed a lesser decline in foliar N concentration over time, and stabilised at approximately 1.3% N until stand age 12 (two years after fertilisation ceased), before also declining.

The relationship between mean ring density and foliar N is shown for selected years in figure 2. Foliar N explained a significant proportion of the variation in both mean and earlywood density of individual rings, though tree age at the time the ring was laid down also accounted for a large proportion of the variation (Table 1). No foliar N by tree age interaction effect on wood density was evident. From stand ages 6 - 20, when foliar N data were available for each plot, tree age effects were comparable in magnitude to foliar N effects (approximately $100kg/m^3$). Earlywood density was significantly influenced by tree age when the ring was laid down, but the effect of age was small compared to the pattern evident in latewood. Latewood density was related to foliar N when the stands were less than age 9 years at the time rings were laid down (analysis not shown), but in an analysis over all years latewood density was significantly related only to tree age (Table 1).

Foliar P and Zn were individually correlated with density, however none of the nutrients tested (P, K, Ca, Mg, Mn, Zn, B, Cu) were related to wood density after the effect of N was taken into account.

**Table 1. Influence of tree nitrogen status and age when ring was laid down on mean, earlywood, and latewood density and latewood percent for individual growth rings sampled at breast height in fertilised and control plots in a fertiliser trial in Woodhill Forest.**

| Regression | Variables | Parameter | Partial $R^2$ | F | Pr>F |
|---|---|---|---|---|---|
| Mean density | Intercept | 590 | | 317.2 | 0.0001 |
| (Model $R^2$ = 0.78) | Foliar N | -156 | 0.23 | 39.00 | 0.0001 |
| | Age | 10.5 | 0.55 | 65.51 | 0.0001 |
| | | | | | |
| Earlywood density | Intercept | 456 | | 766.6 | 0.0001 |
| (Model $R^2$ = 0.61) | Foliar N | -55.8 | 0.23 | 21.5 | 0.0001 |
| | Age | 3.05 | 0.38 | 23.8 | 0.0001 |
| | | | | | |
| Latewood density | Intercept | 552 | | 1902 | 0.0001 |
| (Model $R^2$ = 0.55) | Age | 7.36 | 0.55 | 47.0 | 0.0001 |
| | | | | | |
| Latewood percent | Intercept | 87.3 | | 68.3 | 0.0001 |
| (Model $R^2$ = 0.75) | Foliar N | -55.6 | 0.50 | 48.9 | 0.0001 |
| | Age | 2.50 | 0.25 | 36.7 | 0.0001 |

Latewood percent accounted for 95% of the variation in wood mean density (analysis not shown), so factors influencing latewood percent were expected to also influence wood density. Latewood percent was significantly lower (35 versus 50% at age 8) in fertilised compared to unfertilised stands, particularly prior to age 15. Thereafter, latewood percent increased to approximately 90% irrespective of treatment. Latewood percent was significantly influenced by foliar N status and tree age (Table 1). Mean density is calculated as the area weighted average of earlywood and latewood density. The significant nitrogen effect on mean ring density shown in Table 1 is therefore largely related to a change in latewood percent. However, fertiliser treatment also induced changes in the early and latewood density, particularly at younger ages when foliar N was strongly influenced by fertiliser additions.

**Rainfall effects**

Growth responses to rainfall can be expected at this site, with critical moisture deficits occurring throughout the soil profile during late summer and autumn (Jackson et al., 1983b). Tree N status and the seasonal distribution of rainfall were found to significantly influence the latewood percent, and mean density (Table 2). The variables influencing latewood percent also influenced mean density in a similar way, which was expected, given the observed effects of seasonal water deficits on diameter growth at this site (Jackson et al., 1983b). High cumulative autumn/winter/spring rainfall decreased the latewood percent and decreased mean wood density, while high summer rainfall appeared to have the opposite effect. High foliar N status decreased latewood percent and ring mean density. Foliar N accounted for more variation in the latewood percent and mean wood density than precipitation variables, either singly or in combination.

**Table 2. Influence of tree nitrogen status and precipitation (Autumn A, Winter W, Spring Sp, Summer Su) on ring mean density and latewood percent for individual growth rings sampled at breast height in fertilised and control plots in a fertiliser trial in Woodhill Forest.**

| Regression | Variables | Parameter | Partial $R^2$ | F | Pr>F |
|---|---|---|---|---|---|
| Mean density | Intercept | 940 | | 207.6 | 0.0001 |
| (Model $R^2$ = 0.69) | Precip (A,W,Sp) | -0.350 | 0.23 | 24.1 | 0.0001 |
| | Precip (Su) | 0.593 | 0.07 | 26.6 | 0.0001 |
| | Foliar N | -147 | 0.39 | 23.6 | 0.0001 |
| | | | | | |
| Latewood percent | Intercept | 168 | | 72.0 | 0.0001 |
| (Model $R^2$ = 0.67) | Precip (A,W,Sp) | -0.080 | 0.14 | 13.6 | 0.0008 |
| | Precip (Su) | 0.134 | 0.04 | 14.6 | 0.0006 |
| | Foliar N | -53.4 | 0.49 | 33.6 | 0.0001 |

## DISCUSSION

Wood density is influenced by genotype, climate and soil factors, which can be difficult to separate statistically using survey approaches (Cown 1974, Harris et al. 1978). National wood density surveys undertaken previously showed that density differences of 25 to 30% occur across the latitudinal range of New Zealand, with regional differences primarily related to mean air temperature (Harris 1965, Cown et al., 1991). Subsequently, a national survey suggested that both soil and climate influence density. The latter survey confirmed the importance of temperature and rainfall, though the effect of nitrogen fertility (as reflected by Kjeldahl N in 0-7.5cm of topsoil), and other soil factors (including Olsen P, pH), were found to have only small but significant effects (Cown et al., 1991). However, considerable unexplained variation in wood density was evident within regions (Cown et al., 1991), suggesting that environmental effects could be confounded. The validity of the outer wood density equation reported in Cown et al. (1991) was tested using soil data collected by Baker et al. (1986) when the Woodhill trial was 14 years old. Outer wood density was predicted to be 503 and 502 kg/m³ in the C and LF treatments, respectively, while actual wood densities of rings laid down at ages 14/15 were 641 and 566 kg/m³, respectively. Clearly, the negative effect of nitrogenous fertiliser on wood density was underestimated, possibly partly because Kjeldahl N is only weakly related to site N fertility and tree foliar N status.

In contrast, the equation based on foliar N (given in Table 1) predicted wood density to be 615 and 560 kg/m³, for the rings laid down at stand age 14/15 years in the C and LF treatments, respectively. The temporal and spatial variation in foliar N observed at the Woodhill trial also helps explain both the radial variation in wood density within trees, and differences in density between adjacent stands. N was the primary nutrient influencing density, with no other nutrient of those tested (including P, K, Ca, Mg, Mn, Zn, B, Cu) found to have an influence on density after N effects were accounted for. The strong dependence of wood density on tree N status, as reflected by foliar N, is consistent with results from the BFG study reported previously (Beets 1997).

The N status of trees is strongly influenced by soil N fertility among other factors, so it is reasonable to expected that trees on fertile ex-pasture will, on average, have a lower wood density than trees on less fertile forest sites growing under similar climatic conditions. In support of this conclusion, low outer wood densities (averaging approximately 400 kg/m³) were observed in 23 year old ex-pasture stands at Puruki forest, where foliar N averaged 1.6% (eg. Beets & Brownlie 1987) across a range of stocking levels (McConchie 1997). The effect of high N on wood density could explain why the East Coast forests in the North Island of New Zealand are typically medium wood density but the mean annual air temperature would suggest these forest be classified as high density – these forest were mostly established on abandoned pastureland. Apart from site N fertility, other factors that reduce a trees requirement for N may also be important. For example, luxury accumulation of N in trees exhibiting Mg deficiency symptoms (Beets & Jokela 1994) could explain why wood density was 9 kg/m³ less in Mg deficient trees compared to adjacent healthy trees (McConchie 1997), though in this case genetic factors may also be involved. Likewise, N sometimes accumulates in P deficient stands, depending on site N fertility, which may explain why P deficiency has not been consistently associated with higher wood density (Cown 1974).

In conclusion, improved yield forecasts for radiata pine plantations will be possible using information on the N status of the trees. The role of site fertility as a factor accounting for variation in wood density both within and among the existing wood density regions could be further explored, as a basis for improving estimates of carbon sequestration. High wood density breeds have been suggested previously as a possible management option to increase fibre yield (Cown 1974) and the increasing trend of establishing pine on ex-pasture sites offers further justification for considering this suggestion.


## ACKNOWLEDGEMENTS

Fig. 1. Mean density of individual annual rings of radiata pine, shown in relation to tree age when rings were laid down. Site preparation was initially identical. Two plots were fertilised annually for the first ten years of tree growth, and two plots were retained as unferilised controls
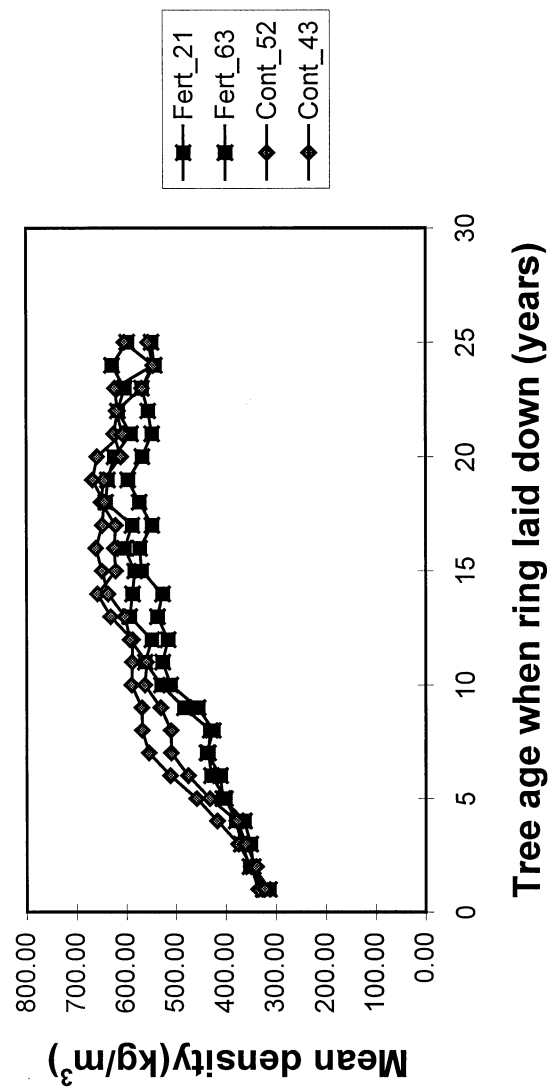
## Fig. 2. Mean density of selected rings versus foliar nitrogen status of trees in the plot. Foliar N was significantly higher in fertilised compared to control plots.
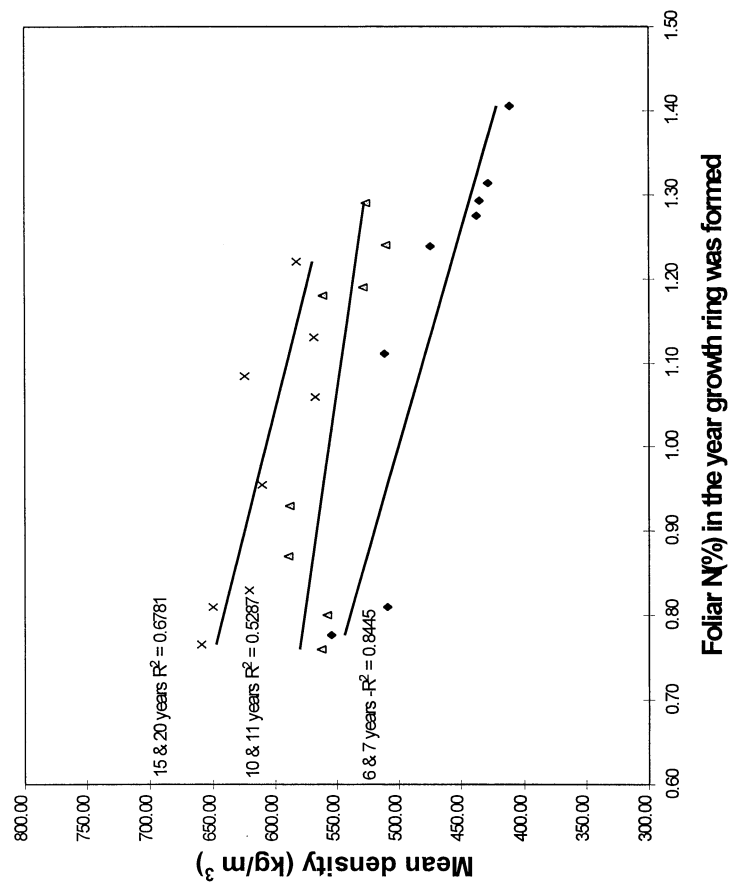
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