WOOD DENSITY AND INTERNAL CHECKING OF YOUNG *EUCALYPTUS NITENS* IN NEW ZEALAND AS AFFECTED BY SITE AND HEIGHT UP THE TREE

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ABSTRACT

Whole-tree basic density and internal checking were assessed in *Eucalyptus nitens* (Deane et Maiden) Maiden at six New Zealand sites, four in the North Island and two in the South Island, by sampling 15 trees/site, each involving one seedlot of Victorian provenance at a stocking of 1111 stems/ha. Sites ranged in altitude from 40 to 540 m and in latitude from 35°52´S (Dargaville) to 45°55´S (Drumfern). Site mean whole-tree density ranged from 428 kg/m^3 at Raweka (Whakatane) to 476 kg/m^3 at Mangakahia (Dargaville). Density at Kinleith, Wainui (both central North Island), and Millers Flat and Drumfern (southern South Island) varied little, from 445 kg/m^3 to 459 kg/m^3. From these and previous results, there was some indication that very high rainfall and high levels of foliar nitrogen, phosphorus, and magnesium led to extremely low wood density. Whole-tree density increases with age and, after an initial decrease in the lower bole, increases with height up the stem by 50 kg/m^3 and more as age increases, resulting in lower density in the butt log than in upper logs.

Internal checking, assessed in one breast-height disc per tree, was prevalent at all sites, especially in outer heartwood in both slowly kiln-dried and air-dried samples. More checks were found in air-dried discs than in kiln-dried. Many more checks were found at the North Island sites Mangakahia, Raweka, and Kinleith than at the high-altitude central plateau site Wainui or the South Island sites. Higher numbers of checked rings and total checks were associated with higher mean annual temperatures, short green crowns, and poor crown health. Far fewer checks were found at cooler sites where trees had much better crown health and longer green crowns.

Checking data were reanalysed from an earlier study of twenty 15-year-old trees from Kaingaroa Forest (altitude 230 m) from four kiln-dried discs per tree at heights of 0, 1.4, 6.4, and 11.4 m, and from a 1-m air-dried diametral board sawn from the base of each tree. Numbers of checks varied enormously among trees and fell to zero above height 11.4 m. Numbers of checks in the board cross-section correlated moderately with those in the breast-height disc. It is considered that excessive checking in *E. nitens* may seriously reduce its potential for utilisation for appearance-grade lumber, particularly on warmer New Zealand sites where crown health is poor.

Keywords: whole-tree basic density; wood drying; internal checking; site; temperature; rainfall; nutrition; within-tree variation; between-tree variation; *Eucalyptus nitens.*

INTRODUCTION

Eucalyptus nitens has become the most widely planted eucalypt in New Zealand because of its wide adaptability, including frost resistance, its rapid growth and good form, and its suitability for kraft pulping (Miller *et al*. 1992). However, there is increasing evidence that plantations of *E. nitens* on warm, low-altitude sites with moderate to high rainfall in the North Island are affected by fungal leaf diseases, which result in poor health, reduced growth, and even death (Low & Shelbourne 1999; Shelbourne *et al*. 2000; Hood *et al*. 2002).

The pulp yield of *E. nitens* is high — 56% for 15-year-old trees from Kaingaroa Forest, 55.6% for 11-year-old, and 54.7% for 8-year-old trees from Northland (Kibblewhite *et al*. 1998, 2000) — but, as we will show, its wood density is medium to low, especially for trees under 12 years old. Wood density is recognised as the second most important factor (after growth rate) in the profitability of kraft pulp production (Borralho *et al*. 1993; Greaves *et al*. 1997), and strongly determines kraft handsheet quality, especially handsheet bulk, an important property for which *E. nitens* pulps are often deficient (Kibblewhite *et al*. 1998, 2000). Wood density also largely determines strength and stiffness of structural timber. It shows a high heritability (Gea *et al*. 1997) but little is known about the effects of site on its expression in New Zealand, and defining these effects was an important objective of this study.

Eucalyptus nitens is grown widely for pulp in Tasmania, in South Africa, and in Chile as well as in New Zealand, but there is increasing interest overseas in growing some stands for solid-wood products, including appearance-grade lumber (Wardlaw & Neilsen 1999). Internal checking is a drying defect which has proved to be widespread with *E. nitens* on some sites in New Zealand (Haslett 1988; Haslett & Young 1992; Lausberg *et al*. 1995; McKenzie, Turner, & Shelbourne in press; McKenzie, Shelbourne, Kimberley, McKinley, & Britton in press). Internal checking, expressed in disc samples as well as in sawn timber, is strongly influenced by drying methods, which have not yet been standardised. Internal checking shows major species differences; for instance, closely-related *E. maidenii* Labill. has zero checking compared with *E. nitens* on the same site (McKinley *et al*. in press). Increasing the knowledge of its incidence in *E. nitens* on different New Zealand sites was another main objective of this study. As background to the experimental study, published and unpublished reports on density and checking were reviewed and a fresh extended analysis of data from an earlier study is included here.

PREVIOUS STUDIES

Basic Density

Whole-tree basic density increases rapidly with age up to about age 15 years, thereafter increasing more slowly. McKinley *et al*. (2000) summarised the limited New Zealand whole-tree data available in the New Zealand Forest Research Institute database, across sites, and showed an average increase in whole-tree basic density with age from 453 kg/m^3 (age 9), to 477 (age 15), to 495 (age 20), to 519 kg/m^3 at age 30 years. The data were very limited below age 9 and above age 17 years.

Milne (1991) measured whole-tree basic density on 14–25 trees per site at four South Island trials of Victorian provenances (Table 1). These were at Berryman's Nursery, Golden Downs Forest (Nelson), Callaghan's Ridge (near Ahaura, Westland), and Longwoods Forest

TABLE 1–Whole-tree basic density of *E. nitens* at South Island sites (Milne 1991)

Site	Age (yr)	Latitude (°S)	Altitude (m)	Mean annual rainfall (mm)	Mean annual temp. (°C)	Provenances	No. trees	Whole-tree basic density (kg/m³)
Berrymans's (Nelson)	11	41°27′	210	1130	11.5	Toorongo/ Rubicon	25	483
Callaghan's ridge (Westland)	12	42°24′	330	1900	11.5	??	19	419
Longwoods (Southland)	11	46°14′	95	1260	10.0	Macalister/ Toorongo	20	438
Glentunnel (Canterbury)	30	43°29′	350	880	10.3	Victoria	14	565

(west of Invercargill, Southland), aged 11 and 12 years, and at Glentunnel in Canterbury, aged 30 years. Site mean densities were respectively 483, 419, and 438 kg/m^3 (ages 11–12) and 565 kg/m^3 (age 30).

In studies of biomass for energy (F.Jamieson unpubl. data; Nicholas *et al.* 2000; Nicholas, Jansen & McNeil in prep.; Nicholas, Jamieson, McConchie & Hawke in prep.), 15 trees per seedlot of *E. nitens* were sampled at ages 5–9 years by 5-mm increment cores taken at breast height at four sites in the North Island (Kaikohe, Rotorua, Clive, and Palmerston North), and at Christchurch in the South Island. Latitudes varied from 35°25' at Kaikohe to 43°39' at Christchurch and altitudes were mainly less than 50 m, except at Rotorua (300 m) and near Kaikohe (250 m). Seedlots of southern New South Wales and central Victorian provenances were sampled. Mean increment core density ranged from 399 to 419 kg/m^3 and differences between seedlots and sites were small. Predicted whole-tree densities of this material ranged from 422 kg/m^3 to 442 kg/m^3.

G.Jansen (unpubl. data) did biomass studies on 10-year-old trees of *E. nitens*, *E. globulus* Labill., and *E. maidenii* at Clive, near Napier (latitude 39°36', altitude 5 m) and at Kaikohe, at age 6 years, on five trees/site. Mean whole-tree basic densities were respectively 449, 489, and 582 kg/m^3 at Clive and 431, 479, and 555 kg/m^3 at Kaikohe.

Lausberg *et al.* (1995) preselected 20 trees for a wide range of increment-core pith-to-bark basic density from 100 trees in a 15-year-old provenance/progeny trial in Kaingaroa Forest (latitude 38°26', altitude 230 m). These had a mean increment-core basic density of 435 kg/m^3 and mean whole-tree density, based on discs, of 467 kg/m^3 (this was the same material whose pulping was reported by Kibblewhite *et al.* 1998).

J.D.Richardson (unpubl. data) and J.B.Ford-Robertson, G.D.Young, & I.D.Nicholas (unpubl. data) reported mean whole-tree basic densities for 26 trees of 15-year-old *E. nitens* (from central Victoria) and eight each of 15-year-old *E. regnans* F.Mueller and *E. fastigata* Deane et Maiden. All were grown in Kinleith Forest, near Tokoroa (altitude ca.350 m) in the central North Island. The mean whole-tree densities of 15-year-old *E. nitens* of central Victorian provenance and of *E. fastigata* were similar (474 and 479 kg/m^3) and that of *E. regnans* was appreciably lower (426 kg/m^3). Density increased with log height in *E. nitens* from 456 kg/m^3 in the 6-m butt log to 533 kg/m^3 for the fourth log (18–24 m height).

McKinley *et al.* (2002) reported whole-tree basic densities in species/provenance trials of *E. nitens*, *E. globulus*, and *E. maidenii* grown at two sites in Northland, aged 8 and 11 years. At age 8 years these were respectively 440, 476, and 567 kg/m^3 and at age 11 years 451, 540, and 574 kg/m^3.

Internal Checking

Information about internal checking on drying in wood from young plantation stands of *E. nitens* is limited, especially individual-tree studies examining checking at different heights on the stem. McKimm *et al.* (1988) sawed logs from seven 20-year-old plantation trees, grown at Mt Beenak, near Powelltown in central Victoria. They sawed four logs, 3 m long, from the butt of each tree, alternately into structural and appearance grades and dried the products using four different drying schedules. Internal and face checking were found in all products; face checking was less in quarter-sawn boards than back-sawn but the reverse was true for internal checking. Air-drying followed by high-temperature kiln-drying resulted in the least internal checking. Face and internal checking were moderately correlated within trees, and there were large differences between trees in amount of checking. Mean whole-tree density of this 20-year-old stand was 488 kg/m^3.

One of the most extensive individual-tree studies of internal checking in eucalypts was reported by King *et al.* (1993); in that study 323 8-year-old trees from a provenance trial of *E. delegatensis* R.T.Baker in Southland, New Zealand, were sampled by breast-height discs. The researchers recorded numbers of checks in each ring, with a subjective rating of severity of each check. They found twice as many checks in mainland provenances as in Tasmanian provenances. Their methods formed the basis of subsequent studies of checking in *E. nitens* in New Zealand.

Yang & Waugh (1996) reported high levels of internal checking of timber from 15-, 25-, and 29-year-old *E. nitens* after air- and kiln-drying. Haslett & Young (1992) reported high levels of checking in sawn boards from a 30-year-old plantation of *E. nitens* in Canterbury, in the South Island.

Purnell (1988) assessed a variety of wood properties in an 11-year-old trial of New South Wales and Victorian provenances of *E. nitens* at Jessievale State Forest (latitude 26°14'S, longitude 30°31'E, altitude 1733 m) in the eastern Transvaal highveld of South Africa. Assessment was confined to properties measured on logs taken at 2.4-m intervals and on adjacent discs. Log-end splitting was assessed as “triangular” and “elliptical” splits on all log ends. Collapse was high in discs from the bases of the trees, and reduced with height to 12 m. Trees varied widely in the amount of collapse, but provenance differences were not significant. Triangular splitting was not correlated with elliptical splitting, both of which varied a lot between trees and were often severe. Elliptical splits (which appear to indicate checking) were severe at the base, decreasing to zero by height 9.6 m, whereas triangular splits (apparently indicating growth stresses) also had higher values in the lower parts of the tree, decreasing somewhat by height 12 m.

J.B.Ford-Robertson, G.D.Young, and I.D.Nicholas (unpubl.data) and J.D.Richardson (unpubl.data) reported the subjective scoring of internal checking on discs from 26 trees of 15-year-old *E. nitens* from central Victoria and 8 trees each of 15-year-old *E. regnans* and

E. fastigata. Discs were taken at the base and at 6-m intervals up the stem, and oven dried at 103°C (a method later shown by McKenzie, Shelbourne, Kimberley, McKinley, Britton (in press) to give only weak correlations with board checking). Checking was assessed on a scale of 0 = no checks, 1 and 2 = minor checking, to 3, 4, and 5 indicating increasing severity of and numbers of checks. Checking score decreased rapidly up the stem, to near-zero levels in the 18-m-height discs of *E. nitens*, and slightly higher scores in *E. regnans* and *E. fastigata*. With the small numbers of 15-year-old *E. fastigata* and *E. regnans* sampled, there were no apparent species differences, with species mean checking scores at the base ranging from 3.67 to 2.50, and at 6 m from 2.25 to 1.38.

Lausberg *et al*. (1995) assessed internal checking of the same 20 15-year-old trees of *E. nitens* from Kaingaroa Forest in the central North Island, as were assessed for density. Internal checking was recorded as number of checks per ring from discs, taken at height intervals up to 20 m. Checking was widespread but there was a large variation between trees in number of checks. A basal 1-m billet was also removed from each tree, a diametral board was sawn from each billet, and internal checking was assessed. The comprehensive checking data will be reanalysed later in this paper.

McKenzie, Turner, & Shelbourne (in press) and McKenzie, Shelbourne, Kimberley, McKinley, & Britton (in press.) carried out a comprehensive utilisation study on 15 trees of 15-year-old, very fast-grown *E. nitens* from Golden Downs Forest near Nelson, the same site as was sampled by Milne (1991). Each tree was sampled by discs at about 5-m intervals and a butt log was quarter-sawn into 40-mm boards which were air-dried to 17% m.c. and later kiln-dried and steam-reconditioned. A 1-m billet was removed from height 6–7 m and quarter-sawn into 25-mm boards. Various wood, sawn-timber, and veneer end-product characteristics were studied tree by tree and, in particular, checking and collapse were measured in butt-log boards, in 6-m-height discs (both oven-dried and dehumidifier-dried), and in 1-m boards from height 5–6 m (air- and dehumidifier-dried).

Internal checking was recorded as number of checks per millimetre of ring circumference in the discs, as number of checks per millimetre of ring radius in the 1-m boards, and as number of checks at top and bottom ends of the butt-log boards. Checking was prevalent in all but two trees in the butt-log boards, was much worse at the bottom than at the top ends, and boards from all but two trees showed substantial collapse. All trees showed a lot of face checking after steam reconditioning. In the 1-m boards, the amount of checking varied a lot between trees and there was less checking in the air-dried than in the dehumidifier-dried boards. The number of checks in 6-m-height discs varied enormously among trees and there were more checks in oven-dried than in dehumidifier-dried discs. There were high correlations of individual tree values of amounts of checking in dehumidifier-dried discs *vs* air-dried 1-m boards and butt-log boards, all over 0.90, but poor correlation with checking in oven-dried discs. Correlations of amounts of checking in butt-log boards *vs* 1-m boards were also all over 0.90. Collapse in butt-log boards correlated well with their checking, and with checking in 1-m boards and dehumidifier-dried discs.

McKinley *et al*. (2002) assessed checking in air-dried discs from height 6 m of ten 11-year-old trees of *E. nitens*, *E. globulus*, and *E. maidenii*. Total number of checks in *E. nitens* varied widely between trees, from 3 to 104, but was mainly 15 or more. One tree only of *E. globulus* showed checking and none of *E. maidenii*.

In the checking studies reviewed above, trees came from Northland (lat. 36°S), central North Island medium-altitude sites (lat. 38°S), and a 230-m-altitude site at Golden Downs, Nelson (lat. 41°S). At all of these sites *E. nitens* has shown plenty of internal checking. In the study reported here, results on these sites were compared with those on some colder, higher-altitude, and more southern (lat. 45°S) sites.

MATERIALS AND METHODS

Field Trials and Their Sampling

Between 1990 and 1992 a series of silvicultural regime trials of *E. nitens* were established at six sites throughout New Zealand (Table 2). These included one near Dargaville in Northland, three trials in the central North Island, and two in the southern South Island, all planted with a commercial seedlot of central Victorian origin. Plots established at 1111 stems/ha and unthinned, as used for commercial pulp production, were sampled at each site. At all sites except Kinleith, there were three replications of this treatment with 25-tree measurement plots. At Kinleith, there were two replicates, at separate sites, with a 100-m difference in altitude. All trials were planted with stock of seedlot number 89/20 which was collected from thinning a 1979-planted progeny trial at Rotoaira Forest of 80 open-pollinated native population families, almost entirely of central Victorian provenances.

TABLE 2–Site and trial details

Location	Altitude (m)	Latitude (°S)	Longitude (°E)	Planted (year)
Mangakahia, Northland	40	35º52´	173º52´	1990
Raweka, Bay of Plenty	250	38º09´	176º55´	1990
Kinleith, Bay of Plenty	300& 400	38º21´	175º51´	1990
Wainui, Taupo	540	38º54´	176º11´	1990
Millers Flat, Otago	440	45º41´	169º29´	1992
Drumfern, Southland	140	45º55´	168º15´	1991

The sites were very discontinuous in their latitudinal distribution, with four clustered in the central North Island and none in Nelson, Canterbury, or Westland. Altitudes were quite varied in the North Island, from 40 m near Dargaville to 540 m at Wainui, and in the South Island from 440 to 140 m.

Mean annual temperature and mean annual rainfall, derived from BIOCLIM (Nix 1986; Mitchell 1991), varied widely (Table 3) from 14.7°C at Mangakahia to 8.6°C at Millers Flat, and 2060 mm at Raweka, 1400–1650 mm at other North Island sites, to 740 mm at Millers Flat. Mean daily maximum and minimum temperatures followed a similar trend to mean annual temperature.

With only six sites sampled in this study, there is no possibility of developing predictive models for wood density and internal checking in relation to climatic variables. However, the wide differences between sites in some of the variables may allow some hypotheses to be proposed about these relationships that could be tested further in future, by extending the sites sampled.

TABLE 3–Climatic data of study sites (from BIOCLIM — Mitchell 1991)

Location	Altitude (m)	Mean daily minimum temp. (°C)	Mean daily maximum temp. (°C)	Mean annual temp. (°C)	Mean annual rainfall (mm)
Mangakahia	40	10.2	19.2	14.7	1370
Raweka	250	7.0	18.1	12.6	2060
Kinleith	400	7.1	16.8	11.9	1650
Kinleith	300	7.2	17.5	12.3	1490
Wainui	540	5.6	15.8	10.8	1480
Millers Flat	440	3.7	13.7	8.6	740
Drumfern	140	4.7	15.0	9.8	900

Millers Flat and Drumfern were planted later than the North Island trials (Table 4) and this must be noted in evaluating the density and checking data. Survival was only 77% and 71% at Mangakahia and Raweka respectively, when these trials were assessed at age 8 or 9 years, but was 88% at Kinleith and over 93% at Wainui and the two South Island sites. Annual height growth was substantially less at the high-altitude Wainui site and the two South Island sites (ca. 2.1 m) than at the other North Island sites (2.4–2.8 m). Mean diameter at breast height and mean annual volume increment, however, did not show these trends, and at Drumfern values were as high as at Mangakahia.

In 2001, at age 9–11 years (Table 4), 30 healthy trees in total at each location were randomly selected from the plot surround of three plots where available (to avoid removing trees from the measurement plots) from across the diameter range of the crop trees. For each tree, diameter at breast height over bark (dbhob) was recorded and two pith-to-bark 5-mm increment cores were extracted for preliminary screening for basic density. This was done using the maximum moisture content method (Smith 1954).

TABLE 4–Tree crop particulars at each site

	Mangakahia	Raweka	Kinleith	Wainui	Millers Flat	Drumfern
Established (year)	1990	1990	1990	1990	1992	1991
Age measured (years)	9	9	9	9	8	8
Stocking (stems/ha)	859	792	988	1042	1037	1050
MTD* (mm)	282.0	270.3	238.0	233.3	215.8	240.3
MTH* (m)	21.9	24.8	21.9	19.1	16.7	17.2
Mean dbh (mm)	210.3	188.0	169.0	163.7	172.5	191.0
Basal area (m^2/ha)	30.2	21.8	23.2	24.1	24.5	30.1
Volume (m^3/ha)	223.3	170.7	170.1	159.0	147.2	185.1
Mean annual height growth (m)	2.43	2.76	2.43	2.12	2.09	2.15
Mean annual increment (m^3/ha)	24.8	19.0	18.9	17.7	18.4	23.1

***** MTD (mean top diameter) and MTH (mean top height) = the mean diameter and height, respectively, of the 100 largest-diameter trees/ha.

Tree, Disc, and Wood Property Measurements

From the initial increment-core density survey of 30 trees in each trial, 15 trees were selected of the same mean value to cover the density range, five trees in each of three plots at each site (two plots at Kinleith). After tree felling, diameter over and under bark, was measured at 0.3, 0.7, 1.4, 5, 10, and 15 m. Total height of each tree was also recorded. Foliage samples were collected to check species identification and for health assessment. A sample of leaves from all 15 trees/site was bulked for foliar nutrient analysis.

Cross-sectional discs were cut at stump height, 1.4 m, 5 m, and at successive 5-m intervals, down to a small-end diameter of 80 mm, for whole-disc analysis of heartwood percentage, bark thickness, moisture content, and green and basic density. Decay (“rot”) was recorded as a percentage of disc area. Estimated mean values for each log, and volume-weighted whole-tree estimates of these properties were derived from the disc measurements for each tree.

An extra disc, 60 mm thick, was cut from each tree at height 1.4 m to provide samples for assessment of internal checking after air- or kiln-drying. Methods used here have evolved from those of King *et al*. (1993) and Lausberg *et al*. (1995). To prevent excessive moisture loss during the sampling period, discs were enclosed in plastic bags and kept refrigerated until all trial locations had been sampled. Discs were then cut diametrically, both halves as similar as possible, to provide one half-disc sample which was slowly kiln-dried for 10 days using a low-temperature schedule (40°C and 60% R.H.), and a second half-disc which was air-dried for approximately 6 months.

After drying, the half-discs were cross-cut to expose an internal face and sanded to give a clean, smooth surface to assess for internal checking. The total number of rings and those containing heartwood were recorded. The number of checks was recorded for each ring and rings were classified as heartwood, transition wood (one complete ring either side of the heartwood boundary), or sapwood.

Statistical Analysis

The data were treated as a fully randomised design and the equation for this model is :

$$Y_{ijk} = \mu + S_i + P_j : S_i + E_{ij}$$

Where: Y_{ijk} = the observation on the kth tree in the j^{th} plot in the i^{th} site
μ = the overall mean
S_i = the effect of the i^{th} site
$P_j : S_i$ = the effect of the j^{th} random plot within the i^{th} site
E_{ij} = the residual random error associated with the k^{th} tree within the j^{th} plot in the i^{th} site.

Analysis of variance (ANOVA) was carried out using PROC GLM of the SAS™ software package (SAS Institute Inc. 1989) with plots nested within sites. Tukey’s multiple range test was used conservatively to test for pairwise differences between site means. PROC CORR (SAS Institute Inc. 1990) was used to obtain correlations between the traits involved in this study.

RESULTS AND DISCUSSION

Growth, Green Crown Length, and Initial Density Screening

Diameter at breast height of 30 randomly selected trees per site ranged from 241 mm at Raweka to 187 mm at Millers Flat, partly because trees at the latter site were 2 years younger than those at the North Island sites (Table 5). Density of pith-to-bark cores ranged from 407 kg/m^3 at Raweka to 444 kg/m^3 at Wainui. Within-site variation in density was high, with standard deviations of 24–31 kg/m^3. Individual-tree values were based on two pith-to-bark cores per tree. About two-thirds of the trees at each site had values for each core within 10 kg/m^3 of each other. However, for the remaining one-third, values could differ widely, up to 50 kg/m^3, possibly reflecting tension wood development.

TABLE 5–Increment core statistics, by sites

Site	Number of trees sampled	Age (years)	Mean dbh (mm)	Basic density (kg/m^3)	
				Mean	Standard deviation
Mangakahia	30	10	223ab*	437ab	24
Raweka	31	10	241a	407c	31
Kinleith	31	10	202bc	422bc	26
Wainui	30	10	209bc	444a	29
Millers Flat	32	8	187c	419bc	26
Drumfern	29	9	207bc	429ab	27

*Tukey letters: differences significant at $p < 0.05$

A sample of 15 or 16 trees at each site was selected for felling, based on increment core density, to cover the range and to be of the same mean as the 30-tree sample. Mean tree height of this sample and the derived length of green crown (Table 6) showed that trees were taller at Raweka and shorter at the two South Island sites, a result of being 1 or 2 years younger and slower in height growth. Green crowns were much shorter at the lower-altitude central North Island and Northland sites than at the high-altitude Wainui site and the two South Island sites. The highest value at Millers Flat (440 m altitude in central Otago, with the lowest

TABLE 6–Site means of felled sample trees for height, volume, and green crown height and length

Site	Number of trees	Height (m)		Volume (m^3)	Green crown height (m)	Green crown length (m)
		Total	Merchantable to 50 mm s.e.d.			
Mangakahia	15	21.3b*	14.9ab	0.363ab	17.3de	4.1c
Raweka	16	24.7	17.0a	0.454a	19.6e	5.1c
Kinleith	15	20.5bc	13.3bc	0.297ab	16.9de	3.6c
Wainui	15	21.7b	13.4bc	0.312ab	14.4c	7.3b
Millers Flat	16	17.6d	10.1d	0.205b	6.7a	10.8a
Drumfern	15	18.8cd	11.4cd	0.258b	11.0b	7.8b

* Tukey letters: differences significant at $p < 0.05$

temperatures of all sites) was for 8-year-old trees, *vs* 9-year-olds at Drumfern and 10-year-olds at the other sites. Unfortunately, no health scoring was undertaken but, anecdotally, crown health was described as very poor at Mangakahia and Raweka, a little better at Kinleith, excellent at Wainui, and equally good at Millers Flat and Drumfern. Crown health is mainly affected by leaf fungi *Mycosphaerella* spp. and Septoria (now called *Phaeophleospora eucalypti* (Hood *et al*. 2002).

Wood Properties

Wood properties, bark thickness, heartwood percentage, moisture content percentage, green density, and basic wood density varied significantly ($p<0.001$) among the sites sampled in this study (Table 7), as shown by the F ratios for sites. Only for heartwood was the plot-within-site effect significant. Heart rot was present in only very small amounts, generally in basal and breast-height (1.4-m) discs, and then only appreciably at Millers Flat, and it showed a strong plot-within-site variance indicating localised occurrence in the stand.

TABLE 7–Site means for volume-weighted whole-tree wood properties

Site	No. of trees	Bark thickness (mm)	Heart-wood (%)	Moisture content (%)	Green density (kg/m^3)	Basic density (kg/m^3)	Rot (% disc area)
Mangakahia	15	7.8a	53a	128bc	1082a	476a	0.36a
Raweka	16	6.3b	52a	152a	1069a	428b	0.38a
Kinleith	15	7.6ab	50ab	139ab	1055ab	445ab	1.10a
Wainui	15	7.6ab	41c	118c	996c	458ab	0.02a
Millers Flat	16	6.8ab	32d	128bc	1034b	459ab	2.59b
Drumfern	15	7.1ab	44bc	123bc	992c	448ab	0.25a
ANOVA F for Sites (5, 74)		3.1*	30.8***	8.4***	27.9***	3.0*	7.7***

Tukey letters significant at $p < 0.05$
* significant at $p \leq 0.05$
** significant at $p \leq 0.01$
*** significant at $p \leq 0.001$

Whole-tree basic density means at each site varied from 476 kg/m^3 at Mangakahia to 428 kg/m^3 at Raweka. Means at the other four sites varied only little, from 445 to 459 kg/m^3. There was no evident effect of temperature on these results. Raweka and Mangakahia had the highest mean annual temperatures of the six sites, both lying within warm areas of the Bay of Plenty and Northland. However, Raweka had by far the highest rainfall of 2060 mm. The two South Island sites shared the prevailing lowest temperatures but trees had similar densities to those on much warmer and wetter sites. The younger age of trees at Drumfern (9 years) and Miller's Flat (8 years) appears to have had little effect on density.

Nutrient levels in the foliage, analysed by bulking individual-tree samples for each site (Appendix Table 1), showed that Raweka (with its lowest basic density) was outstanding, with the highest levels of foliar nitrogen, phosphorus, and magnesium of all sites. Its levels of aluminium, copper, and manganese were also by far the lowest. Beets *et al.* (2001) concluded that foliar nitrogen status was the main variable associated with wood density in

Pinus radiata D.Don, high levels being associated with low density. They also indicated that higher rainfall induces lower density. However, foliar levels of nitrogen at Mangakahia (highest-density site) were about average for the six sites.

In Milne's (1991) study (Table 1), whole-tree basic densities showed a similar range of means in the three 11- to 12-year-old stands sampled in the South Island, ranging from 419 kg/m^3 in Westland to 483 kg/m^3 at Golden Downs. Mean annual rainfall at the Westland site of 1900 mm was almost double that at Golden Downs, adding support to the high-rainfall/low-density hypothesis. By contrast, in the North Island, whole-tree density for 29 15-year-old trees from Kaingaroa Forest (altitude 230 m) averaged 467 kg/m^3 (Lausberg *et al*. 1995) and 26 15-year-old trees from Kinleith averaged 474 kg/m^3 (J.D.Richardson unpubl. data), all of Victorian provenances.

There was wide tree-to-tree variation in whole-tree basic density within all six sites and in corresponding breast height core density. The within-site range of whole-tree density was ca. 111 kg/m^3 at Mangakahia and Wainui and Drumfern, up to 145 kg/m^3 at Millers Flat. With an average within-site standard variation for whole-tree density of 37 kg/m^3, this provides good potential for gain from phenotypic selection for density, as a basis for genetic improvement of this trait.

The other wood properties of bark thickness, heartwood, and stem rot, that are not directly related to density, showed significant differences between sites (Table 7) — minor for bark thickness but substantial for heartwood development. Bark was thinner on trees at Raweka than at the other sites, perhaps in relation to the same factors that caused its very low density. Heartwood percentage was lowest at Millers Flat and was also low at the other "cold" sites, Wainui and Drumfern, with trees aged respectively 8, 10, and 9 years. Stem rot, confined mainly to the basal and breast-height discs, was much worse at Millers Flat than elsewhere. Moisture content was significantly lower in trees at Wainui than other sites and higher at Raweka.

There were clear and strong trends in all wood properties from the base of the tree to the top. These are shown graphically for individual variables in Fig. 1–4 (each site line-plot, based on means of 15 trees, or less for upper logs), and by disc and log height class in Appendix Tables A2 and A3. Differences between sites at each disc sampling height were significant for all wood properties at most sample heights, as shown by ANOVA F-ratios.

Bark thickness (Fig.1) quickly reduced from up to 14 mm at the base to 6–8 mm at 1.4 m height, gradually decreasing to 3–5 mm from 15 m upwards. Heartwood percentage (Fig. 2) at the base, at 1.4 m, and up to 5 m height averaged 41% to 61%, depending on site, and from 10 m upwards decreased rapidly to near zero at 15–20 m. Moisture content (Fig. 3) at each site decreased with height, parallel with the increase in basic density. Green density (not graphed) decreased from the base to height 5 m and then increased again with increasing height. Basic density (Fig. 4) at each site decreased from the base to 1.4 m, by up to 27 kg/m^3 at Kinleith, and then increased strongly to the top sampling point. At Wainui, however, the increase was only 12 kg/m^3.

Internal Checking

Internal checking was assessed only on the breast-height discs, each of which was bisected diametrically to give two semi-circular samples which were respectively air-dried

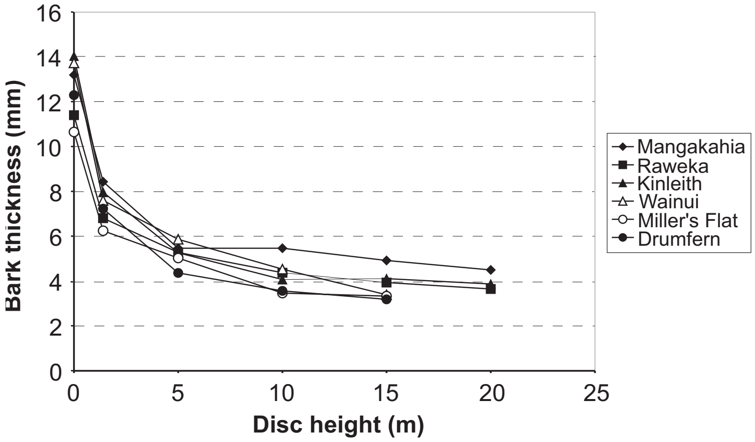

FIG. 1–Average changes in bark thickness with height up the stem, by site.

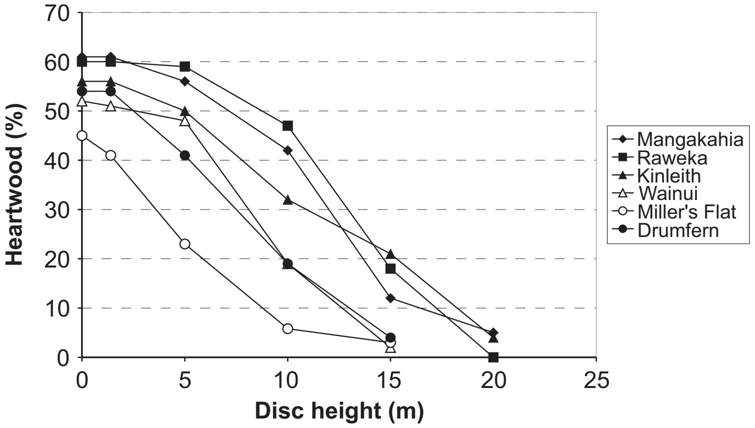

FIG. 2–Average changes in heartwood percentage with height up the stem, by site.

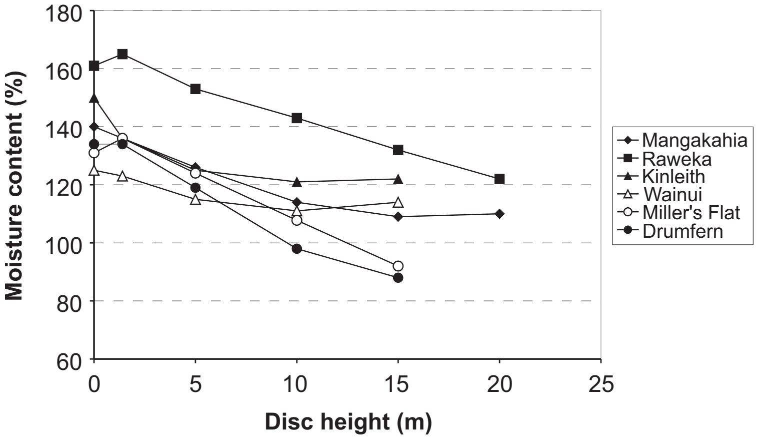

FIG. 3–Average changes in moisture content with height up the stem, by site.

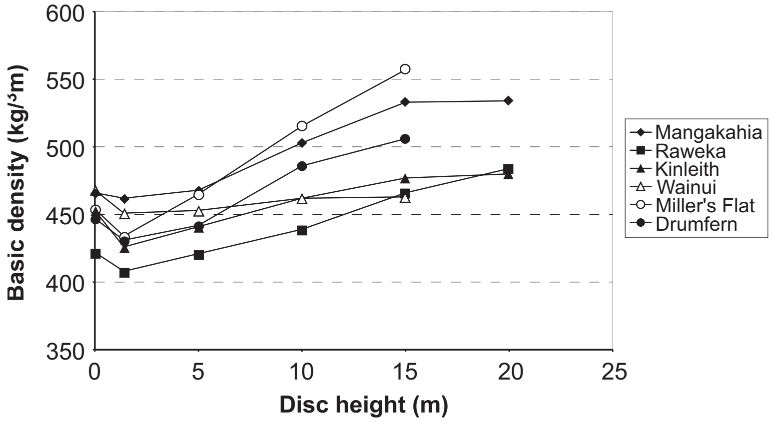

FIG. 4–Average changes in basic density with height up the stem, by site.

and kiln-dried. The number of rings affected by checks, and the number of checks, were recorded for the heartwood, "transition wood" (one ring either side of the heartwood/ sapwood boundary), and sapwood of each sample, and the mean values are given in Tables 8 and 9.

There was much more checking apparent in the air-dried discs than in the kiln-dried discs. More checking occurred in the transition-wood zone in both air- and kiln-dried discs than in the heartwood or sapwood, despite there being, normally, only two rings in the transition-wood zone. Considering all checked rings seen in air-dried discs, an average of 4.0 rings had checks at Raweka and Mangakahia, 3.1 rings at Kinleith, and 2.3 rings or less at the other three sites. The same site effects for total number of checks/disc were evident; at Mangakahia,

TABLE 8–Site means for internal checking of air-dried breast-height discs

Site	No. of trees	No. of rings	No. of heart-wood rings	No. of rings with checking				Total
				Heart-wood	Trans-ition wood	Sap-wood	All	No. of checks per disc
Mangakahia	15	10.5a	5.9a	0.87bc	2.5a	0.67	4.0b	37.8abc
Raweka	16	10.0ab	5.2b	1.13c	2.3ab	0.63	4.0b	43.2bc
Kinleith	15	9.8b	5.1bc	0.40abc	1.8abc	0.87	3.1ab	50.5c
Wainui	15	10.0ab	6.0a	0.33ab	1.5bc	0.27	2.1a	12.3a
Millers Flat	16	7.9d	4.5c	0.13ab	1.4c	0.31	1.8a	15.7ab
Drumfern	15	8.8c	5.0bc	0.07a	1.7abc	0.53	2.3a	19.5ab
ANOVA F for Sites		30.7***	14.3***	4.8***	4.1**	1.8	6.8***	4.5**

Tukey letters significant at $p < 0.05$
* significant at $p \leq 0.05$
** significant at $p \leq 0.01$
*** significant at $p \leq 0.001$

TABLE 9–Site means for internal checking of kiln-dried breast-height discs

Site	No. of trees	No. of rings	No. of heart-wood rings	No. of rings with checking: Heart-wood	Trans-ition wood	Sap-wood	All	Total No. of checks per disc
Mangakahia	15	10.5a	6.0a	0.93b	1.6ab	0.27	2.8bc	18.2ab
Raweka	16	10.0ab	5.2b	1.25b	1.8b	0.19	3.3c	28.3b
Kinleith	15	9.8b	5.1b	0.27a	1.7ab	0.40	2.4abc	30.3b
Wainui	15	10.0ab	5.9a	0.27a	0.8a	0.13	1.2a	7.1a
Millers Flat	16	7.9d	4.4c	0.06a	1.1ab	0.19	1.3ab	10.9ab
Drumfern	15	8.8c	5.0bc	0.13a	1.7ab	0.20	2.1abc	16.2ab
ANOVA F for Sites		30.7***	15.4***	10.2***	3.1*	0.5	4.9***	3.2*

Tukey letters significant at $p < 0.05$
* significant at $p \leq 0.05$
** significant at $p \leq 0.01$
*** significant at $p \leq 0.001$

Raweka, and Kinleith there were on average 44 checks/disc, and at the other sites there were only an average of 16 per disc. Although there were fewer rings checked and fewer checks per disc, the trends in site differences of internal checking in kiln-dried discs were very similar to those for air-dried.

There was wide tree-to-tree variation in checking at the heavily checked sites of Mangakahia and Raweka. Total number of checks per tree in the breast-height disc varied from 95 to 7 and no trees were free of checks. By contrast, at Millers Flat, at Drumfern, and even at Wainui in the central North Island, from one-third to one-half of the trees had zero or only a very few checks in the air-dried breast-height disc, indicating scope for selection. With an average within-site standard deviation of number of checks per disc of 28, there was plenty of variation between trees at a site for selection. The heritability of checking in *E. nitens* is unknown, however.

Lausberg *et al*. (1995) reported five times more checks visible on the inside than on the outside, when dried discs were cross-cut perpendicular to the stem axis. The same was found here where numbers of checks was assessed on the **outside** of a sub-sample of discs from the North Island sites. However, for the two South Island sites (where checking was much less) the reverse was the case. There is no ready explanation for this phenomenon. It is possible that the discs from Millers Flat and Drumfern, which were collected within a week of each other by the same team and were not cold-stored as long as the earlier-collected North Island discs, showed an obscure effect of a different storage history.

On a site-mean basis, amounts of checking in air-dried discs were evidently unrelated to basic density, or to mean annual rainfall, but showed a positive association with mean annual temperature and mean minimum daily temperature (more checking on warm sites). There was also a clear negative association of site means of both number of rings checked and total number of checks, with length of green crown, and thus with crown health — i.e., sites with good crown health had far fewer checks. Length of green crown seemed to reflect the level of ecological adaptation of the species to the site.

Much the same trends in site-mean checking were evident for kiln-dried discs. Checking was again more frequent in the transition wood zone but mean numbers of rings affected in each zone and overall were less at most sites than for air-dried discs. Total numbers of checks were reduced to half to two-thirds of those in air-dried discs at the three northernmost sites, but to more than two-thirds at Wainui and the two South Island sites.

Average Within-site Correlations Amongst Wood Properties, Internal Checking, and Tree Characteristics

These correlations were estimated within each site, z- transformed (Snedecor 1962), and averaged over the six sites, then transformed back to r values. Basic density showed no significant correlations within sites with growth traits, diameter, and volume at the individual-tree level (Table 10). Neither did it show any significant correlation with the amount of heartwood and the length of green crown. There was a strong negative relationship between basic density and moisture content. Diameter and volume were strongly correlated with green crown length, which is considered to reflect crown health. Heartwood percentage showed a weak to moderate correlation with tree diameter and volume.

TABLE 10–Average within-site correlations of individual-tree basic density with other traits, over six sites

	Basic density	Diameter	Volume	Heart-wood percentage	Green crown length	Moisture content
Basic density	1.00					
Diameter	0.00	1.00				
Volume	–0.01	0.98***	1.00			
Heartwood percentage	–0.10	0.42***	0.40***	1.00		
Green crown length	0.03	0.80***	0.80***	0.20	1.00	
Moisture content	–0.87***	0.08	0.09	0.23*	–0.01	1.00

* significant at p ≤0.05
** significant at p ≤0.01
*** significant at p ≤0.001

Average within-site correlations of total number of checks and number of rings that were checked (Table 11) with basic density, bark thickness, diameter, and green crown length were all very low and non-significant, whether measured on air-dried or kiln-dried discs. Number of rings checked had slightly higher correlations with the other traits than total number of checks. Total number of checks was quite strongly correlated with number of rings checked for air- and kiln-dried discs (r = 0.68 and 0.69 respectively, p <0.001) and there was a very weak negative relationship of number of rings checked with density (r = –0.30 and –0.35 respectively, p <0.01).

Average within-site correlations between checking in air- and kiln-dried discs (Table 12) were highly significant but only moderate for total number of checked rings (0.65) and total number of checks (0.77). For each tree, the breast-height disc was bisected diametrally to give semi-circular half-discs for air- and kiln-drying, and thus the circumferential variation

TABLE 11–Mean within-site correlations of individual-tree total numbers of checks with other traits, over six sites

	Total No. of checks	Heart-wood percentage	Bark thickness	Basic density	Diameter under bark	Green crown length	No. of rings checked
Air-dried breast-height discs							
Total No. of checks	1.00						
Heartwood percentage	0.09	1.00					
Bark thickness	0.11	0.34***	1.00				
Basic density	–0.07	–0.10	0.22	1.00			
Diameter under bark	0.10	0.40***	0.70***	–0.03	1.00		
Green crown length	0.08	0.20	0.64***	0.03	0.82***	1.00	
No. of rings checked	0.68***	0.17	0.09	–0.30**	0.25	0.18	1.00
Kiln-dried breast-height discs							
Total No. of checks	1.00						
Heartwood percentage	0.03	1.00					
Bark thickness	0.08	0.34***	1.00				
Density	–0.09	–0.10	0.22	1.00			
Diameter under bark	0.08	0.40***	0.70***	–0.03	1.00		
Green crown length	0.05	0.20	0.64***	0.03	0.82***	1.00	
No. of rings checked	0.69***	0.09	0.04	–0.35***	0.13	0.11	1.00

* significant at $p \leq 0.05$
** significant at $p \leq 0.01$
*** significant at $p \leq 0.001$

TABLE 12–Average correlation coefficients of the same traits between air-dried and kiln-dried discs

Trait name	r value
Number of rings of heartwood	0.95***
Number of checks in heartwood rings	0.67***
Number of checks in “transition rings”	0.40***
Number of checks in sapwood rings	0.33**
Total number of checked rings	0.65***
Total number of checks	0.77***

* significant at $p \leq 0.05$
** significant at $p \leq 0.01$
*** significant at $p \leq 0.001$

in checking within a disc is reflected in these correlations. It is surmised that correlations would have been higher if adjacent whole discs had been given the alternative drying treatments.

A FURTHER ANALYSIS OF THE DATA OF LAUSBERG *et al*. (1995) ON CHECKING IN DISCS AND BOARDS

Discs

As referred to under “Previous Studies” above, Lausberg *et al*. (1995) assessed checking in twenty 15-year-old trees of *E. nitens*, grown in Kaingaroa Forest in the central North

Island, which had been selected for a range of basic density. Discs were taken at 0, 1.4, 6.4, and 11.4 m up the stem, but little checking was observed above this. Discs were cut in half, diametrically, and slowly kiln-dried at 40ºC and 60% RH for 10 days. All internal checks on the external face of the disc were recorded (contrary to practice in this study), by ring, and whether checks crossed latewood bands. A sub-sample of discs was cross-cut to expose checks inside the disc. Checks were in the same areas and in the same proportions but numbers were five times higher than occurrred on the external surface.

There was large tree-to-tree variation (F 19, 60, p <0.001) in numbers of checks per ring (Table 13). There was a rapid decrease in number of checks from the base of the tree (mean of 5.2 checks /ring) to the 11.4-m disc (0.5 checks per ring) (F 60, 1060 p <0.001), where checking became nearly negligible. About one-quarter of the trees showed very large numbers of checks and a few trees had negligible numbers of checks. Trees ranked approximately the same for checking in 0-, 1.4-, and 6.4-m discs. From breast height to 6.4 m numbers of checks per ring were reduced by half, from an overall-discs mean of 4.5 to 2.4 checks/ring (Fig. 5).

Evidently checking in this material would have been a serious problem if the butt log had been sawn but not serious in the second (5.5 m) log. The large increase in numbers of checks visible on fresh-cut inner surfaces of discs raises the question, unanswerable from these data, whether bisecting discs in this manner would have revealed more checks at greater heights up the stem.

TABLE 13–Mean number of checks per ring, by individual trees and by disc heights.
Source: M.J.F.Lausberg (unpubl. data)

Tree No.	Mean number of checks per ring over all 4 discs	Number of checks per ring for each disc/height			
		0.0 m	1.4 m	6.4 m	11.4 m
3	2.0 abcde	4.81	1.94 abc	0.00 a	0.00 a
9	0.6 a	1.31	0.31 a	0.63 ab	0.00 a
11	2.2 abcde	4.75	2.19 abc	0.81 ab	0.13 a
13	1.5 ab	2.69	1.25 a	1.44 ab	0.00 a
16	2.9 abcde	4.94	4.25 abc	1.44 ab	0.00 a
17	7.5 f	8.00	11.25 bc	7.75 c	0.63 ab
35	1.6 ab	2.38	2.06 abc	1.25 ab	0.00 a
37	3.1 abcde	5.38	5.06 abc	0.75 ab	0.00 a
42	2.3 abcde	4.19	2.31 abc	1.31 ab	0.19 a
49	1.9 abcde	3.56	2.38 abc	0.88 ab	2.25 b
57	7.7 f	8.31	11.69 c	6.13 bc	0.25 ab
63	1.7 abc	2.31	2.81 abc	0.25 ab	1.56 ab
64	6.1 ef	9.56	8.56 abc	1.75 abc	0.88 ab
68	6.0 def	9.75	6.38 abc	5.00 abc	0.06 a
73	2.0 abcde	4.00	1.81 ab	1.19 ab	0.06 a
76	5.1 bcdef	7.44	8.56 abc	2.06 abc	0.06 a
77	3.1 abcde	6.81	3.13 abc	0.88 ab	0.06 a
85	1.8 abcd	1.81	3.31 abc	1.25 ab	0.06 a
90	1.5 ab	2.69	1.81 ab	0.75 ab	0.00 a
93	5.9 cdef	7.38	7.13 abc	5.50 abc	0.81 a
Mean of all trees	3.3	5.18 c	4.60 c	2.41 b	0.45 a

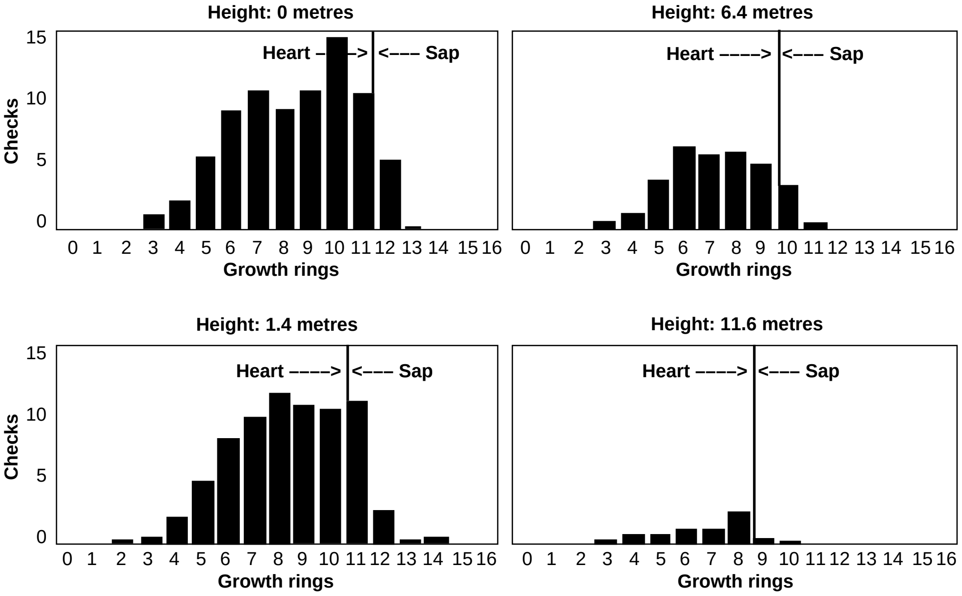

FIG. 5–Mean number of internal checks per ring, by disc height
Source: M.J.F.Lausberg (unpubl. data)

Checks in discs were largely confined to the heartwood and increased in frequency towards the outer rings of heartwood into the sapwood (Fig. 5). This is partly a scalar effect, related to the increasing circumference of rings from pith to bark.

1-m Boards

Checking was also examined in cross-sections of air-dried diametrical boards, sawn from a 1-m billet from below 1.4 m in each tree. The 25-mm diametrical boards were end-sealed and air-dried for 3 months to 30% moisture content (m.c.) and then forced-air-dried to below 20% m.c., before being placed in a 12% m.c. equilibrium room for 2 weeks. They were then cross-cut to give one cross-section for assessing internal checking.

Numbers of checks per ring from opposite sides of the pith were counted for each board, designated arbitrarily as sides A and B. Mean checks per ring in boards are compared with the mean number of checks per ring in the breast-height (kiln-dried) discs in Fig.6, and given by individual trees in Table 13.

There were large and significant differences among trees in mean number of checks in the 1.4-m disc (F 19,15 $p < 0.001$) and, similarly, for the 1-m boards (F 19, 15 $p < 0.001$) each side of the pith and for the whole cross-section (Fig.6, Table 14). Numbers of checks increased steadily from the pith to ring 11 or 12, the outermost heartwood ring, and then reduced to near zero in the outer sapwood rings. These ranged, for the breast-height disc, from 11.7 checks per ring for tree 57 to near zero for tree 9 and, for combined sides of boards, from 4.6 checks per ring for tree 57 to near zero for several trees. Differences between rings were also highly

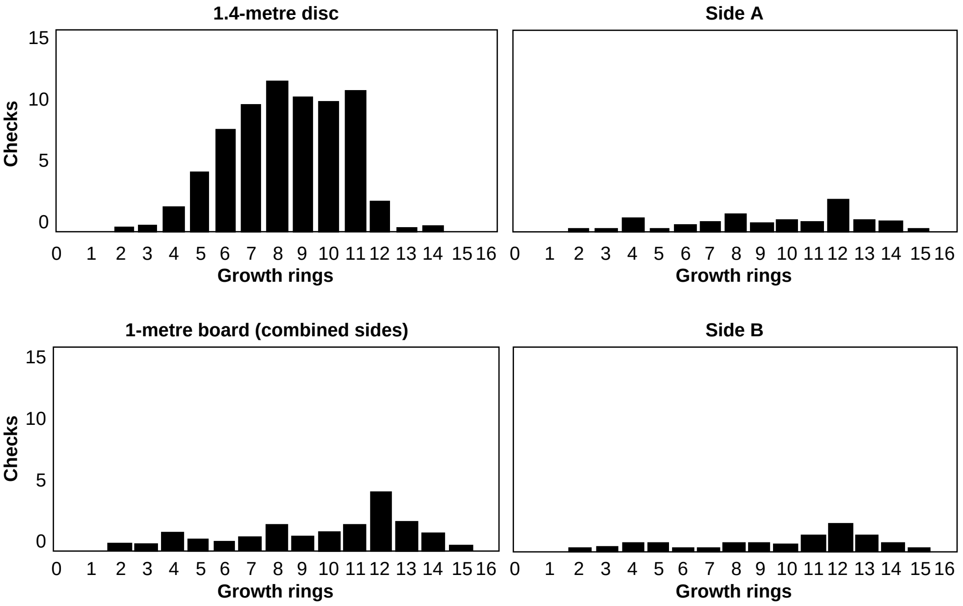

FIG. 6–Mean number of internal checks per ring, for 1.4-m disc and for boards from basal billet
Source: M.J.F.Lausberg (unpubl. data)

significant (F 15, 287 p <0.001). There were on average nearly 4 times the number of checks per ring in the discs that there were in the boards, mainly because the cross-sectional area of the discs was greater than that of the 25-mm-thick boards. There was also appreciable variation in number of checks either side of the pith in the boards.

There was a weak-to-moderate but significant correlation (r = 0.51, p <0.05) between numbers of rings checked in the 1.4-m discs and in the boards. The correlation between total number of checks in the kiln-dried 1.4-m discs and the total number of checks in both sides of the boards combined (r = 0.78, p <0.01) was only moderate, which may indicate that one cross-sectional sample for each board was insufficient. There would also be very different cross-sectional *vs* tangential drying surfaces for checking to be expressed in discs and boards. Also, the kiln-drying of discs was a different treatment to the air-drying of boards.

The correlation between numbers of rings checked on opposite sides of each board was only 0.52 whilst that between total numbers of checks on opposite sides was 0.92. The mean number of checks per ring was very variable, with an average of only 0.6 checks per ring for each side of the board or 1.2 per whole board, indicating that many rings would have no checks.

DISCUSSION AND CONCLUSIONS

This survey of wood density of *E. nitens* was planned to elucidate, if possible, any pattern and/or causes of variation in density and internal checking with site. Site mean whole-tree basic density, estimated from 15 trees/site (each planted with the same seedlot at the same

TABLE 14–Mean number of checks per ring for 1.4-m discs and diametrical boards

Tree	Mean No. of checks/ring for 1.4-m disc	Total No. of checks/ring for board
3	2.1 abc	0.50 a
9	0.3 a	0.63 ab
11	2.3 abc	0.31 a
13	1.3 ab	0.07 a
16	4.3 abc	0.75 ab
17	11.3 bc	3.53 bc
35	2.2 abc	0.60 ab
37	5.4 abc	0.73 ab
42	2.5 abc	0.07 a
49	2.4 abc	0.19 a
57	11.7 c	4.60 c
63	3.2 abc	0.14 a
64	9.1 abc	2.60 abc
68	6.4 abc	1.80 abc
73	1.9 abc	1.33 ab
76	8.6 abc	2.53 abc
77	3.3 abc	1.40 ab
85	3.3 abc	0.00 a
90	1.9 abc	1.33 ab
93	7.6 abc	1.79 abc
93	7.6 abc	1.79 abc
Means	4.56	1.25

Tukey letters significant at $p < 0.05$

spacing), ranged from 428 to 476 kg/m^3. Sites ranged in altitude from 40 to 540 m, and in latitude from 35°52´S to 45°55´S. Mean density was quite similar at four of the sites — Kinleith, Wainui (both central North Island), Millers Flat, and Drumfern (southern South Island) — varying from 445 kg/m^3 to 459 kg/m^3. At Mangakahia (Northland) density was highest (476 kg/m^3), and at Raweka (coastal Bay of Plenty) it was lowest (428 kg/m^3). Raweka had the highest mean annual rainfall of all sites, and Mangakahia the highest mean annual temperature, appreciably higher than Raweka, the next warmest site. Raweka also stood out as having highest foliar levels of nitrogen, phosphorus, and magnesium, and lowest levels of aluminium and copper of the six sites.

Whole-tree density from earlier studies at other sites in New Zealand, at or about the same age, nearly falls within the range for the sites in this study. These include 15-year-old trees at Kaingaroa (altitude 230 m) and Kinleith (altitude ca. 350 m). The highest site mean density was for 11-year-old trees at Golden Downs Forest in Nelson (483 kg/m^3), and the lowest was at Ahaura in Westland (419 kg/m^3), both sites having the same mean annual temperature of 11.5°C, about the same as Kinleith's. Ahaura's mean annual rainfall was 1900 mm, almost double that at Golden Downs, supporting the hypothesis that high rainfall may contribute to low wood density. However, temperature does not seem to have much effect on density, with a mean annual temperature for Mangakahia, the highest density site in this study, of 14.7°C in contrast to that at Golden Downs of 11.5°C.

All whole-tree density studies of *E. nitens*, including this one, show a small decrease in density from the base of the tree to 1.4 m height, sometimes up to 6 m, and thence a steady increase with height. The amount of increase in disc density from 1.4 m up to 15 m height in this study varied with site, from 71 kg/m^3 at Mangakahia to 12 kg/m^3 at Wainui. Lausberg *et al*. (1995), McKenzie, Shelbourne, Kimberley, McKinley, & Britton (in prep.), and Richardson (unpubl. data) all showed increases of up to 77 kg/m^3 from breast height to merchantable top. The extent of the increase appears to increase with age of tree. Mean whole-tree density also increases with age, as shown in a summation of New Zealand data (McKinley *et al.* 2000), though the range is less than that due to site.

The increase of basic density with height found in *E. nitens* has important consequences for utilisation. Log mean values for basic density are lowest for the butt log and increase substantially for the second and third 5-m logs. This trend would favour utilisation of the upper logs for veneers for laminated veneer lumber where stiffness is desirable (McKenzie, Turner, & Shelbourne in prep.; McKenzie, Shelbourne, Kimberley, McKinley, & Britton in prep.). For pulping, whole-tree chip density will always be higher than that of breast height samples.

Internal checking is an artifact of drying wood, rather than a wood property. In this study, a breast-height disc from 15 trees per site was divided into two semi-circular halves, one air-dried and the other slowly kiln-dried. These were cross-cut after drying, and internal checking was measured on internal faces. There were large differences between sites in the total numbers of checks and in the numbers of rings checked. Checking was concentrated mostly in the outer heartwood (“transition wood”). Kiln-drying of discs resulted in fewer rings with checks than air-drying and far fewer checks, especially at the sites with severe checking, but correlations of individual tree values between air- and kiln-dried disc halves were high. Numbers of rings checked and total number of checks were much higher at Kinleith, Raweka, and Mangakahia, the sites with higher mean annual temperatures, than at colder Wainui, Drumfern, and Millers Flat. At the latter sites, green crowns were much longer and health was much better than at the other warmer sites. Incidence of checking was highly variable among trees within sites, which promised well for selective breeding provided some means can be devised for non-destructive assessment of “checkability”.

Average within-site correlations of basic density of individual trees with growth rate, heartwood percentage, and length of green crown were all very low and non-significant, though individual within-site correlations often fluctuated wildly. Average within-site correlations of numbers of rings checked and total number of checks with density, bark thickness, stem diameter, and green crown length were also very low and non-significant, for both air-dried and kiln-dried discs. However, average within-site correlations of diameter and volume with green crown length (which is considered to reflect crown health) were strong. Long green crowns are associated with low checking at the site level but within sites big trees have longer green crowns; however, this appears unrelated to the amount of checking in their dried wood. Wood density and internal checking each generally behaved independently of the other wood and tree properties at each site.

The further analysis of checking data from an earlier study by Lausberg *et al.* (1995) greatly extended the scope of the present study. The disc sampling of 20 trees from Kaingaroa Forest at consecutive heights, as well as by a cross-section of a diametrical board sawn from a basal 1-m billet, showed similar high levels of checking to those at other warmer North Island sites. Discs were kiln-dried and checks on the external surface of the disc were recorded, rather than on the inside of the disc (after cross-cutting) as in the recent study. Checking was highly variable between trees and was found in decreasing amounts up to but not beyond height 11.4 m. Checks were found throughout the heartwood in both air-dried boards and kiln-dried discs, but with some increase in frequency in outer-heartwood rings. There was also considerable variation in checking from one side of the diametrical board to the other. The correlation between number of checks per ring (in one cross-section) of each 1-m board and kiln-dried disc was moderate (r = 0.78). This gives some confidence that the kiln-dried discs were representative of internal checking in sawn timber, fully substantiated later by the sawing study of McKenzie, Shelbourne, Kimberley, McKinley & Britton (in press).

Internal checking is a serious and prevalent drying defect of *E. nitens* sawn timber which is site-dependent in its severity. As an artifact of drying solid wood products, it may prevent some *E. nitens* plantations from providing appearance-grade lumber, especially when grown on warmer sites. The high variability among trees in checking does offer the possibility of selecting against it in breeding programmes, and non-destructive means of evaluation are being developed. Growing *E. nitens* only on sites where it is well-adapted and has long, healthy, green crowns will reduce internal checking.

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REFERENCES

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

BORRALHO, N.M.G.; COTTERILL, P.P.; KANOWSKI, P.L. 1993: Breeding objectives for pulp production of *Eucalyptus globulus* under different industrial cost structures. *Canadian Journal of Forest Research 23*: 648–656.

GEA, L.D.; McCONNOCHIE, R.M.; BORRALHO, N.M.G. 1997: Genetic parameters for growth and wood density traits in *Eucalytus nitens* in New Zealand. *New Zealand Journal of Forestry Science 27(3)*: 237–244.

GREAVES, B.L.; FRENCH, J.; MADDERN, K.N. 1997: Breeding objective for plantation eucalypts grown for production of kraft pulp. *Forest Science 43(4)*: 465–472.

HASLETT, A.N. 1988: Properties and utilisation of exotic speciality timbers grown in New Zealand. Part V: Ash eucalypts and *Eucalyptus nitens*: *E. delegatensis, E. fastigata, E. fraxinoides, E. obliqua, E. regnans, E. sieberi,* and *E. nitens*. *New Zealand Ministry of Forestry, Forest Research Institute, FRI Bulletin No. 119(5).*

HASLETT, A.N.; YOUNG, G.D. 1992: Nitens for sawn timber? *New Zealand Tree Grower 13(2)*: 8–9.

HOOD, I.A.; GARDNER, J.F.; KIMBERLEY, M.O.; MOLONY, K. 2002: Variation among eucalypt species in early susceptibilitty to the leaf spot fungi *Phaeophleospora eucalypti* and *Mycosphaerella* spp. *New Zealand Journal of Forestry Science 32(2)*: 235–255.

KIBBLEWHITE, R.P.; JOHNSON, B.I.; SHELBOURNE, C.J.A. 2000: Kraft pulp qualities of *Eucalyptus nitens*, *E. globulus*, and *E. maidenii*, at ages 8 and 11 years. *New Zealand Journal of Forestry Science 30(3)*: 447–457.

KIBBLEWHITE, R.P.; RIDDELL, M.J.C.; SHELBOURNE, C.J.A. 1998: Kraft fibre and pulp qualities of 29 trees of 15-year-old New Zealand-grown *Eucalyptus nitens*. *Appita Journal 51(2)*: 114–121.

KING, J.N.; BURDON, R.D.; YOUNG, G.D. 1993: Provenance variation in New Zealand-grown *Eucalyptus delegatensis*. 2: Internal checking and other wood properties. *New Zealand Journal of Forestry Science 23(3)*: 314–323.

LAUSBERG, M.J.F.; GILCHRIST, K.F.; SKIPWORTH, J.H. 1995: Wood properties of *Eucalyptus nitens* grown in New Zealand. *New Zealand Journal of Forestry Science 25(2)*: 147–163.

LOW, C.B.; SHELBOURNE, C.J.A. 1999: Performance of *Eucalyptus globulus, E. maidenii, E. nitens*, and other eucalypts in Northland and Hawke's Bay at ages 7 and 11 years. *New Zealand Journal of Forestry Science 29(2)*: 274–288.

McKENZIE, H.M.; TURNER, J.C.P.; SHELBOURNE, C.J.A.: Processing young plantation-grown *Eucalyptus nitens* (Dean et Maiden) for solid-wood products. 1: individual-tree variation in quality and recovery of appearance-grade lumber and veneer (in prep.).

McKENZIE, H.M.; SHELBOURNE, C.J.A.; KIMBERLEY, M.O.; McKINLEY, R.B.; BRITTON, R.A.J.: Processing young plantation-grown *Eucalyptus nitens* (Dean et Maiden) for solid-wood products. 2: Predicting product quality from tree, increment core, disc, and one-metre billet characteristics (in prep.).

McKIMM, R.J.; WAUGH, G.; NORTHWAY, R.L. 1988: Utilisation potential of plantation-grown *Eucalyptus nitens*. *Australian Forestry 51(1)*: 63–71.

McKINLEY, R.B.; SHELBOURNE, C.J.A.; HARRIS, J.M.; YOUNG, G.D. 2000: Variation in whole-tree basic density of a range of plantation species grown in New Zealand. *New Zealand Journal of Forestry Science 30(3)*: 436–446.

McKINLEY, R.B.; SHELBOURNE, C.J.A.; LOW, C.B.; PENELLUM, B.; KIMBERLEY, M.O. 2002: Wood properties of young *Eucalyptus nitens, E. globulus*, and *E. maidenii* in Northland, New Zealand. *New Zealand Journal of Forestry Science 32(3)*:

MILLER, J.T.; CANNON, P.G.; ECROYD, C.E. 1992: Introduced forest trees in New Zealand: Recognition, role and seed source. 11 *Eucalyptus nitens* (Deane et Maiden) Maiden. *New Zealand Ministry of Forestry, FRI Bulletin No. 124(11).*

MILNE, P. 1991: Wood properties of *Eucalyptus nitens* grown in South Island. New Zealand. Dissertation for New Zealand Diploma of Science. AAVA (The Authority for Advanced Vocational Awards).

MITCHELL, N.D. 1991: The derivation of climate surfaces for New Zealand, and their application to the bioclimatic analysis of the distribution of kauri (*Agathis australis*). *New Zealand Journal of the Royal Society 21*: 13–24.

NICHOLAS, I.D.; JANSEN, G.R.; McNEIL, D.L.: Above-ground biomass of the *Eucalyptus nitens* component in a Canterbury 7-year-old mixed species stand (in prep.).

NICHOLAS, I.D.; KIMBERLEY, M.O.; JANSEN, G. 2000: A comparison of biomass productivity for *Eucalyptus nitens*, *E. globulus* ssp. *globulus* and *E. globulus* ssp. *maidenii* on two sites in New Zealand**.** Poster paper: The future of eucalypts for wood products. Page 378 *in* Proceedings of IUFRO Conference, 19 to 24 March, Launceston, Tasmania, Australia.

NICHOLAS, I.D.; JAMIESON, F.; McCONCHIE, M.; HAWKE, A.: Wood density assessment of potential New Zealand bioenergy species **(**in prep.).

NIX, H.A. 1986: A biogeographic analysis of Australian Elapid snakes. Pp. 4–15 *in* Longmore, R. (Ed.) "Atlas of Elapid snakes of Australia". Australian Government Publishing Service, Canberra.

PURNELL, R.C. 1988: Variation in wood properties of *Eucalyptus nitens* in a provenance trial on the eastern Transvaal highveld in South Africa*. South African Forestry Journal 144*: 10–22.

SAS INSTITUTE INC. 1989: "SAS/STAT® User's Guide", Version 6, fourth edition. Cary, North Carolina.

———1990: "SAS® Procedures User's Guide", Version 6, fourth edition. Cary, North Carolina.

SHELBOURNE, C.J.A.; LOW, C.B.; SMALE, P.J. 2000: Eucalypts for Northland: 7- to 11-year results from trials of nine species at four sites. *New Zealand Journal of Forestry Science 30(3)*: 366–383.

SMITH, D.M. 1954: Maximum moisture content method for determining the specific gravity of small wood samples. *United States Department of Agriculture, Forest Service, Forest Products Laboratory Report No. 2014*. 8 p.

SNEDECOR, G.W.1962: "Statistical Methods". The Iowa State University Press, Ames, Iowa, USA.

WARDLAW, T.J.; NEILSEN, W.A. 1999: Decay and other defects associated with pruned branches of *Eucalyptus nitens*. *Tasforests 11*: 49–57.

YANG, J.L.; WAUGH, G. 1996: Potential of plantation-grown eucalypts for structural sawn products. II. *Eucalyptus nitens* (Dean & Maiden) and *E. regnans* F. Muell. *Australian Forestry 59 (2)*: 99–107.

APPENDIX

TABLE A1–MEAN NUTRIENT LEVELS IN FOLIAGE, BY SITES

Site	N (%)	P (%)	K (%)	Mg (%)	C (%)	Ca (%)	Na (%)	Al (ppm)	B (ppm)	Cu (ppm)	Mn (ppm)	Zn (ppm)	Fe (ppm)
Millers Flat	1.58	0.115	0.578	0.121	55.9	0.669	0.02	38	19	3	867	12	26
Drumfern	1.52	0.107	0.544	0.128	56.9	0.623	0.02	29	15	3	448	13	25
Mangakahia	1.50	0.108	0.557	0.127	56.2	0.446	0.06	37	21	3	255	10	27
Wainui	1.53	0.116	0.546	0.126	55.9	0.815	0.01	58	15	5	423	13	29
Raweka	1.76	0.120	0.569	0.147	56.2	0.483	0.01	20	15	1	165	12	28
Kinleith	1.54	0.110	0.605	0.126.	56.0	0.560	0.01	38	16	4	880	12	28

TABLE A2–MEAN DISC/HEIGHT WOOD PROPERTIES, BY SITES (15 TREES PER SITE)

Disc height (m)	Site	No. of trees	Dbh (mm)		Bark thickness (mm)	Heart-wood (%)	Moisture content (%)	Density (kg/m^3)		Rot
			Over bark	Under bark				Green	Basic	
0	Mangakahia	15	271	245	13.2 ab	61 a	140 bc	1111 a	466 a	1.12 a
	Raweka	16	266	244	11.4 ab	60 ab	161 a	1096 a	422 b	0.64 a
	Kinleith	15	249	221	14.0 a	56 abc	144 ab	1101 a	453 ab	0.52 a
	Wainui	15	251	224	13.7 a	52 c	125 c	1051 b	468 a	0.08 a
	Millers Flat	16	231	210	10.7 b	45 d	131 bc	1041 b	454 ab	6.02 b
	Drumfern	15	250	225	12.3 ab	54 bc	134 bc	1042 b	447 ab	0.04 a
	ANOVA F for Sites		1.58	1.69	3.47**	13.9***	8.9***	22.8***	2.9*	17.7***
1.4	Mangakahia	15	232	215	8.4 a	61 a	136 bc	1089 a	462 a	0.32
	Raweka	16	231	217	6.8 ab	60 a	165 a	1072 a	408 b	1.50
	Kinleith	15	208	192	8.0 ab	56 ab	150 ab	1061 a	426 ab	0.12
	Wainui	15	213	198	7.6 ab	51 b	123 c	1004 b	451 a	0.00
	Millers Flat	16	198	185	6.3 b	41 c	136 bc	1016 b	434 ab	2.72
	Drumfern	15	210	196	7.2 ab	54 ab	134 bc	1005 b	431 ab	1.22
	ANOVA F for Sites		1.9	2.0	2.3*	17.6***	12.1***	23.4***	4.6**	2.3*
5.0	Mangakahia	15	194 ab	183 ab	5.5	56 ab	126 bc	1056 a	468 a	0.29
	Raweka	16	207 a	197 a	5.3	59 a	153 a	1057 a	421 b	0.00
	Kinleith	15	176 ab	165 ab	5.3	50 abc	136 ab	1029 a	441 ab	1.37
	Wainui	15	187 ab	175 ab	5.9	48 bc	115 c	972 b	453 ab	0.00
	Millers Flat	16	161 b	151 b	5.0	23 d	124 bc	1034 a	465 a	0.00
	Drumfern	15	171 ab	162 ab	4.4	41 c	119 bc	963 b	442 ab	0.00
	ANOVA F for Sites		3.1**	3.3**	2.1	28.8***	9.4***	18.6***	3.2*	2.1

TABLE A2–cont.

Disc height (m)	Site	No. of trees	Dbh (mm)		Bark thickness (mm)	Heart-wood (%)	Moisture content (%)	Density (kg/m^3)		Rot
			Over bark	Under bark				Green	Basic	
10.0	Mangakahia	15	151 ab	140 ab	5.5 a	42 a	114 bc	1076 a	503 ab	0.00
	Raweka	16	170 a	161 a	4.4 bc	47 a	143 a	1062 ab	439 c	0.04
	Kinleith	14	134 bc	126 bc	4.1 bc	32 b	125 b	1031 b	462 bc	2.90
	Wainui	15	141 ab	132 ab	4.5 ab	19 c	111 bc	969 c	462bc	0.00
	Millers Flat	16	104 c	97 c	3.5 c	6 d	108 c	1062 ab	515 a	0.00
	Drumfern	15	120 bc	113 bc	3.6 bc	19 c	98 c	959 c	486 ab	0.00
	ANOVA F for Sites		7.8***	7.7***	9.3***	45.2***	14.4***	30.2***	8.4***	1.9
15.0	Mangakahia	13	110 ab	101 ab	4.9 a	12 abc	109 bcd	1108 a	533 a	0.00
	Raweka	16	126 a	118 a	3.9 ab	18 ab	132 a	1074 ab	466 b	0.00
	Kinleith	9	114 ab	106 ab	4.1 ab	21 a	121 ab	1050 b	477 b	0.19
	Wainui	14	92 ab	86 ab	3.4 b	2 c	114 abc	985 c	463 b	0.00
	Millers Flat	3	82	75	3.3	3 c	92	1067	557	0.00
	Drumfern	8	90 ab	84 ab	3.2 b	4 bc	88 d	948 c	506 ab	0.00
	ANOVA F for Sites		3.6**	3.7**	6.8***	4.7**	9.6***	28.2***	8.4***	0.3
20.0	Mangakahia	3	92	83	4.5	5	110	1120 a	534	0.00
	Raweka	10	98	91	3.7	0	122	1069 ab	484	0.00
	Kinleith	4	91	84	3.9	4	122	1061 b	480	0.00
	Wainui	1	80	73	3.5	2	85	988 c	534	0.00
	ANOVA F for Sites		0.5	0.6	1.1	0.8	1.2	11.6***	1.9	0

* significant at $p \leq 0.05$
** significant at $p \leq 0.01$
*** significant at $p \leq 0.001$

TABLE A3–MEAN WOOD PROPERTIES, LOG BY LOG, FOR EACH SITE

Log	Site	No. of trees	Volume (m^3)	Bark thickness (mm)	Heart-wood (%)	Moisture content (%)	Density (kg/m^3)		Rot
							Green	Basic	
Butt	Mangakahia	15	0.190	9.8	60 a	135 bc	1091 a	465 a	0.62 a
	Raweka	16	0.199	8.3	60 a	160 a	1078 a	417 b	0.75 a
	Kinleith	15	0.157	9.9	55 ab	144 ab	1071 a	441 ab	0.53 a
	Wainui	15	0.166	9.7	50 b	122 c	1016 b	459 a	0.03 a
	Millers Flat	16	0.134	7.9	39 c	132 bc	1031 b	448 ab	3.70 b
	Drumfern	15	0.156	8.9	51 b	131 bc	1012 b	441 ab	0.42 a
	ANOVA F for Sites		2.2	2.8*	28.2***	9.5***	23.6***	3.2*	9.9***
Second	Mangakahia	15	0.110 ab	5.5 a	51 ab	122 bc	1063 a	480 a	0.18 ab
	Raweka	16	0.135 a	4.9 ab	54 a	149 a	1059 a	428 b	0.02 a
	Kinleith	14	0.093 ab	4.9 ab	46 b	133 ab	1035 a	447 ab	1.41 b
	Wainui	15	0.099 ab	5.4 a	38 c	114 c	971 b	456 ab	0.00 a
	Millers Flat	16	0.064 b	4.6 ab	19 d	119 bc	1042 a	480 a	0.00 a
	Drumfern	15	0.080 b	4.1 b	34 c	112 c	962 b	456 ab	0.00 a
	ANOVA F for Sites		4.7***	3.3*	52.3***	10.5***	27.1***	4.2**	2.6*
Third	Mangakahia	13	0.064	5.4 a	33 a	112 bc	1085 a	514 ab	0.00
	Raweka	16	0.084	4.2 ab	37 a	139 a	1066 a	448 c	0.03
	Kinleith	9	0.068	4.3 ab	37 a	127 ab	1034 a	457 c	3.20
	Wainui	14	0.050	4.3 ab	15 b	111 bc	972 b	462 bc	0.00
	Millers Flat	3	0.040	4.1	17	101	1056	530	0.00
	Drumfern	8	0.043	4.0 b	18 b	97 c	948 b	482 abc	0.00
	ANOVA F for Sites		2.3	3.7**	19.2***	12.8***	29.2***	6.9***	1.3

TABLE A3–cont.

Log	Site	No. of trees	Volume (m^3)	Bark thickness (mm)	Heart-wood (%)	Moisture content (%)	Density (kg/m^3)		Rot
							Green	Basic	
Fourth	Mangakahia	3	0.042	5.5	20	113	1102	517	0.00
	Raweka	10	0.054	4.1	19	133	1071	464	0.00
	Kinleith	4	0.048	4.6	25	123	1052	472	0.28
	Wainui	1	0.023	3.9	4	85	967	522	0.00
	ANOVA F for Sites		0.7	2.1	3.7*	1.8	8.4**	1.6	0.9
Tree	Mangakahia	15	0.363 ab	7.8 a	53 a	128 bc	1082 a	476 a	0.36 a
	Raweka	16	0.454 a	6.3 b	52 a	152 a	1069 a	428 b	0.38 a
	Kinleith	15	0.297 ab	7.6 ab	50 ab	139 ab	1055 ab	445 ab	1.10 a
	Wainui	15	0.312 ab	7.6 ab	41 c	118 c	996 c	458 ab	0.02 a
	Millers Flat	16	0.205 b	6.8 ab	32 d	128 bc	1034 b	459 ab	2.59 b
	Drumfern	15	0.258 b	7.1 ab	44 bc	123 bc	992 c	448 ab	0.25 a
	ANOVA F for Sites		5.0***	3.1*	30.8***	8.4***	27.9***	3.0*	7.7***

* significant at $p \leq 0.05$

** significant at $p \leq 0.01$

*** significant at $p \leq 0.001$