Reprint No. 2884

PREDICTING WOOD DENSITY OF *PINUS RADIATA* ANNUAL GROWTH INCREMENTS

P. N. BEETS*, M. O. KIMBERLEY, and R. B. McKINLEY

Ensis, Private Bag 3020,
Rotorua, New Zealand

(Received for publication 25 September 2006; revision 10 May 2007)

ABSTRACT

The mean density of stem wood growth sheaths laid down annually in *Pinus radiata* D. Don stands was modelled as a function of site mean annual temperature, soil nitrogen fertility, ring age, and stocking. The model was based on measurements of mean outerwood basic density at breast height of 30 trees per stand from a single seedlot established at 17 sites located throughout New Zealand. Soil and climate data were obtained from each site, and stem wood disks were sampled at 5-m intervals along the stem from 10 trees per stand from 15 of these sites. Previously reported breast-height basic density data from a comprehensive national survey were used to examine ring age trends from pith to bark, supplemented with data from four trials to determine the influence of tree stocking on outerwood density. The model was tested using data from an independent study of mean outerwood basic density at breast height (30–120 trees per stand) undertaken at 21 stands selected to cover a wide range in site fertility, temperature, tree stocking, and stand age.

Site mean breast-height outerwood basic density ranged between 356 and 494 kg/m^3 in the model development dataset, and 316 and 482 kg/m^3 in the validation dataset, and increased significantly with site mean annual temperature (T), mineral soil adjusted carbon/nitrogen (C/N) ratio, and stocking. Breast-height density of annual growth rings from pith to bark increased with ring age, and this pattern was consistent at all heights within the stem. The ratio of sheath density to breast-height ring density varied with ring age and increased with increasing nitrogen fertility. To predict the density of annual stem wood growth sheaths, the model firstly estimates the effects of site mean annual temperature, soil nitrogen fertility, and stocking on mean outerwood density at breast height. Secondly, the effect of ring age on annual ring density at breast height from pith to bark is taken into account. Finally, the ratio of sheath density to breast-height ring density for each ring is estimated as a function of stand age and outerwood density.

The national wood density model explained 93% of the variation in outerwood density at breast height for the model development dataset, with model

* Corresponding author: peter.beets@ensisjv.com

predictions within 0.2% of the measured values. The model explained 86% of the variation in breast-height ring density in the model validation dataset, with predictions from the model averaging 3.2% higher than the measured values. Seedlot differences in breast-height outerwood density contributed in part to the greater variability evident in the validation dataset. The modelled ratios used to predict the density of annual growth increments were not directly tested. However, analogous ratios of whole stem wood density/ breast-height outerwood density were derived by site density class for stands across a range of age classes using an independent national dataset, and these were consistent with those predicted using the model. Areas for further model testing and development were identified.

The model can be applied to predict stem biomass and carbon sequestration in *P. radiata* stands from the increment in stem wood volume. The wood density model has been incorporated in a carbon modelling system (C_Change) to facilitate the prediction of carbon stocks and changes in New Zealand's exotic plantation forest estate.

Keywords: carbon sequestration; Kyoto Protocol; site; climate; management effects.

INTRODUCTION

As a signatory to the United Nations framework convention on climate change (UNFCCC), New Zealand needs to report on sources and sinks of carbon, including those in vegetation and soil. The Kyoto Protocol (IPCC 2003) requires parties to report carbon stocks and changes for land subject to afforestation, reforestation, and deforestation after 1 January 1990 over the first commitment period from 2008 to 2012. A network of permanent plots located on a 4-km grid has been proposed for monitoring carbon stocks in New Zealand's planted Kyoto Forest estate. The plot network is intended to provide nationally representative data on tree growth, health, silvicultural management, and site fertility. The tree data from individual plots can be used to predict the gross and net stem volume under bark annually using an empirical stand growth model. Carbon stocks in above- and below-ground biomass, coarse woody debris, and litter pools in *Pinus radiata* stands can then be derived from the measured or modelled stem volume increments, their corresponding wood densities, and the stand management regime using a carbon model (Beets *et al*. 1999). Stem volume increment can be predicted from plot data using models such as the 300 Index stand growth model (Kimberley *et al*. 2005), and a nationally applicable model would be required to predict the mean density of stem wood annual growth increments.

Tian *et al.* (1995) developed a wood density model to predict the density of stem components (logs) from breast-height outerwood density measurements, based on an understanding of wood density variation within trees. Density has been shown to initially increase with ring number from pith (Hughes & Mackney 1949; Cown *et al*.1991), and then level off with increasing ring age (Loe & Mackney 1953), and decrease with height up the stem (Cown *et al*. 1991). This model is based on data from approximately 1000 stems and estimates wood basic density of logs from tree age, ring number from the pith, and height up the stem. However, the model does not predict the mean density of stem wood annual growth increments as a function of site and climate, and is therefore of limited usefulness for carbon modelling purposes. Nevertheless, wood density of *P. radiata* has been extensively researched in New Zealand over the last 30 years, both in national wood density surveys, and in research trials aimed at identifying causes of variation.

National surveys have shown that site differences in *P. radiata* outerwood density at breast height in New Zealand were related to spatial variation in mean annual air temperature (Harris 1965), though other environmental factors such as soil nitrogen were also involved (Cown *et al*. 1991). Mean annual temperature currently underlies the use of the three wood density regions for this species, with density differences of 25–30% across the latitudinal range in New Zealand (Cown *et al*. 1991). While wood density tends to be high in warm regions and low in cool regions, within-region variation in outerwood density can be substantial and suggests that other factors may be important.

Data from experimentally irrigated or fertiliser-treated *P. radiata* stands in New Zealand and Australia showed marked changes in wood density with fluctuations in nitrogen supply (Cown & McConchie 1981; Beets 1997; Beets *et al*. 2001; Nyakuengama *et al*. 2002). For example, a single application of 200 kg nitrogen fertiliser/ha temporarily reduced wood density of the growth ring formed that year by 50–60 kg/m^3 (Cown & McConchie 1981). In contrast, annual applications of nitrogen fertiliser at Woodhill Forest decreased ring density at breast height by approximately 100 kg/m^3 below that of controls without fertiliser during the 10-year period that nitrogen was being applied (Beets *et al*. 2001). Density of annual rings was significantly related to foliar nitrogen status and ring age at Woodhill Forest and at a similar trial at Canberra, Australia (Beets 1997; Beets *et al*. 2001). At a low-rainfall Canberra site, fertiliser (nutrients only), irrigation (water only), and fertigation (nutrients plus water) treatments all increased growth rates. However, fertiliser application and fertigation increased foliar nitrogen and reduced wood density, while irrigation with water decreased foliar nitrogen and increased density (Beets 1997). These trials highlight the importance of nitrogen supply as a factor influencing wood density, through its effect on the latewood ratio, with reductions in wood density induced by nitrogen fertiliser becoming evident from stand age 3 years (Beets *et al*. 2001). These results help explain why ring width has little effect on density, as observed also by Nyakuengama *et al*. (2003).

Silvicultural management operations, such as thinning, also influence wood density. For example, the density of the outer growth rings was lower in thinned stands than in unthinned controls (Cown & McConchie 1981). Genotype was an additional significant source of between-tree variation in wood density, with large-diameter trees tending to have a slightly lower density than small trees within the same stand (Harris *et al*. 1978; Cown *et al*. 1992, 2002; Cown & Ball 2001). Stand sampling needs to be sufficiently intense to overcome tree-to-tree (mostly genetic) variation in density, in order to test for the effects of variation in site factors on density.

The objective of this study was to develop a nationally applicable model to predict the mean density of stem wood annual growth increments as a basis for estimating carbon sequestration by *P. radiata* stands grown in New Zealand, taking into account factors known to affect wood density, including temperature, nitrogen fertility, ring age, and tree stocking.

Model Development

A model of basic density of stem wood annual growth increments was developed by collating existing wood density data, which were analysed using the following steps:

(1) In studies where outerwood density cores and site data were available, breast-height outerwood density at a reference age was estimated as a function of mean annual air temperature, soil nitrogen fertility, and stocking.

(2) In studies with pith-to-bark cores, the stand arithmetic mean density of annual growth rings at breast height was estimated as a function of ring age, consistent with the outerwood density estimate obtained at the reference age (from Step 1).

(3) In studies with sectionally measured trees, the mean density of each annual increment in stem wood volume was estimated from the mean density of individual annual rings at breast height (from Step 2) multiplied by a site and ring age-specific ratio. Each ratio was the area weighted mean density of annual growth increments divided by the arithmetic mean density of the corresponding ring at breast height, and was estimated as a function of ring age and site mean outerwood density.

The wood density model was tested using independent breast-height core samples collected specifically to test the performance of the model. The core samples covered a wide range of sites, stand ages, and stockings.

MATERIALS AND METHODS

Model Development Datasets

The wood density model was based on several trials with the requisite site and tree data to develop parameters, while aiming to ensure that the model would be nationally representative. The effect of site factors on outerwood density was examined using data from a national Genetic Gains trial. The effect of stocking on density was assessed in several trials with a range in final-crop stockings. A large nationally representative database of breast-height density core data was used to develop pith-to-bark density trends. Longitudinal and radial variation in density within stems was calculated using the Genetic Gains trial to estimate the ratio between the mean density of annual growth increments and the mean density of corresponding annual rings at breast height for each site.

Site effects on outerwood density at breast height

A Genetic Gains trial planted in 1978 using “850” Series material (seedlot number WN/72/2, GF 14), and installed at 17 sites throughout New Zealand, was assessed at stand age 25 years (Table 1). Cores were taken at breast height from approximately 30 randomly selected trees per stand, trimmed to 50 mm length (measured from the bark end), and outerwood density was determined using the maximum moisture content method (Smith 1954). The annual growth rings were identified and counted. The average numbers of rings from the pith to the inner and outer ends of the 50-mm-long cores were 13.4 and 23.1, respectively, giving an overall average ring age of 18 years for this trial; this was defined here as the “reference age”. Therefore 2 years were required for trees to attain 1.4 m in height.

TABLE 1–Site characteristics of Genetic Gains trial used to develop a wood density model for *Pinus radiata* in New Zealand.

Forest	Latitude (°S)	Longitude (°E)	Altitude (m)	Mean Temp (°C)	Soil C (%)	Soil N (%)
Kaingaroa 1210	38.45	176.68	521	12.7	5.64	0.28
Golden Downs	41.48	172.89	337	10.8	6.38	0.25
Waimea	41.48	173.07	392	11.3	6.28	0.3
Rabbit Island	41.26	173.12	37	12.8	1.45	0.08
Longwood	46.14	167.80	196	9.2	9.44	0.45
Rowallan	46.06	167.66	196	9.6	7.01	0.35
Blackmount	45.74	167.70	196	8.2	7.26	0.38
Waimate	44.70	170.88	473	9.5	7.57	0.47
Eyrewell	43.41	172.22	195	11.2	3.33	0.17
Ashley	43.06	172.47	521	10.6	3.76	0.26
Ngaumu	41.05	175.88	157	12.2	6.14	0.32
Mohaka	39.06	176.97	280	12.9	5.34	0.31
Ruatoria	37.73	178.26	140	13.8	6.02	0.37
Athenree	37.46	175.90	268	14.1	10.53	0.49
Aupouri	34.88	173.10	38	16.3	0.61	0.04
Lismore	39.99	175.11	19	13.6	3.62	0.29
Kaingaroa 222	38.54	176.42	631	10.8	7.65	0.36

Site mean annual air temperature was estimated from latitude and longitude, using national climate surfaces developed by the National Institute of Water and Atmospheric Research Ltd, New Zealand (NIWA), which were based on climate data collected for the period 1971–2000 (A.Tait, pers. comm.). Soil nitrogen fertility was based on a sample of 40 mineral soil cores per site from the 0–5 cm depth which were bulked prior to chemical analysis of total carbon and nitrogen content using a Leco CNS-2000 analyser (Leco Corp., St. Joseph, MI, USA). An adjusted C/N ratio, C/(N – 0.014) used as an index of the nitrogen fertility of the site, was based on data from a national site productivity survey of 132 *P. radiata* stands (Jackson & Gifford 1976). The adjusted ratio decreased as foliar nitrogen increased. Soil sampling was restricted to the upper 0–5 cm of mineral soil to facilitate sampling of stony soils.

Site mean outerwood density was estimated as a function of air temperature and soil C/(N – 0.014), using the GLM procedure of SAS (Windows Version 8, SAS Institute Inc, Cary, NC, USA, 1999).

Density of stem wood annual growth increments (growth sheaths)

Ten trees were selected from 15 of the 17 Genetic Gains trial sites where 30 trees had previously been sampled for outerwood density. This subsample of trees was selected systematically to represent the mean and range in density within each stand. Each tree was felled and disk samples were cut at 0, 1.4, and 5 m, and thereafter at 5-m height intervals along the stem to a small-end diameter of approximately 100 mm over bark. Pie-shaped segments were cut from opposing sides of each disc, taking care to avoid knots and compression wood where possible. Each segment was cut into five-ring blocks commencing at the pith. Block dimensions were measured green, and the blocks were then dried at 105°C, weighed, and basic density was calculated. The block radial dimensions were used to determine the diameter of the stem in five-ring steps for each disc, based on the measured inside-bark diameter of the discs.

Because density measurements commenced at the pith instead of the bark, the density of annual growth increments was derived according to the following process. Firstly, at each height within each stem, the density of each ring was estimated using a smoothing spline (SAS procedure TPSLINE) fitted to the five-ring density data. The density of each five-ring block was allocated to the mid-ring in the block. Secondly, the inner and outer diameters of the ring were estimated at each height within each stem using smoothing splines fitted to five-ring diameters obtained from the block radial measurements. From these diameters, the cross-sectional area of the ring at each height was determined. The ring area and density at each height were then multiplied to give the relative weight of wood at each height in the stem. Thirdly, the height of each tree at age 15 or 20 years was determined by fitting a smoothing spline to the five-ring block data, to give the number of rings at each height. Tree height at age 15 or 20 years was calculated to be the height when the predicted count equalled 10 or 5 rings. The relative height of each density measurement was obtained by dividing by the total height. A smoothing spline was then used to predict the relative weight of wood and ring area as functions of relative height for each stem in 0.1 steps from 0.05 to 0.95. The mean weight of wood divided by the mean ring area provided an estimate of the mean density of the annual growth increment of each stem.

Ratios for predicting the density of growth increments from breast height ring density

Tree data from 15 sites of the Genetic Gains trial showed that the within-stand pooled correlation between stem diameter at breast height and outerwood density was $r = -0.37$. Therefore the volume-weighted mean density of annual stem growth increments was divided by the corresponding arithmetic mean ring density at breast height, when calculating ring age specific ratios for each stand. Because these ratios differed among sites and also varied with ring number, multiple regression analysis was used to estimate the ratios from ring age and the site mean outerwood density.

Ring age effects on pith-to-bark density profiles

Pith-to-bark cores were collected in extensive surveys of mature *P. radiata* stands throughout New Zealand in 1978 (Cown *et al*. 1991, Appendix 1). These surveys were based on densities at breast height of two 5-mm-diameter pith-to-bark cores from each of 30 trees, and measured in five-ring groups after resin extraction using methanol. Extractives content averaged around 5 kg/m^3 in non-heartwood rings (Cown *et al*. 1991). These data provided comprehensive information for developing a relationship between annual ring mean basic density and ring age at breast height. Because the individual stand tending regimes were not known, the pith-to-bark trends based on this large set of stands represent average stocking conditions.

Stocking effects on density

To account for stocking effects on wood basic density, six stocking rates trials were assessed. At four of the trial sites, final stocking ranged from 100 to 400 stems/ha; the other two sites included a much wider range in final stockings (Table 2). The trial at Otago Coast was planted at approximately 700 stems/ha and thinned to a range of final stockings when the stand was 9 years old. The Tikitere and Whatawhata stands were planted at five times their final crop stocking and thinned to the final stocking when the stands were 8 years old. The Kaingaroa trial was established at four times the final crop stocking, and thinned to the final stocking

TABLE 2–Location of six sites used to model the effect of stocking on outerwood basic density, and one site with two seedlots used to test the breast-height outerwood predictions.

Location	Latitude (°S)	Longitude (°E)	Stocking (stems/ha)	Rings at breast height	Trees sampled per stocking
Otago Coast	46.1	170.1	100, 200, 400	18	15
Tikitere	38.1	176.3	100, 200, 400	16	10
Whatawhata	37.8	175.3	100, 200, 400	16	9
Kaingaroa	38.6	176.6	100, 200, 400	19	20
Tarawera	38.1	176.5	200, 380, 750, 2000	25	14–19
Puruki	38.43	176.21	60, 180, 550, 910	19	4–12
Kaingaroa GF21	38.69	176.41	100, 200, 400, 600	18	30
Kaingaroa GF13	38.69	176.41	100, 600	18	30

when the stand was 7 years old. The Puruki trial was established at approximately 2000 stems/ha and plots were either —

(a) unthinned,

(b) thinned directly to a final stocking of 550 stems/ha at stand age 7 years,

(c) thinned in steps to 560, 290, and 160 stems/ha at ages 8, 11, and 15 years, respectively, or

(d) thinned in steps to 500, 160, and 60 stems/ha at ages 6, 10, and 14 years, respectively (Beets & Brownlie 1987).

The Tarawera trial included plots established at approximately 5000 stems/ha and left unthinned (this was an unusual regime, with approximately 2000 live stems/ha by age 20), or planted at 1400 stems/ha and thinned at age 7 years to 750 stems/ha, or at age 6 years to 380 stems/ha, or at age 18 years to 200 stems/ha.

Seedlings were planted at all sites except Puruki, where the same set of clones was planted at each stocking; this allowed accurate testing of stocking effects because genetic effects were accounted for in the analysis of the wood density data. Wood density cores from stocking trials were measured by annual growth ring using X-ray densitometry after resin extraction using methanol in a Soxhlet extractor for 72 hours (Beets *et al*. 2001).

Stocking effects were not evident during the first 10 years of growth, and so a power function was fitted to the ring 11–15 data to estimate density as a function of final stocking. The stocking-dependent function was combined with the site-dependent function to predict breast-height density of outerwood (at the reference age).

Model Validation Datasets

An independent dataset comprising 21 stands selected to cover a wide range in mean annual temperature, soil nitrogen fertility, tree age, and stocking was obtained in the North Island of New Zealand to test the performance of the new wood density model (Table 3). Stand mean outerwood density at breast height was determined as described for the model development dataset, with at least 30 trees sampled per stand. Soil nitrogen fertility was based on a sample of 20–100 mineral soil cores (0–5 cm depth) which were bulked prior to chemical analysis of total carbon and nitrogen, as described for the model development dataset. More intensive tree and soil sampling was undertaken at the following trials. At Puruki Forest (Beets *et al.* 2003), density was assessed in a trial of four seedlots (GF0, GF7, GF30, and High Density) established at 900 stems/ha, with plots installed on high

TABLE 3–Location of stands in the validation dataset used to test the accuracy of the wood density model for *P. radiata* in New Zealand

Forest	Latitude (°S)	Longitude (°E)	Altitude (m)	Stand age (years)	Mean temp. (°C)	Soil C (%)	Soil N (%)
Puruki GF30	38.43	176.21	610	9	11.2	10.78	0.60
Puruki HD	38.43	176.21	610	9	11.2	10.79	0.61
Puruki Control	38.43	176.21	610	9	11.2	11.50	0.63
Puruki Museum	38.43	176.21	610	9	11.2	10.82	0.60
Tarawera FF	38.13	176.00	75	17	13.5	2.204	0.10
Tarawera WT	38.13	176.00	75	17	13.5	2.934	0.13
Tarawera SO	38.13	176.00	75	17	13.5	4.121	0.19
Manawahe	37.96	176.69	330	13	12.2	4.76	0.40
Pukemoremore 1	38.43	176.21	570	21	10.8	13.21	0.81
Pukemoremore 2	38.43	176.21	570	21	10.8	11.33	0.75
Kaingaroa 1187	38.45	176.63	360	18	11.7	7.29	0.30
Horohoro	38.23	176.15	420	13	11.7	9.62	0.79
Woodhill SO	36.43	174.24	30	21	14.0	1.29	0.05
Woodhill WT	36.43	174.24	30	21	14.0	1.24	0.05
Puruki Tahi	38.43	176.21	570	21	10.8	12.89	0.74
Kaing GF13 100	38.69	176.41	610	20	10.2	7.16	0.31
Kaing GF13 600	38.69	176.41	610	20	10.2	7.83	0.31
Kaing GF21 100	38.69	176.41	610	20	10.2	6.34	0.30
Kaing GF21 200	38.69	176.41	610	20	10.2	7.34	0.31
Kaing GF21 400	38.69	176.41	610	20	10.2	9.18	0.38
Kaing GF21 600	38.69	176.41	610	20	10.2	9.45	0.37

and low radiation aspects in a randomised block design with three replicate plots per treatment. Breast height cores (outer six annual growth rings) were obtained from at least 20 trees per plot (six plots were installed per seedlot, except for GF0 with 2 plots) when the stand was 9 years old and still unthinned. The effects of seedlot and radiation level on outerwood density were tested using the GLM procedure in SAS.

In southern Kaingaroa Forest, the influence of final stocking on density was assessed in a trial of two seedlots (GF13, GF21) at four stocking levels (100–600 stems/ha), with two replicate plots per treatment (Table 2). Breast-height cores (outer five annual growth rings) were obtained from 30 trees per stocking from each of two seedlots when the stand was 20 years old. Intensive harvesting trials at Woodhill and Tarawera Forests with different levels of residue retention (whole tree harvested and forest floor removed, FF; whole above-ground tree harvested, WT; and stem only harvested, SO), were sampled at stand ages 21 and 17 years, respectively. The measured outerwood basic density at breast height of the validation data was compared with the model prediction, taking into account soil fertility, temperature, stand age, and stocking.

Independent data on the ratio of sheath density to breast-height ring density by ring age were not available. However, whole-stem density and breast-height density of the outer five rings, summarised by stand age and site density class by Cown *et al.* (1991), were compared with our sheath to breast-height annual ring density ratios. Whole-stem densities are equivalent to the cumulative area weighted sheath densities at a specified stand age.

Conversion of basic density to biomass density

Stemwood biomass can be obtained by multiplying stem volume under-bark by the density of a representative set of sample disks cut at fixed height intervals along the stem (Beets & Pollock 1987). Volumes of sample disks and of the whole stem are often measured using a diameter tape placed around the circumference of the stem under bark; weight is the oven-dry weight after drying at 65°C. This biomass method is consistent with how stem volume measurements are obtained for stand inventory purposes. However, basic density is defined as green volume measured by water displacement or calculated from the dimensions of green sawn blocks. To be consistent with biomass data, basic density therefore needs to be converted to the corresponding density obtained using diameter tapes. A sample of 17-year-old trees at Puruki Forest was measured using standard biomass procedures that involved sectional measurement of stems and sample disks cut at 2-m intervals along the stem (Beets & Pollock 1987), and also following the procedure for determining basic density. This involved measuring disk green volumes under bark by water displacement, and weighing the disks after they had been dried to constant weight at 105°C. These data were used to calculate the ratio between the mean density from the biomass procedure and the mean basic density from the water displacement method.

Notation Used in the Model

$D_{O,250}$ Wood density (kg/m^3) at breast height of a 50-mm-long outerwood core at the reference age of 18 years and a stocking of 250 stems/ha

D_O Wood density (kg/m^3) at breast height of a 50-mm-long outerwood core at the reference age and adjusted for stocking at stand age 20 years

D_R Wood density (kg/m^3) of a given ring (R) at breast height

D_S Wood density (kg/m^3) of a growth sheath

T Mean annual temperature (°C)

C 0–5 cm mineral soil carbon concentration (%)

N 0–5 cm mineral soil nitrogen concentration (%)

S Stocking of stand (stems/ha)

G Genetic wood density adjustment (%)

R Ring number from pith numbered 0, 1, 2, …

A If Stand age ≤ 30, A = Stand age (years)
If 30 < Stand age ≤ 40, A = 30 + (Stand age – 30)/3
If Stand age > 40, A = 34

RESULTS

Site Effects on Outerwood Density at Breast Height

Mean outerwood density at breast height of 30 trees/site at 17 sites located throughout New Zealand increased as site mean annual air temperature increased and the soil C/(N – 0.014) ratio increased. The model for predicting the mean outerwood density at breast height ($D_{O,250}$) in the 25-year-old stands with an average stocking of 250 stems/ha from temperature and soil C/(N – 0.014) had an R^2 of 0.93 (Equation 1). Standard errors of the coefficients are shown in parentheses.

$$D_{O,250} = \underset{(22)}{143} + \underset{(1.3)}{15.9}T + \underset{(0.8)}{4.1}C/(N - 0.014) \quad (1)$$

The nitrogen fertility index, $C/(N - 0.014)$, performed better than the unadjusted C/N ratio (analysis not shown). While temperature and the soil C/(N – 0.014) ratio were significantly related to outerwood density, neither variable was related to the density of wood formed near the pith, based on the subset of 10 trees per site with pith-to-bark density measurements (Table 4). This is not surprising because density variation between sites is low in young stands.

TABLE 4–Correlations (r) between breast-height density at various ring numbers from the pith, and mean annual temperature and soil C/(N–0.014), and partial correlation with soil C/(N–0.014) ratio after adjusting for temperature.

Breast-height ring number from pith	Correlation with temperature	Correlation with C/(N–0.014)	Partial correlation with C/(N–0.014) adjusted for temperature
3	0.38	–0.26	–0.30
8	0.84**	0.28	0.48
13	0.77**	0.42	0.62*
18	0.83**	0.38	0.64*

* statistically significant at the 5% level
** statistically significant at the 1% level

Stocking Effects on Density

The six stocking rates trials showed a trend for breast-height density to increase with stocking, although the trend was clear only at Tarawera and Puruki which included a wide range in final stocking rates (Fig. 1 and 2). The effect of stocking was more pronounced at the high-density Tarawera site than at the low-density Puruki site. The stocking effect also increased with age. The following function was fitted to the ring 11–15 data for estimating density (D_O) as a function of final stocking (S):

$$D_O = 327.2 + k(h + \sqrt{S}) \quad (2)$$

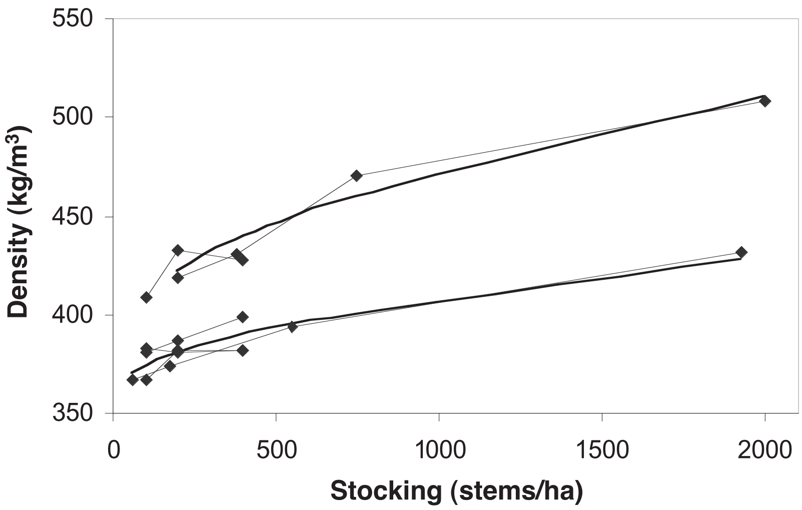

FIG. 1–Mean breast-height density in rings 11–15 across a range of stocking rates. The heavy lines are predictions for the Puruki (low density) and Tarawera (high density) sites using Equation (2).

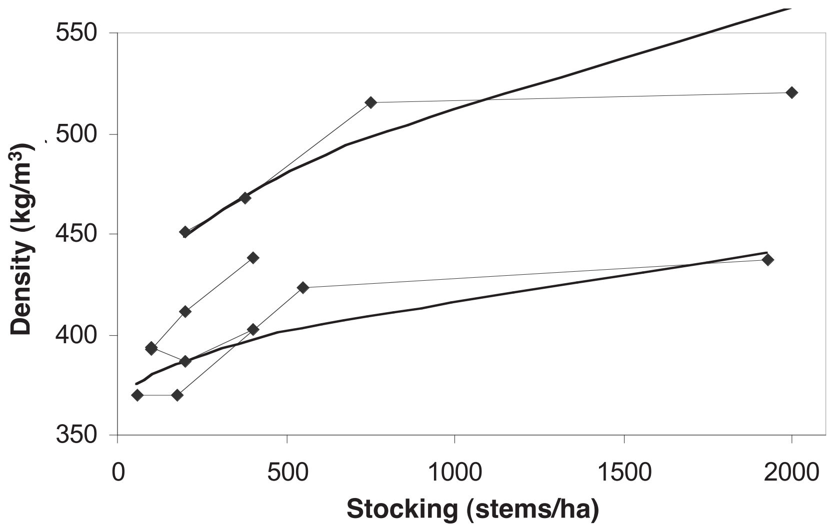

FIG. 2–Mean breast-height density in rings 16–20 across a range of stocking rates. The heavy lines are predictions for the Puruki (low density) and Tarawera (high density) sites from Equation (2).

In Equation (2) the value 327.2 represents wood density at the pith. When estimated directly from the stocking trials, a value of 320 was obtained. However, a value of 332.2 was finally used in Equation (2), based on the analysis of a more comprehensive dataset described in the following section. The parameter *h* has an estimated value of 18.64 (standard error = 3.58) while the parameter *k* is a local site-specific parameter. Equation (2) fitted rings 11–15 well (Fig. 1), and was also adequate for rings 16–20 (Fig. 2) although it over-estimated density at high stocking rates (above 1000 stems/ha) which are seldom encountered in 20-year-old *P. radiata* stands.

Combining Equations (1) and (2) gave the following function for estimating breast-height outerwood density at the reference age. The function includes a percentage genetic adjustment factor *G* which was set to zero for all examples in this paper, but which could be used to adjust densities up or down for a particular seedlot or clone with known high or low density properties.

$$D_O = (1 + G/100)[332.2 + (D_{O,250} - 332.2)](18.64 + \sqrt{S})/(18.64 + \sqrt{250}) \quad (3)$$

Ring Age Effects on the Pith-to-bark Density Profile

The age-dependent increase in pith-to-bark wood density was taken into account when predicting the density of a particular annual ring. The most comprehensive data on pith-to-bark density trends for *P. radiata* were collected by Cown *et al*. (1991), who tabulated wood density at breast height in five-ring steps for seven regions in New Zealand (Fig. 3). Analysis of these data showed that density at the pith did not vary significantly among regions, with stands having a common intercept at age zero, before diverging with increasing stand age. In addition, the increase in density with ring number (i.e., age) decreased linearly with ring number until it approached zero at about ring 25, after which it remained constant and slightly positive. These two features of the relationship suggested that breast-height density variation from pith to bark could be estimated using a quadratic equation with a common intercept for all sites, which switches to a linear function from ring 25. The following change-point function (Equation 4) predicts breast-height density D_R at ring number R, with R numbered from 0 rather than 1 to ensure that there is a common intercept:

$$\begin{aligned} D_R &= a + b(R - cR^2), && R \leq k \\ &= f + bgR, && R > k \end{aligned} \qquad (4)$$

where a, c, and g are global parameters, b is a local parameter which varies between sites to account for local differences in density, and k is the change point when the function switches from a quadratic to a linear form. To ensure that the derivative is continuous at the change point k, it must be:

$$k = (1 - g)/(2c)$$

and to ensure that the function is continuous at the change-point k, the parameter f must be:

$$\begin{aligned} f &= a + bk(1 - g - ck) \\ &= a + b(1 - g)^2/(4c) \end{aligned}$$

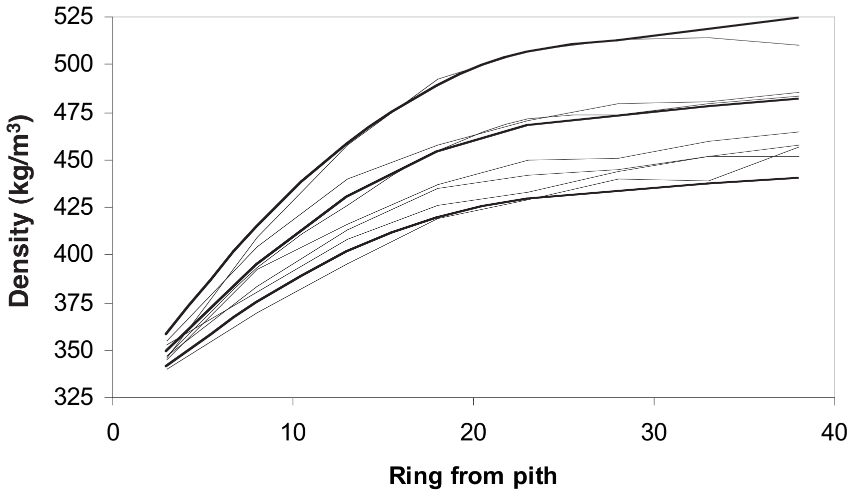

FIG. 3–Breast-height pith-to-bark mean densities for seven regions surveyed in New Zealand by Cown *et al*. (1991). The bold lines show predictions using Equation (4) for low-, medium-, and high-density sites.

Equation (4) was fitted to summary data reported by Cown *et al*. (1991) using the SAS procedure NLIN, and had an R^2 of 0.991 (Table 5). The weight of extractives in sapwood averages approximately 5 kg/m^3 (Cown *et al*. (1991), and therefore the parameter, *a*, was increased to 332.2. Predictions using Equation (4) are shown plotted against the measurement data in Fig. 3.

TABLE 5–Parameter estimates and stand errors (SE) for Equation (4) (based on Cown *et al*. 1991).

Parameter	Estimate	SE
a	327.2	2.3
c	0.0193	0.0008
g	0.0809	0.0177
k	23.8	

If density at the reference age, D_O at ring R_O, is estimated using Equation (3) or measured directly then *b* can be estimated using the following equation:

$$b = (D_O - a)/(R_O - cR_O^2), \qquad R_O \leq k$$
$$= 4c(D_O - a)/([1 - g]^2 + 4cgR_O), \qquad R_O > k$$

Substituting the equation for *b* into Equation (4) produced the following function (Equation 5) for estimating breast-height density D_R at ring *R*, given the reference density D_O at ring R_O:

$$D_R = 332.2 + b(R - 0.0193R^2), \qquad R \leq 23.8 \qquad (5)$$
$$= 332.2 + b(10.94 + 0.0809R), \qquad R > 23.8$$

where

$$b = (D_O - 332.2)/(R_O - 0.0193R_0^2), \qquad R_O \leq 23.8$$
$$= (D_O - 332.2)/(10.94 + 0.0809R_0), \qquad R_O > 23.8$$

Within-tree Variation in Wood Density

The most prominent feature in the vertical and radial unextracted wood density trends for the Genetic Gains trial, when averaged across all sites, was the strong increase in density from pith to bark at all heights, which eventually flattened after ring 20 from the pith (Fig. 4 and 5). However, there was no strong trend in density with height for a fixed ring number counted from the pith, with only a slight increase evident in rings 3 and 8, from 5 m height and above (Fig. 5). For example, from 5 m height and above, the average density three rings from the pith increased by 0.5 kg/m^3 with every metre of height. However, there was no change in density with height evident in the outer rings.

Mean Density of Stem Wood Annual Growth Sheaths

The volume-weighted mean densities of stem annual growth increments for each stand were slightly lower than the unweighted means, because large trees within a

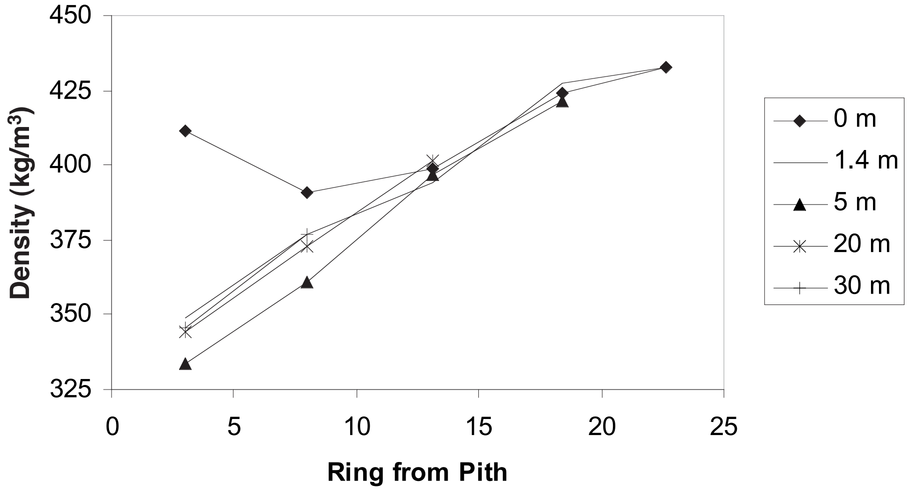

FIG. 4–Mean basic wood density across all sites by five-ring group and height class. For clarity, only 0-, 1.4-, 5-, 20-, and 30-m height classes are shown.

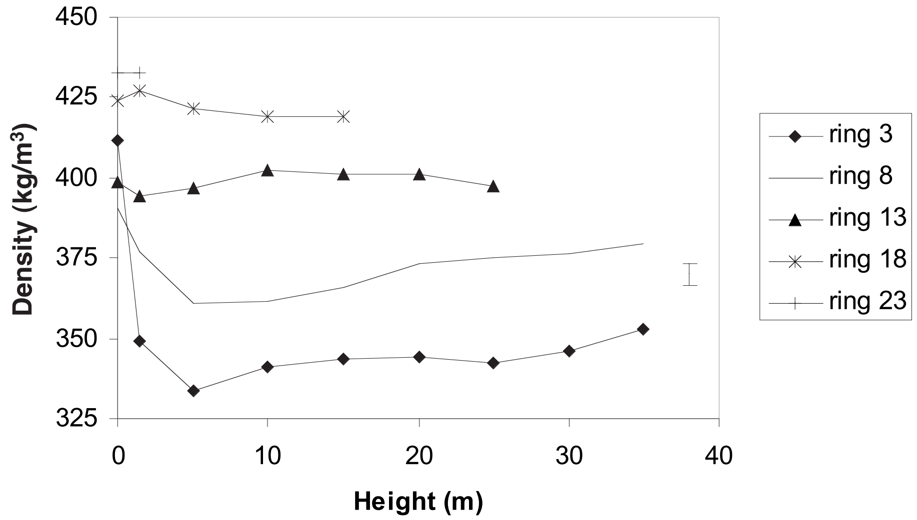

FIG. 5–Mean basic wood density across all sites by five-ring group and height. The error bar to the right of the chart is the least significant difference (LSD). Radial or vertical differences in density greater than the LSD are statistically significant (α=0.05).

stand had a slightly lower density than the small trees. While the impact on the sheath/breast-height density ratio was small (0.936 versus 0.943), it was nevertheless statistically significant when tested across the 15 sites (paired t-test, $t_{14} = 3.33$, $p = 0.002$).

The volume-weighted mean density of the growth sheath and the arithmetic mean density of the corresponding breast-height ring, together with the computed sheath/breast-height ring density ratio, are shown by site for the eleventh ring from the bark (Table 6).The ratio ranged from 0.86 at Rabbit Island to 1.00 at Ashley.

TABLE 6–Estimated mean wood density of the eleventh growth ring, counted from the bark, at breast height and for the growth sheath, for stands located throughout New Zealand. The sheath density is the volume-weighted average for the stand and the breast-height density is the arithmetic average for the stand. The ratio of the sheath to breast-height ring mean density is also given for each stand.

Location	Density of eleventh ring from bark (kg/m^3)		Ratio of sheath/BH ring density, based on stand means
	Growth sheath	Breast height	
Ashley	350	350	0.999
Athenree	387	433	0.895
Aupouri	433	482	0.898
Eyrewell	374	401	0.932
Golden Downs	365	386	0.946
Kaingaroa 1210	358	384	0.933
Kaingaroa 222	345	383	0.903
Lismore	374	383	0.977
Mohaka	354	377	0.939
Ngaumu	370	391	0.947
Rabbit Is	403	468	0.860
Ruatoria	380	409	0.929
Southland	332	333	0.996
Waimate	342	348	0.983
Waimea	370	411	0.901
Overall	369	396	0.936

The effect of site and ring age on the sheath/breast-height annual ring density ratio at low-, medium-, and high-density sites (with breast-height outerwood densities at ring 22 of 428, 466, and 504 kg/m^3, respectively) was estimated for ages ranging between 5 and 35 years in 5-year steps (Fig. 6). Low ratios occurred at high-density sites, and high ratios occurred at low-density sites. A trend with ring age was also apparent, with the ratio decreasing until about age 17 years and then increasing at ages beyond this. High ratios in early growth rings reflected the large proportion of the growth sheath that was composed of relatively high-density wood below breast height, while high ratios in later-aged growth rings occurred because the density of the growth sheath to a considerable height was similar to that at breast height (based on data shown in Fig. 5). The following multiple regression equation based on stand

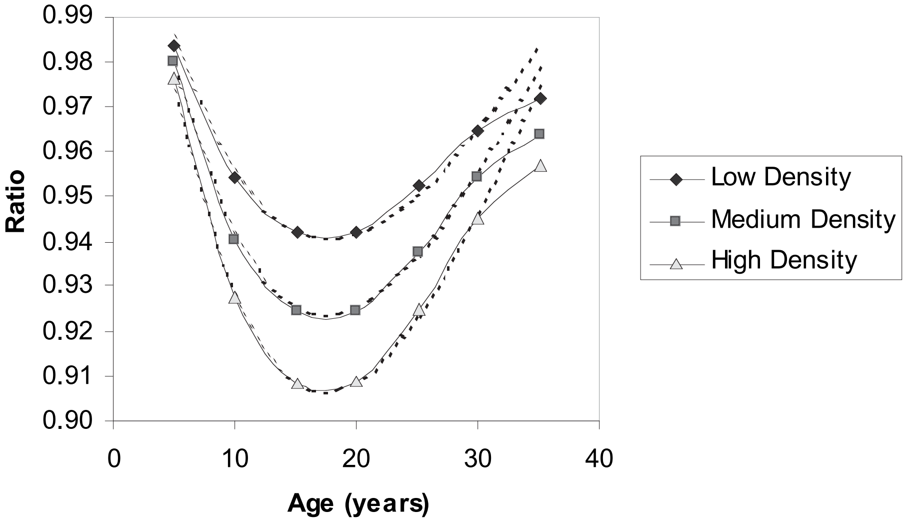

FIG. 6–Ratios of growth sheath to breast-height ring density estimated for rings formed at a range of ages on low-, medium-, and high-density sites. The dashed lines were obtained using Equation (6).

age (A) and breast-height outerwood density ($D_{O,250}$) was fitted to the ratios, excluding the age-35-years values, and accounted for almost all the variation:

$$Ratio = 1.334 - 0.01082A - 0.0009638D_{O,250} + 0.00006177A^2 + 0.00002435AD_{O,250} \quad (6)$$

As shown in Fig. 6, estimates from Equation (6) closely approximate the ratios derived from the data, over the age range 5 to 30 years.

Wood Density Model

The functions developed to account for the effects of site, stocking, ring age, and height together can be used to predict the mean basic density of *P. radiata* growth increments, weighted across all trees in a stand, for stands located throughout New Zealand. The model inputs include mean annual air temperature, soil nitrogen fertility (C/(N – 0.014), stocking (generally stocking at age 20 years is used), and stand age. This national model is intended for use with *P. radiata* of "typical" genetics, but can be adjusted when required to account for genetic differences in density using the adjustment factor G. The complete model is as follows:

$$D_{O,250} = 143 + 15.9T + 4.1C/(N - 0.014)$$

$$D_O = (1 + G/100)[332.2 + (D_{O,250} - 332.2)](18.64 + \sqrt{S})/(18.64 + \sqrt{250})$$

$$D_R = 332.2 + (0.08513D_O - 28.28)[(A) - 0.0193(A)^2],\ A \le 26$$

$$= 332.2 + (0.08513D_O - 28.28)[10.94 + 0.0809(A)],\ A > 26$$

$$D_S = D_R[1.334 - 0.01082A - 0.0009638D_R + 0.00006177A^2 + 0.00002435D_RA]$$

Predictions of the sheath basic density for various combinations of model inputs covering the likely ranges of these variables in Kyoto stands are given in Table 7. These predictions illustrate the individual effects of temperature, nitrogen fertility, stand age, and management factors on *P. radiata* wood density. Temperature and stand age had the greatest influence, followed by site fertility, and stocking. The combined effects of several factors can be large. For example, the 15-year growth sheath of a stand of standard genetics, at a low stocking (200 stems/ha) on a fertile (adjusted C/N=12) cool (8°C) site had a predicted density of 339 kg/m^3, while a stand of the same age and genetics at a high stocking (500 stems/ha) on a moderately fertile (adjusted C/N=25) warm (16°C) site had a predicted density of 467 kg/m^3. The range in site and management factors across New Zealand's entire exotic forest estate is expected to be greater than found on Kyoto land, in particular with respect to nitrogen fertility. For example, the adjusted C/N in the validation dataset ranged from 12 to 42.

TABLE 7–Influence of various site and management factors on predicted density of stem wood growth sheaths, based on inputs considered appropriate at Kyoto Forest sites.

Factor		Range in predicted density	
		(kg/m^3)	(%)
Temperature:	8 versus 16°C	359–439	19.9
Age:	10 versus 30 years	380–446	16.4
Soil C/(N–0.014) ratio:	12 versus 25	384–418	8.3
Stocking:	200 versus 500 stems/ha	395–411	3.8

Validation of the Model

The predicted outerwood density at breast height is shown in relation to the measured outerwood density for the model and validation datasets in Fig. 7. The model R^2 was 0.93 based on the model development dataset. The 86% of the variance in the validation dataset was explained by the model. The model prediction error was small but statistically significant (3.2%, $p = 0.014$).

The validation dataset included a GF30 seedlot with a significantly lower breast-height outerwood density (Bonferroni comparisons) than the other seedlots in the Puruki trial. Seedlot least squares mean densities (outer six growth rings) are shown in Table 8, adjusted for small but statistically significant aspect effects on wood density. Selection for high density raised the density at age 9 to levels observed in the unimproved Museum and Puruki Control seedlots. The breast height cores from Puruki had a mean assessment age of 4 years and basic densities less than estimated for the model intercept (332.2 kg/m^3).

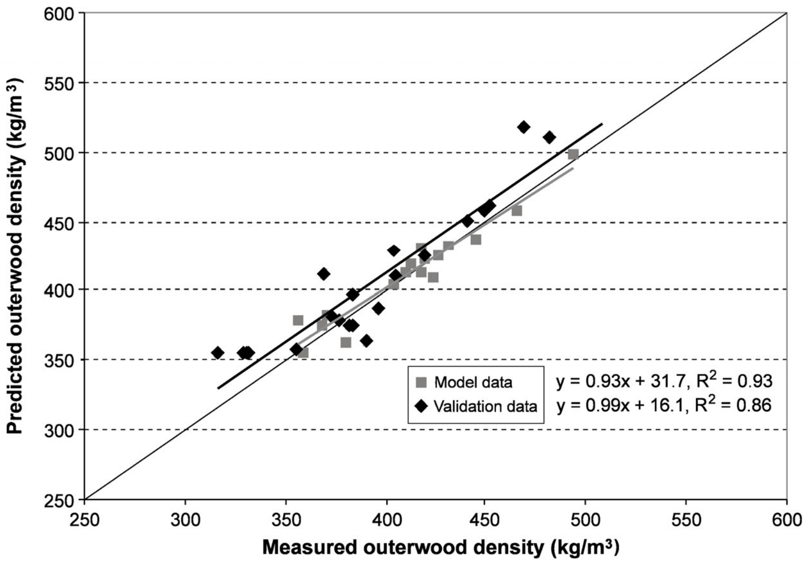

FIG. 7–Performance of the national wood density model for *P. radiata* based on the model outerwood density data and the validation data.

TABLE 8–Actual and predicted mean breast-height outerwood density for treatments from the Puruki Trial. Letters show statistical significance ($\alpha = 0.05$) of differences between seedlots, and between aspects.

	Actual density (kg/m^3)	Predicted density (kg/m^3)
GF30	316 b	353
High density	331 a	353
Puruki control	332 a	354
Museum	332 a	353
High radiation site	331 a	353
Low radiation site	325 b	353

The effect of stocking on breast-height outerwood density is shown in Fig. 8 for the validation dataset and the model. The model largely followed the trend observed in the data, with seedlot differences in density evident.

Ratios of whole-stem density/breast-height outerwood density by site density class and stand age were derived for the validation dataset (Table 9). Noteworthy features regarding these ratios were that (1) they increased as the site density class decreased, and (2) they ranged between 0.88 and 0.95. Like the annual growth sheath ratios (Fig. 6), these increased as site mean density decreased. Furthermore, they typically ranged from 0.91 to 0.94 for rings aged 15–20 years. Accepting the explanation we provided earlier for high ratios at young and old ages, the model dataset was broadly consistent with the independent dataset of Cown *et al*. (1991).

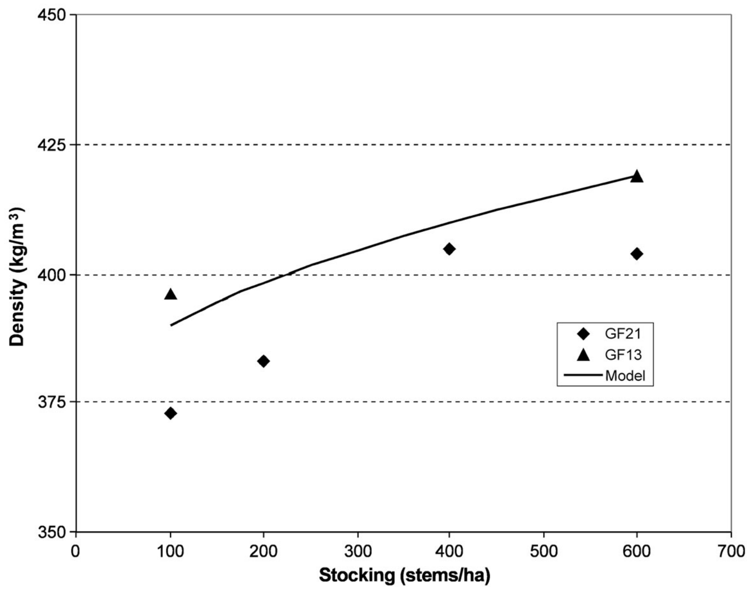

FIG. 8–Breast-height wood density (outer five growth rings) of two seedlots measured at stand age 20 years growing at a range of final stockings. Predictions from the model are represented by the solid line.

TABLE 9–Site mean whole stem wood density and corresponding density of five outer growth rings at breast height by stand age class, and derived ratios (based on Cown *et al.* 1991).

Site density class	Stand age (years)	Outerwood density (kg/m^3)	Whole stem density (kg/m^3)	Ratio
High	15	450	405	0.90
High	25	500	445	0.89
High	35	515	455	0.88
High	45	520	460	0.88
Medium	15	400	365	0.91
Medium	25	460	410	0.89
Medium	35	475	420	0.88
Medium	45	485	425	0.88
Low	15	375	355	0.95
Low	25	430	390	0.91
Low	35	445	400	0.90
Low	45	455	405	0.89

Conversion of Basic Density

The basic whole-stem wood density determined for 13 trees at Puruki slightly exceeded the whole-stem wood density of the same set of trees measured using standard biomass methods. The factor (stand error of individual tree ratios is shown in parentheses) for converting basic density to the equivalent diameter-tape-based measurement of whole-stem wood density was 0.995 (0.0029). The correction factor was not significantly different from 1, which indicated that the error from using a higher oven-dry weight in biomass studies (after drying at 65°C versus 105°C for basic density determination) and the error from using a higher disk volume in biomass studies (disk volume measured with a diameter tape versus by water displacement) cancelled each other and could therefore be ignored.

This new wood density model therefore predicts basic density of annual growth sheaths, and this density can be used to estimate biomass of stem wood from stem volume obtained using standard biomass and forest inventory procedures.

DISCUSSION

Site and Silvicultural Management Effects on Wood Density

Both mean annual air temperature and nitrogen fertility are important site factors known to determine variation in outerwood density. The importance of nitrogen supply was demonstrated by previous research undertaken in a fertiliser trial at Woodhill Forest, which showed that nitrogen fertiliser increased foliar nitrogen and reduced wood density (Beets *et al*. 2001). This finding is consistent with results from the Genetic Gains trial, which showed that outerwood density was related to nitrogen fertility. While density in outer rings can be predicted from site variables, it was necessary to assume that density at the pith was constant across all sites

Silvicultural thinning effects on density were relatively small compared to site effects, although stocking rates within the range normally encountered in *P. radiata* plantations resulted in statistically significant differences in outerwood density. The effect of final stocking on outerwood density was therefore included in the model to avoid bias. The more subtle influence of timing of thinning operations was not examined.

Ring Age Effects from Pith to Bark

The age-related increase in wood density from pith to bark is an important consideration when modelling variation in wood density. All sites commence at a common initial density at age zero, with density then increasing with stand age. Site effects, although difficult to show at young ages because the differences are small, were evident already by age 3. The pith-to-bark trend lines for high- versus low-density sites do not normally cross with increasing age, and therefore the model predictions based on outerwood density ought to be valid at young ages.

Nitrogen supply can influence the trend line — for example, an ephemeral reduction in outerwood density after a single application of nitrogen was found at a fertiliser trial examined by Cown & McConchie (1981). Furthermore, repeated applications of nitrogen fertiliser can influence the normal pattern of density variation at breast height from pith to bark, with consistently lower wood densities evident in stands receiving annual additions of nitrogen fertiliser over a 10-year period compared with untreated stands (Beets *et al*. 2001). These trial results are somewhat atypical. A normal pith-to-bark pattern of density variation can be expected at Kyoto Forests as they do not have fertiliser applied because of the fertility of the site while the land was still under pasture.

The pronounced increase in density in rings 3 and 8 at heights 0 and 1.4 m (Fig. 4) was due primarily to the increased resin content of heartwood in these rings. The model functions are for predicting density in growth sheaths of sapwood, ignoring the presence of resin in heartwood. If required, increased density in heartwood could be predicted separately by modelling the development of resin content over time, but the effect on density is expected to be relatively minor.

Performance of the Model

An independent dataset from the North Island of New Zealand was acquired to test the validity of wood density predictions at breast height using the model. The national model was robust for this region, with an average model prediction error of 3.2%. The model development dataset was restricted to a single seedlot. Genetic differences in density in the validation dataset contributed at least partly to the discrepancy between measured and predicted densities. For example, seedlot differences in density were 5% at the stocking rates trial in Kaingaroa Forest and Puruki, where aspect effects on density were also evident.

The annual growth sheath/breast-height ring density ratio used in the model was not independently tested; however, the function fitted to the development dataset worked well from ages 5 to 30 years, after which the function over-estimated the ratio. Whole-stem wood density/breast-height outerwood density ratios derived from data given by Cown *et al.* (1991) were broadly consistent with the modelled ratios.

Consideration of Genetic Effects

The outerwood density data based on the Genetic Gains trial averaged approximately 9% lower than found during the1978 survey conducted by Cown *et al*. (1991). Seedlot and site factors would both contribute to this difference. For example, the overall average nitrogen fertility observed at the Genetic Gains trial sites was moderately high, with an adjusted C/N ratio of 18, compared with ratios of around 24–26 found at typical forest sites. Given the likely wide range in seedlots planted in Kyoto Forests, it will nevertheless be important to further test the model and, if necessary, use appropriate genetic adjustment factors based on a sample of stands.

To ensure model predictions are accurate when applied to specific genotypes of *P. radiata*, breast-height outerwood density could be directly measured, replacing step 1 in the model.

CONCLUSIONS

The national wood density model, developed to predict the mean density of stem wood annual growth increments from mean annual temperature, soil nitrogen fertility, ring age, and final stocking, incorporates a number of calculation steps to obtain: firstly, outerwood density at breast height; secondly, breast-height density by ring age from pith-to-bark; and finally, density of the growth sheath by ring age.

Carbon sequestration in *P. radiata* stands can therefore be derived by multiplying the predicted mean density of annual growth sheaths by the corresponding stem volume increment from, for example, an empirical stand growth model.

The model accounted for the effects of site, silviculture, and tree age on wood density variation, and predictions apply to typical seedlots. Genetic effects could be taken into account by developing genetic adjustment factors for seedlots or clones grown under comparable site conditions and stocking rates. Assuming there is no site × genotype interaction, adjustment factors could be developed at one site, or preferably a small set of sites. Alternatively, breast-height outerwood density could be directly measured at all sites, replacing step 1 in the model.

ACKNOWLEDGEMENTS

Historical data from a wide range of studies undertaken by a number of researchers referred to in this paper were compiled in order to develop a new wood density model, using underpinning funding provided through the New Zealand Ministry for the Environment, in support of climate-change related research. In addition, more recent research on environmental factors influencing outerwood density was funded by a research consortium (WQI Limited), whose support is also gratefully acknowledged.

REFERENCES

BEETS, P.N. 1997: Wood density and nitrogen supply. Pp. 23–24 *in* Ridoutt, B.G. (Ed.) "Managing Variability in Resource Quality", Proceedings of the 2nd New Zealand Wood Quality Workshop, 12 September 1997. *New Zealand Forest Research Institute Limited, FRI Bulletin No. 202*.

BEETS, P.N.; POLLOCK, D.S. 1987: Accumulation and partitioning of dry matter in *Pinus radiata* as related to stand age and thinning. *New Zealand Journal of Forestry Science 17*: 246–271.

BEETS, P.N.; GILCHRIST, K.F.; JEFFREYS, M.P. 2001: Wood density of radiata pine: effect of nitrogen supply. *Forest Ecology and Management 145*: 173–180.

BEETS, P.N.; OLIVER, G.R.; KIMBERLEY, M.O.; PEARCE, S.H.; RODGER, B. 2003: Genetic and soil factors associated with variation in visual magnesium deficiency symptoms in *Pinus radiata*. *Forest Ecology and Management 189*: 263–279.

BEETS, P.N.; ROBERTSON, K.A.; FORD-ROBERTSON, J.B.; GORDON, J.; MACLAREN, J.P. 1999: Description and validation of C_Change: a model for simulating carbon content in managed *Pinus radiata* stands. *New Zealand Journal of Forestry Science 29*: 409–427.

COWN, D.J. 1973: Effects of severe thinning and pruning treatments on the intrinsic wood properties of young radiata pine. *New Zealand Journal of Forestry Science 3(3)*: 379–389.

——1974: Comparison of the effect of two thinning regimes on some wood properties of radiata pine. *New Zealand Journal of Forestry Science 4(3)*: 540–551.

——1977: Summary of wood quality studies in fertiliser trials. Pp. 307–310 *in* Ballard, R. (Comp.) "Use of Fertilisers in New Zealand Forestry". *New Zealand Forest Service, FRI Symposium No.19*.

——1980: Radiata pine: wood age and wood property concepts. *New Zealand Journal of Forestry Science 10(3)*: 504–507.

COWN, D.L.; BALL, R.D. 2001: Wood densitometry of 10 *Pinus radiata* families at seven contrasting sites: influence of tree age, site and genotype. *New Zealand Journal of Forestry Science 31(1)*: 88–100.

COWN, D.L.; McCONCHIE, D.L. 1981: Effects of thinning and fertiliser application on wood properties of *Pinus radiata*. *New Zealand Journal of Forestry Science 11*: 79–91.

——1982: Rotation age and silvicultural effects on wood properties of four stands of *Pinus radiata. New Zealand Journal of Forestry Science 12(1)*: 71–85.

COWN, D.J.; McCONCHIE, D.L.; YOUNG, G.D. 1991: Radiata pine wood properties survey. *New Zealand Ministry of Forestry, FRI Bulletin No. 50 (revised edition)*.

COWN, D.J.; McKINLEY, R.B.; BALL, R.D. 2002: Wood density variation in 10 mature *Pinus radiata* clones. New Zealand Journal of Forestry Science 32(1): 48–69.

COWN, D.J.; YOUNG, G.D.; BURDON, R.D. 1992: Variation in wood characteristics of 20-year-old half-sib families of *Pinus radiata*. *New Zealand Journal of Forestry Science 22(1)*: 63–76.

DONALDSON, L.A.; EVANS, R.; COWN, D.J.; LAUSBERG, M.J.F. 1995: Clonal variation of wood density variables in *Pinus radiata. New Zealand Journal of Forestry Science 25(2)*: 175–188.

HARRIS, J.M. 1965: A survey of the wood density, tracheid length, and latewood characteristics of radiata pine grown in New Zealand. *New Zealand Forest Service Technical Paper 47*. 31 p.

HARRIS, J.M.; McCONCHIE, D.L.; POVEY, W.A. 1978: Wood properties of clonal radiata pine grown in soils with different levels of available nitrogen and water. *New Zealand Journal of Forestry Science 8(3)*: 417–430.

HUGHES, R.V.; MACKNEY, A.W. 1949: Density and moisture content of New Zealand *Pinus radiata* D. Don. *Appita 3*: 387–407.

IPCC 2003: "Good Practice Guidance for Land Use, Land-use Change, and Forestry". Institute for Global Environmental Studies (IGES) for the IPCC.

JACKSON, D.S.; GIFFORD, H.H. 1974: Environmental variables influencing the increment of radiata pine: (1) Periodic volume increment. *New Zealand Journal of Forestry Science 4(1)*: 3–26.

KIMBERLEY, M.O.; WEST, G.; DEAN, M.; KNOWLES, L. 2005: The 300 Index — A volume productivity index for radiata pine. *New Zealand Journal of Forestry 50*: 13–18.

LAUSBERG, M.J.F.; COWN, D.L.; GILCHRIST, K.F.; SKIPWITH, J.H.; TRELOAR, C.R. 1995: Physiological aging and site effects on wood properties of *Pinus radiata*. *New Zealand Journal of Forestry Science 25(2)*: 189–199.

LOE, J.A.; MACKNEY, A.W. 1953: Effect of age on density and moisture content of New Zealand *Pinus radiata*. A*ppita 7*: 183–194.

McCONCHIE, D.L. 1995: Wood quality of radiata pine on fertile sites. Pp. in Klitscher, K.; Cown, D.L.; Donaldson, L. (Ed.) "Forest Research Wood Quality Workshop '95". *New Zealand Ministry of Forestry, FRI Bulletin No. 201*.

McKINLEY, R.B. 1995: Factors affecting wood density of radiata pine — An update (1995). Pp. in Klitscher, K.; Cown, D.L.; Donaldson, L. (Ed.) "Forest Research Wood Quality Workshop '95". *New Zealand Ministry of Forestry, FRI Bulletin No. 201*.

NYAKUENGAMA, J.G.; DOWNES, G.M.; NG, J. 2002: Growth and wood density responses to later-age fertilizer application in *Pinus radiata*. *IAWA Journal 23(4)*: 431–448.

——2003: Changes caused by mid-rotation fertilizer application to the fibre anatomy of *Pinus radiata*. *IAWA Journal 24(4)*: 397–409.

SMITH, D.M. 1954: Maximum moisture content method for determining the specific gravity of small wood samples. *USDA Forest Service, Forest Products Laboratory, Paper No. 2014*.

TIAN, X.; COWN, D.L.; McCONCHIE, D.L. 1995: Modelling of *Pinus radiata* wood properties. Part 2: Basic density. *New Zealand Journal of Forestry Science 25(2)*: 214–230.