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Key words : *Eucalyptus nitens*, whole-tree basic density, internal checking, site, temperature, rainfall, nutrition, within-tree, between-tree variation

SUMMARY

Whole-tree basic density and internal checking was assessed at 6 New Zealand sites, 4 in the North Island and 2 in the South Island, by sampling 15 trees / site, each planted with the same *Eucalyptus nitens* seedlot of Victorian provenance at the same stocking of 1111 stems/ha. Sites ranged in altitude from 40 - 540 m and in latitude from 35°52´S (Dargaville) to 45°55´S near Invercargill. 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 results and those from previous studies, there was some indication that very high rainfall and high levels of foliar nitrogen, phosphorus and magnesium were responsible for extreme 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 valuable butt log than in upper logs.

Internal checking, assessed only in a breast-height disc from each tree, was prevalent at all sites and was concentrated more in outer heartwood in both slowly kiln-dried and air-dried samples. More checks were found in air-dried discs than in kiln-dried. Much larger numbers of checks were found at North Island sites, Mangakahia, Raweka and Kinleith than at the high altitude central plateau site, Wainui, or the two South Island sites. Higher number of checked rings and total numbers of checks were associated with sites with higher mean annual temperatures, short green crowns and poor crown health. Much fewer checks were found at sites with low mean annual, mean maximum and minimum temperatures, where trees had longer green crowns and much better crown health.

Checking data had been collected in an earlier study for 20 15-year-old trees from Kaingaroa Forest (altitude 230 m) from 4 kiln-dried discs per tree, heights 0, 1.4, 6.4 and 11.4 m and from an air-dried diametral board, sawn from a one-metre billet from the base of each tree. These showed that numbers of checks varied enormously among trees and decreased to zero above height 11.4 m. Numbers of checks in the board cross-section correlated moderately well with those in the breast height disc. It was concluded that checking is so severe in *E. nitens* to prevent its utilisation for appearance-grade lumber, particularly in logs from warmer sites with poor crown health.

INTRODUCTION

Eucalyptus nitens (Deane et Maiden) 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 attacked by fungal leaf diseases, and this results in poor health, reduced growth and even eventual death (Low and Shelbourne, 1999; Shelbourne *et al.*, 2000: *Hood et al.*, in prep.).

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 ; Kibblewhite *et al.* 2000), but, as will become apparent from this study, 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 quality characteristic for which *E. nitens* pulps are often deficient (Kibblewhite *et al.*, 1998; Kibblewhite *et al.*, 2000). Wood density also 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 filling this gap in knowledge is an important objective of this study.

Eucalyptus nitens has been planted widely for pulp in Tasmania, in South Africa and in Chile as well as in New Zealand, but there is a increasing interest overseas in growing some of these stands for solid wood products, including appearance grade lumber. However internal checking of *E. nitens* has been found to be widespread on some sites in New Zealand (Haslett, 1988, 1992 ; Lausberg *et al.*, 1995 ; McKenzie *et al.*, in press). Internal checking shows major species differences, for instance closely-related *E. maidenii* has no checking at all on the same Northland site (McKinley *et al.*, in press). Increasing the knowledge of its incidence in *E. nitens* on different sites was the other main objective of this study.

PREVIOUS STUDIES

Basic density

Whole-tree basic density increases rapidly with age up to about age 15 years, thereafter, increases more slowly. McKinley *et al.*, (2000) summarised the limited whole tree data available in the ***Forest Research*** database, across sites, and showed an average increase in whole-tree basic density with age from 453 kg/m^3 (age 9), 477 (age 15), 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 4 South Island trials of Victorian provenances. These were located at Berryman's Nursery, Golden Downs Forest (Nelson), Callaghan's Ridge (near Ahaura, Westland) and Longwoods

Forest (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 (age 11-12) and 565 kg/m^3 (age 30).

Table 1–Whole-tree basic density at South Island sites (Milne, 1991)

Site	Age	Latitude	Altitude	Mean annual rainfall	Mean annual temp.	Provenance	No. trees	Whole tree basic density
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

Jamieson (1997) and Nicholas, Jamieson, McConchie and Hawke (in prep.) sampled 15 trees per seedlot by breast height (BH) 5 mm increment cores in species trials at 4 sites in the North Island, Kaikohe, Rotorua, clive and Palmerston North and at Christchurch in the South Island. One to 3 seedlots were sampled at each site, including, in some cases, southern New South Wales and central Victorian provenances. Differences between *E. nitens* seedlots were small and provenance means at each site were quite uniform from 399-419 kg/m^3, with the exception of the Christchurch (South Island) site with 441 kg/m^3 (Table 2). This study showed a BH core density of 441 kg/m^3 at Lincoln, near Christchurch. However a subsequent sampling of 24 trees by BH discs at age 7 years of the same stand gave a mean density of 414 kg/m^3 (Nicholas, Jansen and McNeil, in prep.). Predicted whole-tree densities of this material range from 422 kg/m^3 at Kaikohe to 464 kg/m^3 at Christchurch.

Table 2–Breast-height increment-core basic density of *E. nitens* at 6 sites (Nicholas *et al.* (in prep.) ; Nicholas, Jansen and McNeil (in prep.)

Site	Provenance	Age	No. of trees	Core density (kg/m^3)	Predicted whole-tree density**
Kaikohe	NSW	5	15	417	440
	Victoria	5	15	399	422
Rotorua	Victoria	6	53	400	423
Clive	NSW	9	15	419	442
	Victoria	9	15	409	432
Palmerston North	Victoria	6	43	408	431
Christchurch	Victoria	6	42	441	464
	Victoria	7	24	414	437

** Predicted from y=1.0x + 22.7 (estimated from results of present study)

Jansen (1998) (in Low and Shelbourne 2000) carried out biomass studies on 10-year-old trees of *E. nitens*, *E. globulus* and *E. maidenii* at Clive, near Napier (latitude. 39°36′, altitude 5m) and at Kaikohe (latitude 35°25′, altitude 250m), age 6 years, on 5 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 Cpt. 1217, 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).

Richardson (unpubl. data) and Ford-Robertson, Young and Nicholas (unpubl.data) reported mean whole-tree basic density (Table 3) for:

- 19 trees of 8-year-old *E. nitens* (Mt. Toorongo, Vic.) from Cpt. 1090, Kaingaroa Forest - 468 kg/m^3
- 26 trees, aged 15 years (Rubicon, Toorongo and Macalister, Vic. mixed seedlot) from Tram Road, Kinleith Forest - 474kg/m^3
- 9 trees, aged 15 (Nimmatabel, NSW) from Maire Road, Kinleith Forest - 461 kg/m^3
- 8 trees, aged 15 years of *E. regnans* from Maire Road species trial - 426 kg/m^3
- 8 trees, aged 15 years of *E. fastigata* from Maire Road species trial - 479 kg/m^3

Internal checking

The information about internal checking in young plantation stands of *E. nitens* is more 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 4 logs, 3 m long, from the butt of each tree, alternately into structural and appearance grades and dried the products using 4 different drying schedules. Internal and face checking was 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 which 323 8-year-old trees from a provenance trial *of E. delegatensis* in NZ Southland were sampled by breast height discs. They recorded numbers of checks in each ring, with subjective rating of severity of each check. They found a two-fold greater number of checks in mainland provenances than in Tasmanian provenances. Their methods formed the basis of subsequent studies of checking in *E. nitens* in NZ.

Yang and Waugh (1996) reported high levels of internal checking of timber from 15-, 25- and 29-year-old *E. nitens* following air and kiln drying. Haslett and 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 provenance trial 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 resulting discs, and log end splitting was assessed as "triangular" and "elliptical" splits on all log ends. Collapse was high in discs from the base of the trees and reduced with height to 12 m. There was large variation between trees 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 12m.

Ford-Robertson, Young and Nicholas (unpubl.data) and Richardson (unpubl.data) reported the subjective scoring of internal checking on discs from trees of 8- and 15-year-old *E. nitens,* and 15-year-old E. *regnans* and *E. fastigata* (Table 3). Discs were taken at the base and at 6 m intervals up the stem, and oven dried at 103°C. Checking was assessed on a scale of 0, no checks, 1 and 2, very minor checking, to 3, 4 and 5 indicating increasing severity of and numbers of checks. It was evident that checking score decreased up the stem, to zero levels in the 24 m height disc. With species mean checking scores at the base of from 3.67 to 2.50, and at 6 m from 2.25 to 1.38 in the 15-year-old trees, there appeared to be no major differences between *E. nitens*, *E. regnans* and *E. fastigata* in checking scores.

Table 3–Provenance/species mean density and checking scores at increasing heights (Richardson, unpubl.data ; Ford-Robertson, Young and Nicholas, unpubl.data)

Species	Provenance	Site	Age years	No. of trees	Height m	Check -ing score	Log no.	Whole tree basic density
E nitens	Nimmatabel NSW	Maire Road, Kinleith	15	8	0	3.67	1	466
					6	1.38	2	444
					12	0.89	3	467
					18	0.38	4	492
					24	0	**Tree**	**461**
E. nitens	Rubicon, Toorongo, Mcalister	Tram Road, Kinleith	15	26	0	3.58	1	456
					6	2.19	2	480
					12	0.88	3	509
					18	0.12	4	533
					24	0	**Tree**	**474**
E. nitens	Toorongo Plateau	Cpt. 1090. Kaingaroa	8	21	0	3.60	1	469
					6	0.14	2	465
					12	0	**Tree**	**468**
E. regnans	Kinleith	Maire Road Kinleith	15	8	0	2.50	1	423
					6	1.63	2	422
					12	1.50	3	429
					18	0.63	4	442
					24	0.17	5	440
							Tree	**426**
E.fastigata	Oberon NSW	Maire Road Kinleith	15	8	0	3.38	1	476
					6	2.25	2	479
					12	1.25	3	474
					18	1.28	4	490
							Tree	**479**

Lausberg *et al.*, (1995) reported on wood properties of the same 20 trees of *E. nitens* from a 15-year-old provenance-progeny trial at Cpt 1217 Kaingaroa Forest (latitude. 38°26′ altitude 230 m) that were individually pulped by Kibblewhite *et al.*, (1996). (Their density and chip density were given above). Internal checking was recorded as number of checks per ring from discs, taken at 0, 1.4, 6.4, 11.4, 16.4 and 21.4 m up the stem. A basal one-metre billet was also removed from each tree and a diametral board sawn from each billet. Discs were cut in half, diametrally, and slowly kiln dried at 40ºC and 60% RH for 10 days. All internal checks were recorded by ring, and whether checks crossed latewood bands. The 25 mm diametral boards from the one-metre basal billet were end-sealed and air-dried for 3 months to 30% and forced-air dried to below 20% mc, before being placed in a 12% mc equilibrium room for 2 weeks. They were then crosscut to give an internal checking sample, and one cut end scanned for collapse.

They reported that internal checking in the kiln dried discs was confined mainly (89%) to the outer heartwood, 9.5% in the inner heartwood and very little in the sapwood. There was large variation between trees in number of checks observed. Checking tended to follow heartwood boundary shape, rather than rings. When discs were cut in half perpendicular to the longitudinal direction, numbers of checks visible increased 5-fold in the fresh-cut face.

By contrast, in the air-dried boards from the basal one-metre billet, 51% of the checks occurred in the sapwood and 49% in the heartwood, with rather more occurring in the outer heartwood rings. The comprehensive checking data was not analysed further and will be examined later in this paper.

McKenzie *et al.*, (in prep.) 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 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% mc and later kiln dried and steam reconditioned. A one-metre billet was removed from height 6–7 m and a diametral board removed, before quarter-sawing into 25 mm boards. A variety of wood, sawn-timber and veneer end-product characteristics were studied on an individual tree basis and, in particular, checking and collapse were measured in butt-log boards, in 6 m height discs (both oven-dried and demumidifier-dried), and in one-metre boards from height 5-6 m.

Internal checking was recorded as number of checks per mm of ring circumference in the discs (a method that allows comparisons with other data from different sized trees) and in the one metre boards, as number of checks per mm of ring radius. Number of checks were recorded at top and bottom ends of the butt-log boards. Checking was prevalent in all but 2 trees of 15 in the butt log boards and was much worse at the bottom than at the top ends. All but 2 trees showed substantial collapse. All trees showed a lot of face checking, even after steam reconditioning. In the one-metre boards, amount of checking varied a lot between trees and there was less checking in the air-dried than in the dehumidifier-dried boards.

There were more checks in oven-dried discs than in dehumidifier-dried. Number of checks varied enormously between trees. There were high correlations between amounts of checking in dehumidifier-dried discs with air-dried one-metre boards and 5 m (butt-log) boards, all over 0.90, but poor correlation with checking in oven-dried discs. Correlations of amounts of checking in air-dried butt log boards with dehumidifier-dried and air-dried one metre boards were also all over 0.90. Collapse in butt log boards also correlated well with checking in one and 5-metre boards and dehumidifier–dried discs.

In the New Zealand checking studies reviewed above, trees were derived from Northland, central North Island medium-altitude sites and from a 230 m altitude site at Golden Downs, Nelson. At all of these sites *E. nitens* has shown large amounts of internal checking. Comparing results on these sites with some colder, higher altitude and more southern sites will be undertaken in this study.

MATERIALS AND METHODS

Field trials and their sampling

Between 1990 and 1992 a series of silvicultural regime trials of *Eucalyptus nitens* were established at six sites throughout New Zealand. 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 (Table 4). Regime 3, similar to that being followed for commercial pulp production, was established at 1111 stems/ha and has remained unthinned. At all sites except Kinleith, there were three replications of this treatment with 25-tree plots, from the outer surround of which trees were sampled for assessing basic wood density and checking. 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 4–Site and trial details

Location	Altitude (m)	Latitude (°)	Longitude (°)	Topex*	Planted (year)
Mangakahia, Northland	40	35°52′	173°52′	37.7	1990
Raweka, Bay of Plenty	250	38°09′	176°55′	73.7	1990
Kinleith, Bay of Plenty	350	38°21′	175°51′	62.0	1990
Wainui, Taupo	540	38°54′	176°11′	36.0	1990
Millers Flat, Otago	440	45°41′	169°29′	51.5	1992
Drumfern, Southland	140	45°55′	168°15′	32.7	1991

* Topex=sum of all the angles of elevation to the skyline at the eight cardinal points of the compass

The sites are very discontinuous in their latitudinal distribution, with 4 sites clustered in the central North Island and none in Nelson, Canterbury or Westland. Elevations are quite variable 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 temperatures varied widely (Table 5), from 14.7°C at Mangakahia, around 12°C at Raweka and Kinleith, 10.8°C at the high altitude site at Wainui, to 8.6°C at the high altitude site at Millers Flat. Mean annual rainfall was highest at Raweka with 2060 mm, between 1400 and 1650 mm at other North Island sites and was only 740 mm at Millers Flat and 900 mm at Drumfern. Mean daily maximum and minimum temperatures followed a similar trend to mean annual temperature. Drumfern was notable in having a much higher wind speed than any other site.

With only 6 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 parameters may allow proposing some hypotheses about these relationships that could be tested further in future, by extending the sites sampled.

Table 5–Climatic data

	Elevation	Wind	Solar	Mean daily minimum temp.	Mean daily maximum temp.	Humidity	Mean annual temp.	Evap-oration	Mean annual rainfall
Mangakahia	40	7.49	14.88	10.17	19.20	82.27	14.68	2.42	1370
Raweka	250	6.85	15.04	7.04	18.11	82.96	12.58	3.63	2060
Kinleith (Karaka)	400	8.18	14.62	7.10	16.76	83.92	11.89	3.18	1650
Kinleith (Smythe)	300	7.98	14.64	7.18	17.49	83.65	12.32	2.83	1490
Wainui	540	8.37	14.61	5.63	15.82	80.00	10.75	2.93	1480
Millers Flat	440	6.88	12.75	3.67	13.68	78.16	8.61	1.79	740
Drumfern	140	11.62	12.78	4.68	15.03	78.21	9.84	2.29	900

Millers Flat and Drumfern were planted 2 years and one year later respectively than the North Island trials (Table 6) and this will have to kept in mind in evaluating the density and checking data. Survival was only 77 and 71% at Mangakahia and Raweka when these trials were assessed at age 8 or 9 years, and was 88% at Kinleith and over 93% at Wainui and the two South Island sites. Annual height growth is substantially less at the high altitude Wainui site and the two South Island sites (about 2.1 m) than at the other North Island sites (2.4-2.8 m). Mean DBH and mean annual increment however do not show these trends, and equally high values were found at Drumfern as at Mangakahia.

Table 6–Tree crop characteristics

		Mangakahia	Raweka	Kinleith	Wainui	Millers Flat	Drumfern
Established	yr	1990	1990	1990	1990	1992	1991
Age measured	yr	9	9	9	9	8	8
Stems/ha	#/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
BA	m^2/ha	30.2	21.8	23.2	24.1	24.5	30.1
Vol/ha	m^3/ha	223.3	170.7	170.1	159.0	147.2	185.1
Mean annual increment	m^3/ha/year	24.8	19.0	18.9	17.7	18.4	23.1

* MTD = Mean Top Diameter and MTH, Mean Top Height – the diameter and height of the 100 largest diameter trees/ha.

At each location 30 healthy trees were randomly selected from three replicated plots (where available) from across the diameter range of the crop trees in the plot surround (to avoid removing trees from the measurement plots). For each tree, diameter at breast height over bark (DBHOB) was recorded and two pith-to-bark 5 mm increment cores were extracted for determining basic density. This was done using the maximum moisture content method (Smith 1954).

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. 5 trees were distributed in each of 3 plots at each site (at Kinleith there were two replications, located on different sites, from which trees were drawn). After tree felling, diameter over and inside bark, was measured at 0.3 m, 0.7 m, 1.4 m, 5 m, 10 m and 15 m. Total tree height for each tree was also recorded. Foliage samples were collected to check species identification and for health assessment.

Cross-sectional discs were cut at butt, and at consecutive 5 m intervals, down to a small-end diameter (SED) of 80 mm, for whole-disc analysis of heartwood %, bark thickness, moisture content and green and basic density. Log volume and log mean estimates of these properties for successive log heights were derived from the disc measurements for each tree, as well as volume-weighted whole-tree estimates.

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 wrapped in plastic bags and kept in refrigerated storage until all trial locations had been sampled. Discs were then cut diametrally, so that both halves were 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 six months.

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

Statistical analysis

The data were treated as a randomised complete block design. The equation for the model of a randomised complete block layout is as follows:

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

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 j[th] site

$P_j : S_i$ = the effect of the j[th] plot within the i[th] site

E_{ij} = the random error associated with the j[th] plot in the i[th] site

Analysis of variance was carried out using PROC GLM of the SAS™ software package (SAS Institute 1989) according to the model for a randomised complete block design, with plots nested within sites. Tukey's multiple range test was used to obtain the significance of the differences between site means. PROC CORR (SAS Institute 1990) was used to obtain correlations between the traits that are estimated in this study.

RESULTS AND DISCUSSION

Initial density screening

The results of the survey of density at each site of 30 randomly selected trees per site by pith-to-bark cores showed a range from 407 kg/m^3 at Raweka to 444 kg/m^3 at Wainui. Raweka had the largest mean DBH of 241 mm and Millers Flat, the smallest, of 187 mm, caused partly by its being 2 years younger than the North Island sites. (Table 7).

Table 7–Increment core data

Site	Number of trees sampled	Age	Mean DBH	Increment core basic density	Within-site standard deviation
		years	mm	kg/m³	kg/m^3
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

The within-site standard deviations of 24-31 kg/m^3 show that there was much more variation within sites than between sites. Individual-tree values were based on two pith-to-bark cores per tree. Inspection of the density of these paired cores, indicated that 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. It seems likely that such circumferential variation may be caused by tension wood development (Appendix).

Tree height and crown length

A sample of 15 or 16 trees at each site was selected from the increment core density data on 30 trees to cover the range of density and to be of the same mean. Their height, height of green crown and merchantable height were measured and the length of green crown derived (Table 8). Trees were notably taller at Raweka and considerably shorter at the two South Island sites, a result of being 1 or 2 years younger and of slower height growth.

Table 8–Site means for height and crown data

Site	Number of trees	Height	Green crown height	Merch-antable height	Green crown length
Mangakahia	15	21.3b	17.3de	14.9ab	4.1c
Raweka	16	24.7	19.6e	17.0a	5.1c
Kinleith	15	20.5bc	16.9de	13.3bc	3.6c
Wainui	15	21.7b	14.4c	13.4bc	7.3b
Miller Flat	16	17.6d	6.7a	10.1d	10.8a
Drumfern	15	18.8cd	11.0b	11.4cd	7.8b

Green crown length was much shorter at the lower-altitude central North Island and Northland sites than at the high altitude site at Wainui and the two South Island sites. The highest value by far was at Millers Flat, a 440 m altitude site in central Otago with by far the lowest mean daily minimum and mean annual temperature of all sites (Table 5). Unfortunately no health scoring was undertaken, but anecdotally, crown health was described as very poor at Mangakahia and Raweka, with prospects that growth would decline in the near future, and a little better at Kinleith. Crown health was excellent at Wainui, the high altitude central plateau site, and equally good at Millers Flat and Drumfern. Crown health is mainly affected by leaf fungi *Mycosphaerella* spp. and Septoria (now called *Phaeophloeospora eucalypti* (Hood *et al.*, in press).

Wood properties

Wood properties, bark thickness, heartwood %, moisture content %, green density and basic wood density varied significantly between the sites sampled in this study (Table 9), as shown by the F ratios for Sites. Only in the case of heartwood was the plot-within-site effect significant. Heart rot was present in only very small amounts, generally in basal and breast height (1.4m) discs, and then only seriously at Millers Flat, and it showed a strong plot-in-site variance indicating localised occurrence in the stand.

Table 9–Volume-weighted whole-tree wood properties

Site	No. of trees	Volume m^3	Bark thick-ness	Heart-wood %	Moisture content %	Green density kg/m^3	Basic density kg/m^3	Rot
Mangakahia	15	0.363ab	7.8a	53a	128bc	1082a	476a	0.36a
Raweka	16	0.454a	6.3b	52a	152a	1069a	428b	0.38a
Kinleith	15	0.297ab	7.6ab	50ab	139ab	1055ab	445ab	1.10a
Wainui	15	0.312ab	7.6ab	41c	118c	996c	458ab	0.02a
Millers Flat	16	0.205b	6.8ab	32d	128bc	1034b	459ab	2.59b
Drumfern	15	0.258b	7.1ab	44bc	123bc	992c	448ab	0.25a
ANOVA F For Sites		5.0***	3.1*	30.8***	8.4***	27.9***	3.0*	7.7***

Whole-tree basic density is the principal wood property of interest in this study and it varied from a mean of 476 kg/m^3 at Mangakahia to 428 kg/m^3 at Raweka. Mean wood density at the other 4 sites from Kinleith in the central plateau to Drumfern in Southland varied only little, from 445 to 459 kg/m^3. There is no evident effect of temperature on these results. Raweka and Mangakahia have the highest mean annual temperatures of the 6 sites, both lying within warm areas of the Bay of Plenty and Northland. However, Raweka has by far the highest rainfall of 2060 mm. The two South Island sites share lowest mean annual and mean daily minimum temperatures but have similar densities as much warmer and wetter parts of the country.

Green crown length was very much greater at Wainui, the high altitude central plateau site, and the two South Island sites than at Mangakahia, Raweka and Kinleith (Table 8).

Nutrient levels in the foliage were analysed by bulking individual-tree samples for each site (Appendix Table 1). Raweka (with its lowest basic density) stands out as having the highest levels of foliar nitrogen, phosphorus and magnesium of all sites. Levels of aluminium, copper and manganese were also by far the lowest of all sites. Beets *et al.*, (2001) concluded that foliar nitrogen status was the main variable associated with wood density in radiata pine, high levels being associated with low density. They also indicate that higher rainfall also induces lower density. However, foliar levels of nitrogen at Mangakahia (highest density site) were about average for the 6 sites.

Whole-tree basic densities from Milne's (1991) study show a similar range of density in the three 11-12 year-old stands he sampled in the South Island. These ranged from 483 kg/m^3 at Golden Downs Forest in Nelson province to 419 kg/m^3 in Westland (rainfall at the Westland site of 1900 mm was almost double that at Golden Downs). 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 (Richardson unpubl.data) averaged 474 kg/m^3. All were of Victorian provenances. Another 9 trees of NSW provenance averaged 461 kg/m^3.

The unpublished data of Nicholas, Jamieson, McConchie and Hawke on breast height increment core density was mainly from younger trees of 5 and 6 years, and in these cases can be expected to be lower than for 10 year-old stands. Values for 5-7 year-old trees varied from 399-417 kg/m^3 (excluding anomalous results from Lincoln) and for 9 year-old trees at Clive were 409-419 kg/m^3. These compare with the core data in this study which ranged from 407 at Raweka to 444 kg/m^3 at Wainui. Predicted whole-tree density (Table 2) was within the range of site means estimated in the present study.

The other wood properties of bark thickness, heartwood and stem rot that are not directly related to density, show significant differences between sites (Table 9), minor for bark thickness but substantial for heartwood development. Bark was thinner at Raweka than the other sites, perhaps in relation to the same factors that caused its very low density. Heartwood % was lowest at Millers Flat and was also low at the other "cold" sites, Wainui and Drumfern, ages respectively 8, 9 and 10 years. Stem rot, confined mainly to the basal and breast height discs, was much worse at Millers Flat than at other sites.

Moisture content was significantly lower at Wainui than other sites and higher at Raweka.

There were clear and strong patterns of change in all wood properties from the base of the tree to the top. These are shown graphically in Figs. 1-4 and in Tables 10 and 11. Differences between sites at each disc sampling height were highly significant for all wood properties at all but the topmost sample height, as shown by ANOVA F ratios.

Bark thickness (Fig.1), at the base varied from 11 mm at Millers Flat to 14 mm at Kinleith, quickly reduced to between 6 and 8 mm at 1.4 m height, gradually decreasing to between 3-5 mm at the 20 m height level.

Heartwood % (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, depending on the height of the tree, and thus on the site (Table 8).

Moisture content (Fig. 3) at each site decreases with height, slowly at first and then more rapidly, parallel with the increase in basic density. Green density 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/m3 (at Kinleith) and then increased strongly to the top sampling point. An exception to this trend was at Wainui, where the increase was only 12 kg/m^3.

Figure 1 - Bark thickness

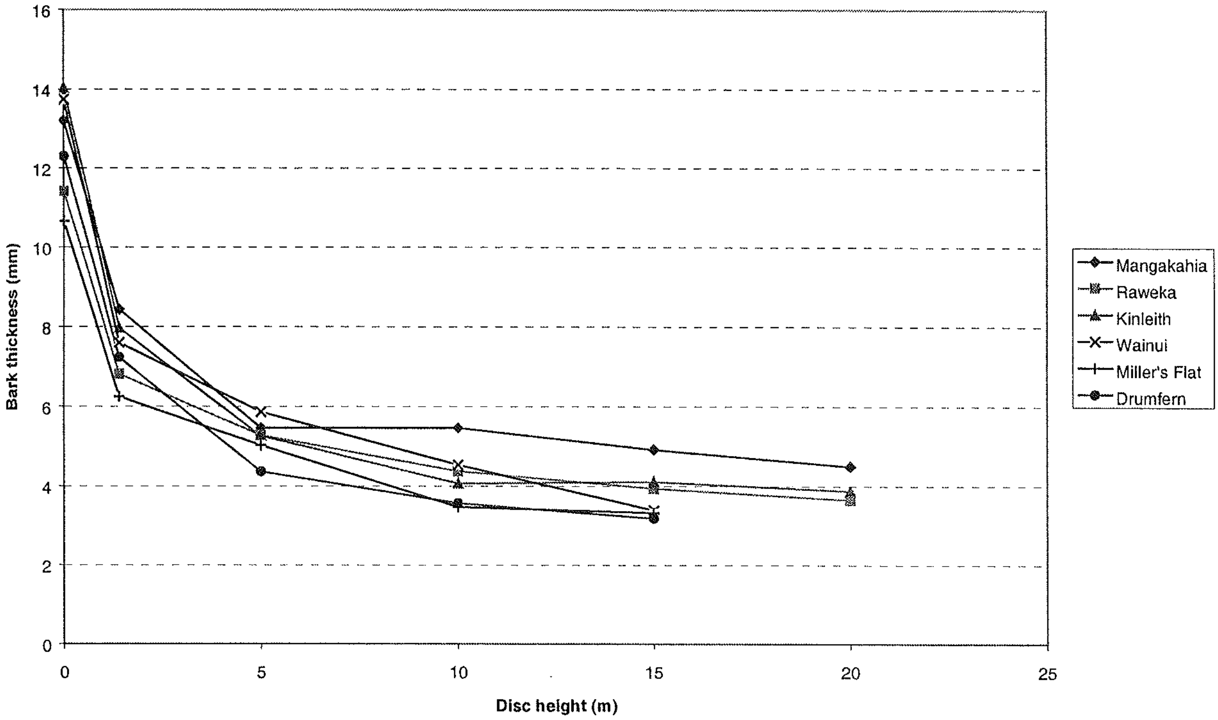


Figure 2 - Heartwood

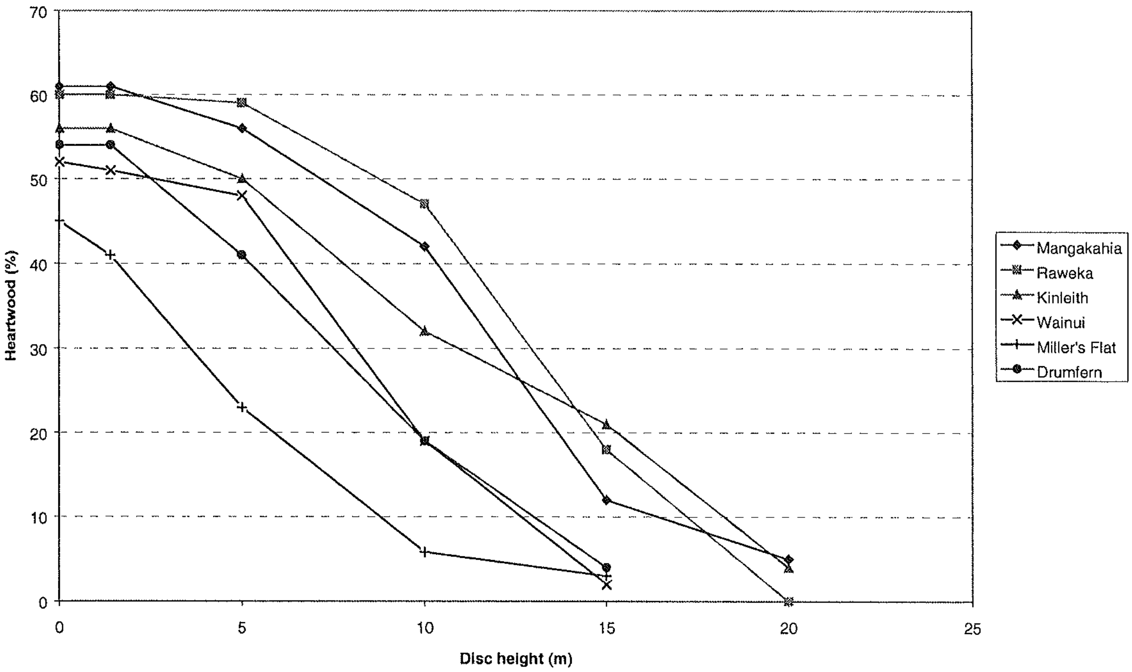


Figure 3 - Moisture content

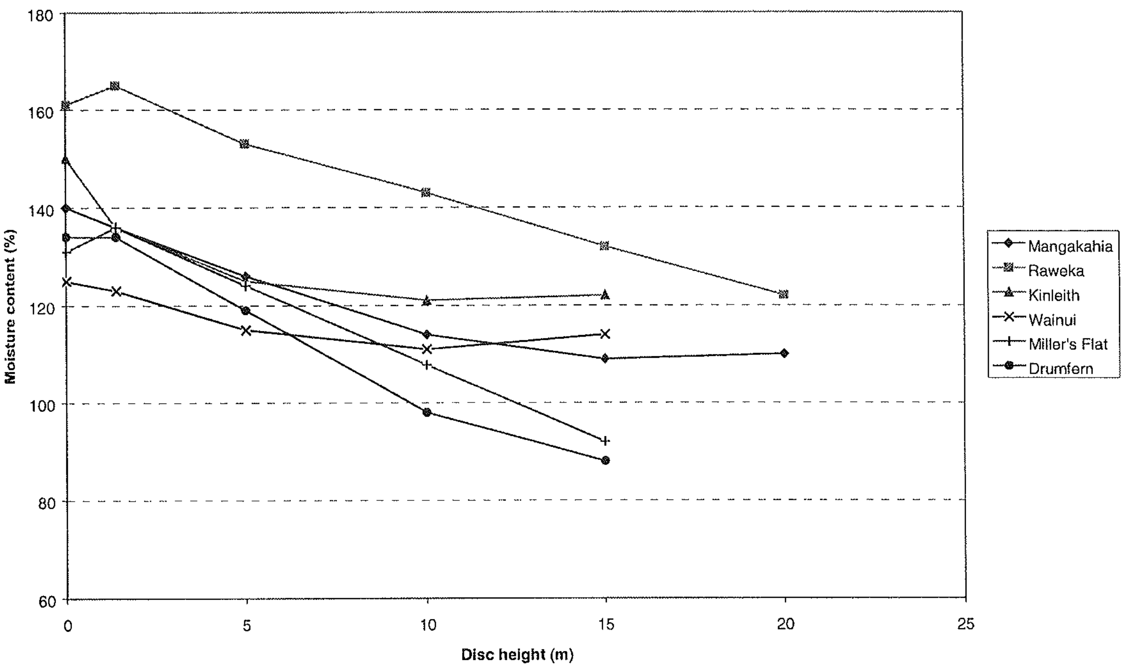


Figure 4 - Basic density

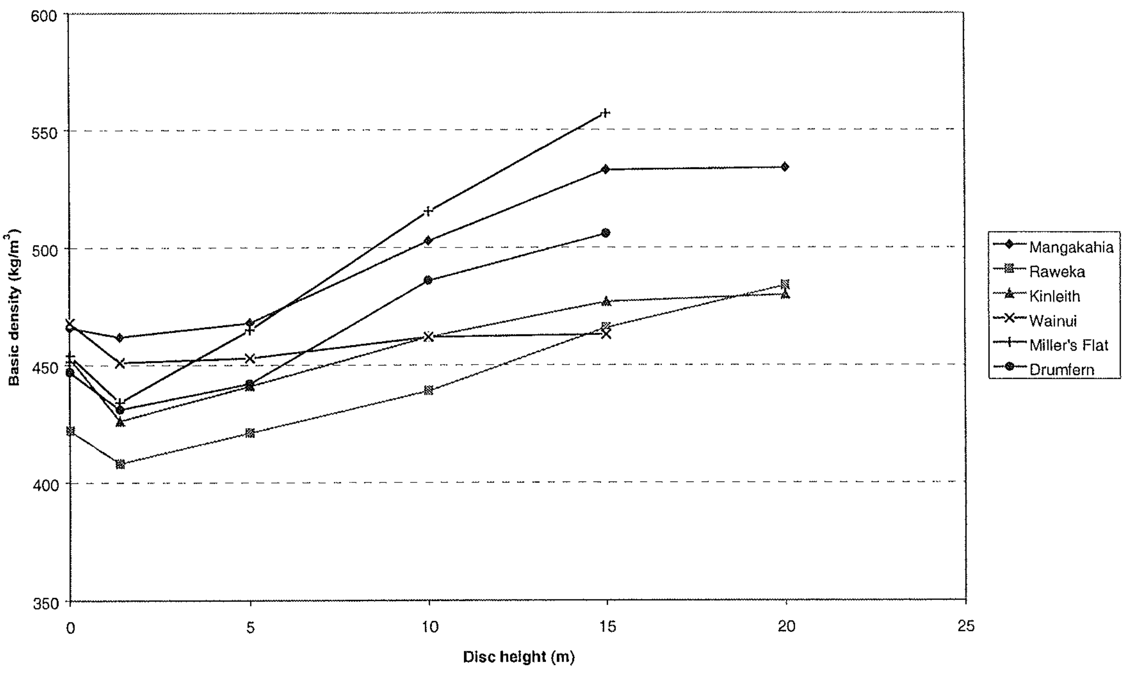


Table 10–Mean disc/height wood properties

Disc height	Site	No. of trees	DOB mm	DIB mm	Bark thickness mm	Heart-wood %	Moisture content %	Green density kg/m^3	Basic density kg/m^3	Rot
0	Mangakahia	15	271	245	13.2 ab	61 a	140 bc	1111 a	466 a	1.12 a
0	Raweka	16	266	244	11.4 ab	60 ab	161 a	1096 a	422 b	0.64 a
0	Kinleith	15	249	221	14.0 a	56 abc	144 ab	1101 a	453 ab	0.52 a
0	Wainui	15	251	224	13.7 a	52 c	125 c	1051 b	468 a	0.08 a
0	Miller Flat	16	231	210	10.7 b	45 d	131 bc	1041 b	454 ab	6.02 b
0	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
1.4	Raweka	16	231	217	6.8 ab	60 a	165 a	1072 a	408 b	1.50
1.4	Kinleith	15	208	192	8.0 ab	56 ab	150 ab	1061 a	426 ab	0.12
1.4	Wainui	15	213	198	7.6 ab	51 b	123 c	1004 b	451 a	0.00
1.4	Miller Flat	16	198	185	6.3 b	41 c	136 bc	1016 b	434 ab	2.72
1.4	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 ab	56 ab	126 bc	1056 a	468 a	0.29
5.0	Raweka	16	207 a	197 a	5.3 ab	59 a	153 a	1057 a	421 b	0.00
5.0	Kinleith	15	176 ab	165 ab	5.3 ab	50 abc	136 ab	1029 a	441 ab	1.37
5.0	Wainui	15	187 ab	175 ab	5.9 a	48 bc	115 c	972 b	453 ab	0.00
5.0	Miller Flat	16	161 b	151 b	5.0 ab	23 d	124 bc	1034 a	465 a	0.00
5.0	Drumfern	15	171 ab	162 ab	4.4 b	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
10.0	Mangakahia	15	151 ab	140 ab	5.5 a	42 a	114 bc	1076 a	503 ab	0.00
10.0	Raweka	16	170 a	161 a	4.4 bc	47 a	143 a	1062 ab	439 c	0.04
10.0	Kinleith	14	134 bc	126 bc	4.1 bc	32 b	125 b	1031 b	462 bc	2.90
10.0	Wainui	15	141 ab	132 ab	4.5 ab	19 c	111 bc	969 c	462 bc	0.00
10.0	Miller Flat	16	104 c	97 c	3.5 c	6 d	108 c	1062 ab	515 a	0.00
10.0	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
15.0	Raweka	16	126 a	118 a	3.9 ab	18 ab	132 a	1074 ab	466 b	0.00
15.0	Kinleith	9	114 ab	106 ab	4.1 ab	21 a	121 ab	1050 b	477 b	0.19
15.0	Wainui	14	92 ab	86 ab	3.4 b	2 c	114 abc	985 c	463 b	0.00
15.0	Miller Flat	3	82 b	75 b	3.3 b	3 bc	92 cd	1067 ab	557 a	0.00
15.0	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
20.0	Raweka	10	98	91	3.7	0	122	1069 ab	484	0.00
20.0	Kinleith	4	91	84	3.9	4	122	1061 b	480	0.00
20.0	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

Table 11–Log mean wood properties

Log	Site	No. of trees	Volume m^3	Bark thickness mm	Heart-wood %	Moisture content %	Green density kg/m^3	Basic density kg/m^3	Rot
Butt	Mangakahia	15	0.190	9.8	60 a	135 bc	1091 a	465 a	0.62 a
Butt	Raweka	16	0.199	8.3	60 a	160 a	1078 a	417 b	0.75 a
Butt	Kinleith	15	0.157	9.9	55 ab	144 ab	1071 a	441 ab	0.53 a
Butt	Wainui	15	0.166	9.7	50 b	122 c	1016 b	459 a	0.03 a
Butt	Miller Flat	16	0.134	7.9	39 c	132 bc	1031 b	448 ab	3.70 b
Butt	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***
2nd	Mangakahia	15	0.110 ab	5.5 a	51 ab	122 bc	1063 a	480 a	0.18 ab
2nd	Raweka	16	0.135 a	4.9 ab	54 a	149 a	1059 a	428 b	0.02 a
2nd	Kinleith	14	0.093 ab	4.9 ab	46 b	133 ab	1035 a	447 ab	1.41 b
2nd	Wainui	15	0.099 ab	5.4 a	38 c	114 c	971 b	456 ab	0.00 a
2nd	Miller Flat	16	0.064 b	4.6 ab	19 d	119 bc	1042 a	480 a	0.00 a
2nd	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*
3rd	Mangakahia	13	0.064	5.4 a	33 a	112 bc	1085 a	514 ab	0.00
3rd	Raweka	16	0.084	4.2 ab	37 a	139 a	1066 a	448 c	0.03
3rd	Kinleith	9	0.068	4.3 ab	37 a	127 ab	1034 a	457 c	3.20
3rd	Wainui	14	0.050	4.3 ab	15 b	111 bc	972 b	462 bc	0.00
3rd	Miller Flat	3	0.040	4.1 ab	17 b	101 c	1056 a	530 a	0.00
3rd	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
4th	Mangakahia	3	0.042	5.5	20 ab	113	1102 a	517	0.00
4th	Raweka	10	0.054	4.1	19 ab	133	1071 a	464	0.00
4th	Kinleith	4	0.048	4.6	25 a	123	1052 a	472	0.28
4th	Wainui	1	0.023	3.9	4 b	85	967 b	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
Tree	Raweka	16	0.454 a	6.3 b	52 a	152 a	1069 a	428 b	0.38 a
Tree	Kinleith	15	0.297 ab	7.6 ab	50 ab	139 ab	1055 ab	445 ab	1.10 a
Tree	Wainui	15	0.312 ab	7.6 ab	41 c	118 c	996 c	458 ab	0.02 a
Tree	Miller Flat	16	0.205 b	6.8 ab	32 d	128 bc	1034 b	459ab	2.59 b
Tree	Drumfern	15	0.258 b	7.1 ab	44 bc	123 bc	992 c	448ab	0.25 a
	ANOVA F For Sites		5.0***	3.1*	30.8***	8.4***	27.9***	3.0*	7.7***

Internal checking

Internal checking was assessed only on the breast height disc of each tree. The disc was bisected diametrally, rather than perpendicularly to the stem, to give two semi-circular samples which were respectively air dried and kiln dried. The number of rings affected by checks was recorded in the heartwood, "transition wood" (one ring either side of the heartwood/sapwood boundary) and sapwood of each sample. The total number of checks across the three zones was also recorded. The mean values for these checking characteristics are shown in Tables 12 and 13, along with F ratios for Sites from the ANOVA, and Tukey letters indicating significant differences between site means.

Table 12–Site means for internal checking of **air-dried** breast-height discs

				No. rings with checking				
Site	No. of trees	No. rings	No. heart-wood rings	Heart-wood	Trans-ition wood	Sap-wood	All	Total no. checks
Mangakahia	15	10.5a	5.9a	0.87bc	2.5a	0.67	4.0b	163ab
Raweka	16	10.0ab	5.2b	1.13c	2.3ab	0.63	4.0b	201ab
Kinleith	15	9.8b	5.1bc	0.40abc	1.8abc	0.87	3.1ab	225b
Wainui	15	10.0ab	6.0a	0.33ab	1.5bc	0.27	2.1a	40a
Miller Flat	16	7.9d	4.5c	0.13ab	1.4c	0.31	1.8a	54a
Drumfern	15	8.8c	5.0bc	0.07a	1.7abc	0.53	2.3a	60a
ANOVA F for Sites		30.7***	14.3***	4.8***	4.1**	1.8	6.8***	4.0**

Table 13–Site means for internal checking of **kiln dried** breast height discs

				No. rings with checking				
Site	No. of trees	No. rings	No. heart-wood rings	Heart-wood	Trans-ition wood	Sap-wood	All	Total no. checks
Mangakahia	15	10.5a	6.0a	0.93b	1.6ab	0.27	2.8bc	63
Raweka	16	10.0ab	5.2b	1.25b	1.8b	0.19	3.3c	103
Kinleith	15	9.8b	5.1b	0.27a	1.7ab	0.40	2.4abc	107
Wainui	15	10.0ab	5.9a	0.27a	0.8a	0.13	1.2a	30
Miller Flat	16	7.9d	4.4c	0.06a	1.1ab	0.19	1.3ab	30
Drumfern	15	8.8c	5.0bc	0.13a	1.7ab	0.20	2.1abc	43
ANOVA F For Sites		30.7***	15.4***	10.2***	3.1*	0.5	4.9***	2.4*

There was much more checking apparent in the air-dried discs than in the kiln dried discs. More checking occurs in the transition-wood zone in both air- and kiln-dried discs than in the heartwood or sapwood, in spite of the fact that there are, by definition, only 2 rings in the transition-wood zone, 4.5–6 rings in the heartwood and 3-5 rings in the sapwood, depending on site and varying much with individual tree.

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 3 sites. The same site effects for total number of checks were evident for air-dried discs, which varied from 163 to 225 at Mangakahia, Raweka and Kinleith, and were only 40-60 at the other sites.

Lausberg *et al.* reported 5 times the number of checks visible on the inside versus the outside, when dried discs are cross cut, perpendicular to the stem axis. The same was found here in a sub-sample of discs from the North Island sites. In the South Island sites, 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, received some treatment that was different from that given the other lots.

Amounts of checking in air–dried discs were evidently unrelated to basic density, on a site mean basis, or to mean annual rainfall but showed a positive relationship with mean annual temperature and mean minimum daily temperature (more checking on warm sites). There was also a clear negative relationship between site means of number of rings checked and total number of checks, with length of green crown, and thus with crown health. Length of green crown seems to express the level of ecological adaptation of the species to the site.

Much the same relationships between site mean checking with climatic variables and green crown length are evident for kiln-dried discs. Checking was again more frequent in the transition wood zone but mean number of rings affected in each zone and overall were less at most sites than for air-dried discs. Total number of checks were reduced to half or less than those in air-dried discs at the 3 northernmost sites but to about 2/3 at Wainui and the two South Island sites.

Internal checking in discs and a basal 1.5 m diametral board in 15 year-old *E. nitens* (a further analysis of Lausberg *et al.*, (1995) data)

As described under "Previous studies" above, Lausberg *et al.*, (1995) studied checking in 20 15-year-old trees of *E. nitens*, grown in Kaingaroa Forest in the central North Island, that had been selected for a range of basic density. As he observed, there was large tree-to-tree variation in checking in kiln-dried discs taken at 0, 1.4, 6.4 and at 11.4 m up the stem, but little checking was observed above this. Individual-tree values for mean number of checks per ring are shown here (Table 14) as well as mean values by disc height.

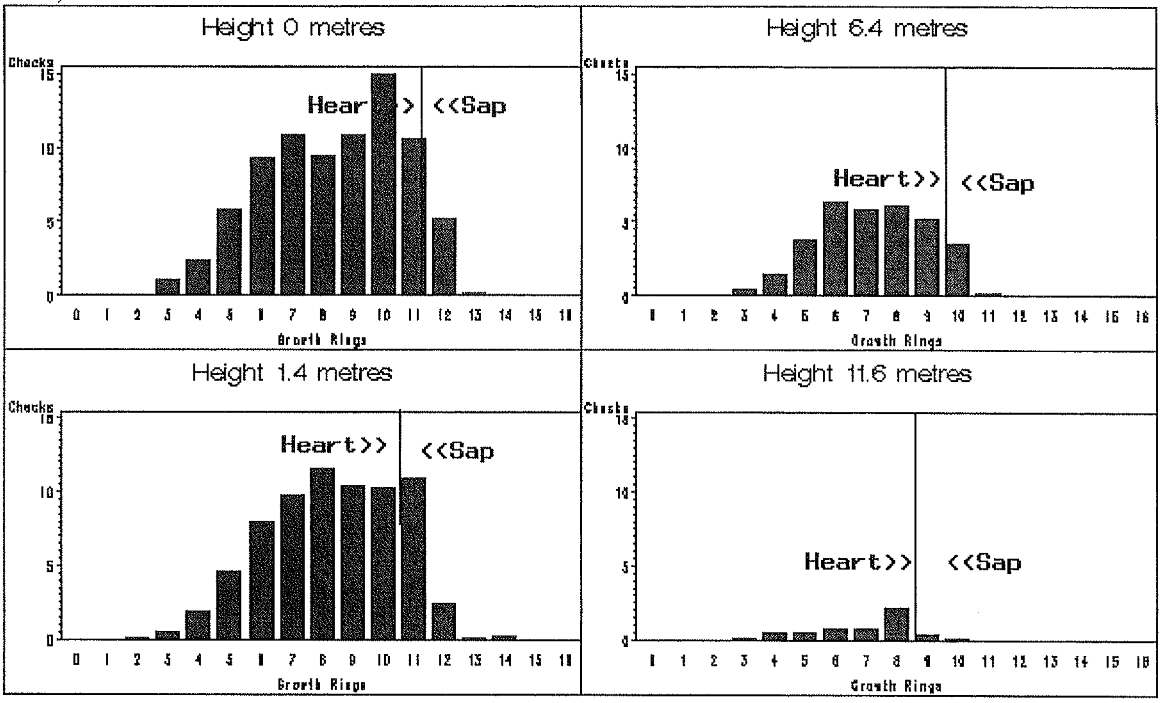
Table 14–Mean number of checks per ring, by individual trees and by disc heights (Lausberg *et al.*, unpubl. data)

Tree no.	Total no. of rings in 4 discs	Mean no. of checks / ring	Disc height m	Total no. of rings across 20 trees	Mean no. of checks / ring
3	55	2.0 abcde	0	315	5.2 c
9	56	0.6 a	1.4	307	4.6 c
11	58	2.2 abcde	6.4	272	2.4 b
13	59	1.5 ab	11.4	246	0.5 a
16	59	2.9 abcde			
17	59	7.5 f			
35	58	1.6 ab			
37	57	3.1 abcde			
42	55	2.3 abcde			
49	58	1.9 abcde			
57	59	7.7 f			
63	54	1.7 abc			
64	56	6.1 ef			
68	59	6.0 def			
73	56	2.0 abcde			
76	57	5.1 bcdef			
77	58	3.1 abcde			
85	55	1.8 abcd			
90	56	1.5 ab			
93	56	5.9 cdef			

Table 15–Analyses of variance for mean number of checks per ring

Disc heights nested within trees			Disc heights across all trees		
Source	Degrees of freedom	F test	Source	Degrees of freedom	F test
Tree	19	6.14***	Tree	19	6.77***
Disc ht(Tree)	60	2.34***	Disc height	3	31.29***
Error	1060		Error	1117	

Fig. 6–Mean number of internal checks per ring, by disc height (Lausberg *et al.*, unpubl. data)



Average number of checks per ring (Table 14) decreased from 5.2 in the basal disc, to 4.6 at breast height, 2.4 at 6.4 m and 0.5 at 11.4 m. There was virtually no checking in discs taken above the top of the second 5m log. Average number of checks per ring over these four disc heights varied from 0.6 for tree 9 to 7.5 for tree 17. Analysis of variance at the level of rings-within-trees (Table 15), showed that there is much variation within trees, by disc height as well as within discs, but differences between trees were highly significant, even though tree means are not precisely estimated.

Checks in discs were largely confined to the heartwood and increased in frequency towards the outer rings of heartwood into the sapwood (Fig. 6). This is partly a scalar effect, related to the increasing circumference of rings from pith to bark.

Lausberg *et al.* (1995) also examined checking in cross-sections of air dried diametral boards, sawn from a basal 1.4 m billet from each tree. Numbers of checks per ring were counted separately from opposite sides of the pith of each board, and are shown, with the mean number of checks per ring in the breast-height (kiln-dried) disc, in Table 16.

Differences between trees in mean number of checks for the 1.4 m disc and for boards, both by each side and combined, were highly significant (Tables16 and 17). These ranged from 11.7 checks for the breast height disc for tree 57 to near zero for tree 9, and for combined sides of boards, from 4.6 checks for tree 57 to near zero for several trees. There were on average nearly 4 times the number of checks per ring in the discs versus the boards, owing to the far greater cross-sectional area of the disc versus the 25 mm-thick boards. It is evident from Table 17 that there was wide variation in number of checks between board sides A and B, either side of the pith.

Table 16–Analyses of variance of mean number of checks per ring for 1.4 metre discs and opposite sides of diametral boards

Mean number of checks / ring for 1.4 metre disc			Mean number of checks / ring for boards		
Source	Degrees of freedom	F test	Combined	Side A	Side B
Tree	19	4.63***	5.32***	4.90***	3.98***
Ring	15	11.60***	4.80***	3.92***	3.21***
Error	287				

Variance components for mean number of checks per ring (analysis as above)

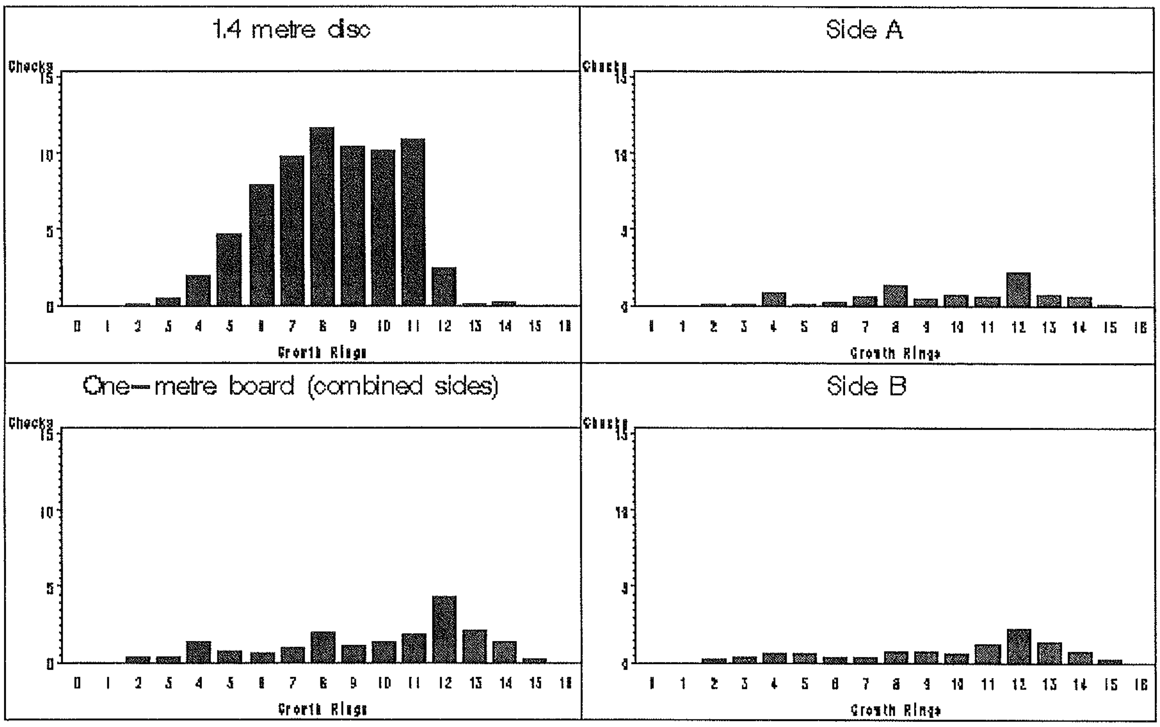
Source	Degrees of freedom	1.4 metre disc	Combined sides	Side "A"	Side "B"
Tree	19	8.939***	1.275***	0.402***	0.348***
Ring	15	20.905***	0.895	0.240***	0.20***
Error	267	39.455	4.433	1.545	1.762

Table 17–Mean number of checks per ring for 1.4 metre discs and opposite sides of diametral boards (with Tukey test letters)

Mean number of checks / ring for 1.4 metre disc		Mean number of checks / ring for boards		
Tree	Mean no. of checks	Board total	Side A	Side B
3	2.1 abc	0.50 a	0.13 a	0.38 a
9	0.3 a	0.63 ab	0.00 a	0.63 a
11	2.3 abc	0.31 a	0.06 a	0.25 a
13	1.3 ab	0.07 a	0.07 a	0.00 a
16	4.3 abc	0.75 ab	0.19 a	0.56 a
17	11.3 bc	3.53 bc	1.07 a	2.47 b
35	2.2 abc	0.60 ab	0.13 a	0.47 a
37	5.4 abc	0.73 ab	0.47 a	0.27 a
42	2.5 abc	0.07 a	0.07 a	0.00 a
49	2.4 abc	0.19 a	0.19 a	0.00 a
57	11.7 c	4.60 c	2.93 b	1.67 ab
63	3.2 abc	0.14 a	0.00 a	0.14 a
64	9.1 abc	2.60 abc	1.13 a	1.47 ab
68	6.4 abc	1.80 abc	0.80 a	1.00 ab
73	1.9 abc	1.33 ab	0.13 a	1.20 ab
76	8.6 abc	2.53 abc	0.93 a	1.60 ab
77	3.3 abc	1.40 ab	1.07 a	0.33 a
85	3.3 abc	0.00 a	0.00 a	0.00 a
90	1.9 abc	1.33 ab	1.00 a	0.33 a
93	7.6 abc	1.79 abc	1.07 a	0.71 ab
93	7.6 abc	1.79 abc	1.07 a	0.71 ab
Means	4.56	1.25	0.57	0.67

Average distribution of checks by rings from the pith is shown for the 1.4 m discs and boards in Fig. 7. Checking in the air-dried boards occurs in the same rings as in the 1.4 m discs, is largely confined to the heartwood and shows a real increase in frequency in rings 11-13 from the pith.

Fig. 7–Mean number of internal checks per ring, for 1.4 m disc and for boards from basal billet (Lausberg *et al.*, unpubl. data)



There was a weak but significant correlation (0.51) between number 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 (0.78) was moderate. The relatively low correlation values between checking measured in an almost identical part of each treee, in kiln-dried disc and in air-dried board, indicates that there are different conditions in discs versus boards for checking to be expressed. Alternatively or in addition, kiln drying has provided a different drying treatment that evokes a different response.

The correlation between number of rings checked on opposite sides of each board was only 0.52 whilst that between total number of checks was 0.92. The mean number of checks per ring was very variable with anaverage fo only 0.6 checks/ring for each side of the board or 1.2 per whole board, indicating that many rings would have no checks, which may have contributed to these results.

Average within-site correlations amongst wood properties, internal checking and tree characteristics

Basic density shows no correlation within sites with growth traits, diameter and volume, at the individual tree level (Table 18). Neither does it show any significant correlation with the amount of heartwood and the length of green crown. These correlations are estimated within each site and averaged over the 6 sites. There is a strong relationship between density and moisture content. Diameter and volume are strongly correlated with green crown length, and thus with crown health. Heartwood % shows a weak relationship with tree diameter and volume.

Table 18–Mean within-site correlations of individual-tree basic density with other traits, over 6 sites

	Basic density	Diameter	Volume	Heart-wood %	Green crown length	Moisture content
Basic density	1.00					
Diameter	0.00	1.00				
Volume	-0.01	0.98	1.00			
Heartwood %	-0.09	0.41	0.38	1.00		
Green crown length	0.03	0.80	0.78	0.19	1.00	
Moisture content	-0.85	0.08	0.09	0.22	-0.01	1.00

Average within-site correlations of total number of checks and number of rings that were checked (Table 19) with basic density, bark thickness, diameter and green crown length are all very low and non-significant, whether measured on air-dried or kiln-dried material. Number of rings checked had slightly higher correlations with the other traits than total number of checks. Total number of checks was moderately correlated with number of rings checked for air and kiln-dried discs (0.77) and there was a very weak negative relationship of number of rings checked with density.

Bark thickness was moderately positively correlated with tree diameter within sites and also positively with green crown length, probably because of the causal association of this trait with diameter.

Internal checking is an artifact of processed solid wood, which results from drying, and appears in sawn boards and discs. Within sites, it appears to be essentially unrelated to other traits measured in this study, particularly density and growth rate, though as shown above, was much less serious at the sites with lower temperatures and with long green crowns.

Table 19–Mean within-site correlations of individual-tree total numbers of checks with other traits, over 6 sites

Air-dried breast height discs

	Total no. of checks	Heart-wood %	Bark thickness	Basic density	Diameter I.B.	Green Crown length	No. of rings checked
Total no. of checks	1.00						
Heartwood %	0.07	1.00					
Bark thickness.	0.05	0.30	1.00				
Basic density	-0.08	-0.17	0.21	1.00			
Diameter I.B.	0.07	0.38	0.68	-0.06	1.00		
Green crown length	0.07	0.19	0.59	0.02	0.80	1.00	
No. of rings checked	0.77	0.15	0.08	-0.24	0.20	0.15	1.00

Kiln-dried breast-height discs

	Total no. of checks	Heart-wood %	Bark thickness	Basic density	Diameter I.B.	Green Crown length	No. of rings checked
Total no. of checks	1.00						
Heartwood %	0.04	1.00					
Bark thickness	0.02	0.30	1.00				
Density	-0.13	-0.17	0.21	1.00			
DIB	0.07	0.38	0.68	-0.06	1.00		
Green crown length	0.06	0.19	0.59	0.02	0.80	1.00	
No. of checked rings	0.77	0.10	0.04	-0.30	0.11	0.08	1.00

DISCUSSION AND CONCLUSIONS

Mean whole-tree basic density of *E. nitens* at 6 sites was estimated from 15 trees / site, each planted with the same seedlot at the same spacing. Sites ranged in altitude from 40 to 540 m and in latitude from 35°52´S (Mangakahia near Dargaville) to 45°55´S (Drumfern in Southland). Mean density was quite similar at 4 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 Managakahia density was the 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 (2060 mm). Mangakahia (altitude 40 m) had the highest mean annual, daily minimum and daily maximum temperatures, 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 6 sites.

Whole-tree density from other studies at other sites in New Zealand (NZ) at or about the same age, almost fall within the range for the sites in this study of 428-476 kg/m^3. These include 15-year-old trees at Kaingaroa (altitude 230 m) and Kinleith (altitude). Density was a little higher at Berrymans, Golden Downs, in Nelson province for 11 year-old trees (483 kg/m^3) and a little lower at Ahaura in Westland (419 kg/m^3). Ahaura's annual rainfall was 1900 mm, almost double that at Golden Downs, supporting the hypothesis that high rainfall may contribute to low wood density.

Mean whole-tree density increases with age, as shown in the survey of NZ data, from a mean of 453 kg/m^3 (9 years), 477 kg/m^3 (15 years) to 495 kg/m^3 (20 years) but this range is less than that due to site.

All whole-tree density studies, 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 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.* showed an average increase of 57 kg/m^3 from height 1.4 m to 22 m with 15-year-old trees at Kaingaroa, and McKenzie *et al.*, an increase of 76 kg/m^3 between heights 6 m to 25 m at Golden Downs. Richardson (unpubl.data) showed an increase of 77 kg/m^3 from the butt log to the fourth log (18-25 m). There is agreement that density increases up the tree after an initial decrease, and that the extent of the increase gets bigger with age of tree.

This increase of basic density with height found in *E. nitens*, has important consequences for utilisation. Log mean values for basic density (Table 11) are lowest for the butt log and increase substantially for the second and third 5 m logs. This means that for solid wood utilisation, the most valuable sawlog has the lowest density. This trend would benefit utilisation of the second log for veneers for laminated veneer lumber (McKenzie *et al.*, in press). For pulping, whole–tree chip density will always be higher than that of breast height samples.

In this study, internal checking was only measured on a breast height disc of each of 15 trees/site. This was divided into two semi-circular halves, one air dried and the other slowly kiln dried. There were large differences between sites in the total numbers of checks and in the number of rings checked. Checking was concentrated more in the outer heartwood ("transition wood"). Kiln drying resulted in fewer rings with checks and fewer checks, especially at the sites with severe checking, than air drying. Number of rings checked and total number of checks was much higher at Kinleith, Raweka and Mangakahia than at Wainui, Drumfern and Millers Flat. The latter three sites have much lower mean annual, maximum and minimum temperatures, than the other sites. At these sites, green crowns were much longer and health much better than at the other warmer sites. Checking appears to be much more frequent in wood of trees at sites where crowns were short and unhealthy.

Checking data from an earlier study by Lausberg et al. (1995) was analysed further and greatly extended the scope of the present study. Twenty 15-year-old trees from Kaingaroa

Forest (altitude 230 m), were sampled by discs at 0, 1.4, 6.4 and 11.4 m height as well as by a cross-section of a diametral board sawn from a basal one metre billet. These showed similar high levels of checking to other warmer North Island sites. This 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 wide variation from one side of the diametral board to the other. The correlation between number of rings checked in boards versus discs was low (0.51) but higher for total number of checks (0.78).

Basic density of individual trees showed very low and non-significant average within-site correlations with growth rate, heartwood %, and length of green crown. Average within-site correlations of number 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, both for air-dried and kiln-dried discs. Wood density and internal checking each behaved independently of the other wood and tree properties at each site.

Internal checking is a serious and prevalent defect of *E. nitens* which is site-dependent in its severity. It is an artifact of drying solid wood products which may well prevent *E. nitens* plantations from being utilised for appearance grade lumber, especially when grown on warmer sites. The high variability among trees in amounts of checking does offer the possibility of selecting against it in breeding programmes but non-destructive means of evaluation have not yet been developed. The effect of checking on sawn timber from logs grown on colder sites needs to evaluated. Growing *E. nitens* only on sites where it has long, healthy green crowns offers that best management option for controlling internal checking.

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APPENDIX

Appendix Table 1–Nutrient levels in foliage

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

Appendix Table 2–pH and nutrient levels in soil

Site.	pH	Bray-P (3 extractions) (mg/kg)			Bray-Cations (cmol/kg)						
		1	2	3	P	K	Ca	Mg	C %	N %	C:N
Drumfern	5.1	14.95	12.67	7.97	11.86	0.23	3.51	0.71	5.62	0.340	16.5
Millers Flat	4.9	28.01	18.99	10.74	19.25	0.2	2.8	1.26	5.56	0.365	15.2
Mangakahia	*5.2	27.82	18.99	15.37	20.73	0.48	8.43	2.21	4.78	0.454	10.5
Wainui	*6.2	122.73	157.64	90.23	123.53	0.25	10.74	0.90	6.17	0.525	11.8
Raweka	*5.7	98.21	65.72	34.83	66.25	0.26	4.17	0.69	3.17	0.296	10.7
Kinleith	*5.6	27.68	46.82	33.72	36.07	0.44	1.53	0.325	2.78	0.152	18.0

* At establishment