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ABSTRACT

In species trials of *Eucalyptus nitens* (Deane et Maiden) Maiden, *E. globulus* Labill, and *E. maidenii* Labill aged 8 years and 11 years, 10 trees of each species/age were selected to compare wood properties and some lumber properties, ancillary to a previously-reported kraft pulping study. The trees were selected across the range of wood density for destructive sampling to approximate the species mean. Wood properties were measured on breast-height increment cores, on discs removed at 5-m intervals, and on a billet from height 5–6 m, and clearwood mechanical properties were measured from six test sticks/tree, cut from the billet.

Eucalyptus maidenii and *E. globulus* had much higher density than *E. nitens*. Whole-tree densities averaged, respectively, 574, 540, and 451 kg/m^3. There was no pith-to-bark gradient in density in the 6-m-height discs of *E. nitens*, but *E. globulus* and *E. maidenii* showed appreciable commensurate increases in density. In *E. nitens*, density decreased initially from the base to a height of 6 m, then increased rapidly upwards. Density increased steadily from the base in *E. globulus*, but decreased in *E. maidenii*. Bark was thickest in *E. maidenii*, especially at the tree base, and *E. nitens* had a higher proportion of heartwood than the other species.

Tangential shrinkage, measured in the 6-m disc, was 17% for *E. nitens*, 12% for *E. globulus*, and 10% for *E. maidenii*. Tangential and radial collapse, measured as the reduction in shrinkage by steam reconditioning, was much higher in *E. nitens* than in *E. globulus*, which in turn was higher than in *E. maidenii*. Internal checking (assessed on the 6-m disc) was general and often severe in *E. nitens*, very occasional in *E. globulus*, and completely absent in *E. maidenii*. Average spiral grain angles for all species were less than 2.5°, and unlikely to cause drying distortion. Mechanical properties of the three species paralleled their wood densities. MoE values (GPa) for the outer rings 7 to 9 at height 5–6 m averaged 14.4 for *E. maidenii*, 13.7 for *E. globulus*, and 9.6 for *E. nitens* (at about 14% mc). Corresponding MoR values were 131, 122, and 88 MPa.

The continued good growth and health of *E. maidenii* in Northland, combined with its lack of checking, low spiral grain angle, low shrinkage, low collapse, and excellent strength and stiffness, indicate its promise for solid wood products. However, growth-stress-related characteristics in sawn timber, and drying distortion remain to be evaluated.

Keywords: juvenile wood properties; density; shrinkage; collapse; spiral grain; checking; mechanical properties; stiffness; strength; *Eucalyptus nitens*; *E. globulus*; *E. maidenii*.

INTRODUCTION

The principal species currently grown for short-fibred pulp in New Zealand are *Eucalyptus nitens* and *E. fastigata*. *Eucalyptus regnans* F. Mueller was favoured earlier, particularly in the plantations established in the 1970s in the central North Island by New Zealand Forest Products Forests Ltd (NZFP) (now Carter Holt Harvey Forests), but because of health problems it is no longer being planted (Kay 1993). *Eucalyptus globulus* has a reputation in New Zealand for poor frost tolerance and susceptibility to fungal disease and insect attack, but is the preferred species worldwide for kraft pulping because of its rapid growth, high pulp yield, and good fibre and handsheet properties.

Plantations of *E. globulus* for chipwood export are developing rapidly in Tasmania, Victoria, South Australia, and Western Australia, but already there is some interest in its possibilities for solid wood products (Washhusen *et al.* 1999, 2000; Yang &Waugh 1996a). However, severe drying degrade of appearance-grade lumber from distortion, splitting, and internal checking was found in this species. Results from sawing for structural products were better as checking did not affect structural performance, but end-splitting and distortion on sawing, from growth stresses and tension wood, were a problem. A parallel study of 15-, 24-, and 29-year-old plantation-grown *E. nitens* for structural timber (Yang & Waugh 1996b) showed more checking than in *E. globulus* but less distortion on drying. Growth-stress-related end-splitting was less in *E. nitens* than in *E. regnans* and both species showed far less serious end-splitting than *E. globulus*.

Haslett & Young (1992) reported serious problems in sawing and drying in a study of 30-year-old *E. nitens* from Canterbury in the South Island of New Zealand. Growth stresses were moderate, and complicated sawing, but a main degrading factor was internal checking, a serious problem for appearance-grade timber. Lausberg *et al.* (1995) also reported high levels of internal checking for 15-year-old trees grown in Kaingaroa Forest. For both studies the timber was initially air-dried before being kiln-dried.

In a recent individual-tree sawing and veneers study of 15-year-old *E. nitens*, McKenzie, Turner & Shelbourne (in press) and McKenzie, Shelbourne, Kimberley, McKinley & Britton (in press) found that sawing characteristics of bow and crook were closely correlated with log end-splitting and with growth stresses, measured at breast height. There were also strong correlations of checking and collapse in butt-log sawn boards with that occurring in boards from a 1-m billet taken between heights 6 and 7 m, and in discs. Modulus of elasticity (MoE) of clearwood test sticks cut from 1-m billets also correlated well with MoE of veneers. These results prompted the application of similar methods in the study reported here.

Species and provenance trials that included *E. globulus*, *E. maidenii*, *E. nitens*, and several other species were established on warm low-altitude sites in Northland (by NZFP) in 1988 and 1991 (Shelbourne *et al.* 2000) and a close-spaced coppice-fuelwood trial was established by the Forest Research Institute at Clive (Hawke's Bay) in 1987 which included, amongst others, the same three species (Low & Shelbourne 1999). Recent assessments of these trials on four Northland sites and at Clive have shown excellent health of *E. maidenii*, and extremely poor health of Victorian provenances of *E. nitens*, and of *E. globulus*. An earlier study of whole-tree basic density of five trees per species (Jansen 1988) at age 6 years at one of these Northland sites showed values of 431 kg/m^3 for *E. nitens*, 479 kg/m^3 for *E. globulus*, and 555 kg/m^3 for *E. maidenii*; at Clive (Hawke's Bay), densities at age 10 years were respectively, 447, 489, and 582 kg/m^3.

A recent kraft pulping study (Kibblewhite *et al.* 2000) compared the pulp properties of *E. globulus*, *E. maidenii*, and *E. nitens* of southern New South Wales (NSW) provenance from 8-year-old and 11-year-old trials, the same as reported on for growth and health by Shelbourne *et al.* (2000). Ten trees of each species were felled from each trial, and were also sampled for wood properties. Of the six species/age combinations, pulps of premium quality were obtained from *E. globulus* aged 11, and from *E. maidenii* aged 8 years. The remaining species/ages gave pulps that were either too high in bulk and required excessive refining (*E. maidenii*, age 11 years) or deficient in bulk and unsuitable for many eucalypt market kraft end-uses (*E. nitens*, ages 8 and 11 years).

Wood properties (basic and green density, moisture content, heartwoood percentage, and bark thickness) were measured on the same 10 individual trees per species/age combination as had been used for the pulping study (Kibblewhite *et al.* 2000). In addition, for the 11-year-old trees only, drying properties, air-dry shrinkage (radial, tangential, and volumetric) before and after steam reconditioning, collapse and internal checking, and spiral grain were measured from discs. Mechanical properties were measured from a diametral board, cut from a 1-m billet from height 5–6 m of each sample tree. This study was designed to get limited solid-wood product performance information for young trees of the three species.

MATERIALS AND METHODS

Field Trial Design and Sampling

Eucalypt species and provenance trials were planted at two sites in Northland in 1988 and 1992. These sites were located at Carnation Road and Knudsen Road (latitude 35°30′S; altitude 180–195 m), 20 and 12 km respectively south of Kaikohe (Low & Shelbourne 1999; Shelbourne *et al.* 2000). Both sites were ex-pasture, on similar Northland clay soils, with mean annual temperatures of 14.2°C and 14.4°C, and mean annual rainfalls of 1920 mm and 1770 mm, respectively. The trials were not designed as a single experiment to compare the same seedlots on different sites, but have been opportunistically utilised to provide material for a pulping study (Kibblewhite *et al.* 2000) and for this study of wood properties. The effects of age and site are confounded, as well as effects of different genetic origins of seedlots of each species at each site.

The trial designs were randomised complete blocks. However, at Carnation Road (aged 11 years) *E. maidenii* and *E. globulus* were growing in one trial with four replicates of 20-tree plots, while the *E. nitens* came from an adjacent trial with less exposure, located further down the slope, with four replicates of 64-tree plots. The *E. nitens* seedlot was a bulked mixture of three seedlots from Tallaganda, Nimmatabel, and Bondo (NSW); the *E. maidenii* seedlot was from a few trees of unknown provenance, growing at Waiohiki, Napier (New Zealand) and the *E. globulus* seedlot was of unknown provenance, collected in California. At Knudsen Road (age 8 years) with 49-tree plots of each provenance, the 30 sampled trees were evenly distributed through two replicates of two provenances of *E. maidenii* from Black Range, Eden, and Bolaro Mountain, Batemans Bay (NSW), two provenances of *E. globulus* from Huonville, Tasmania (Tas.) and Jeeralang, Victoria (Vic.), and three provenances of *E. nitens* (from southern NSW, Brown Mountain, Tallaganda, and Badja).

Standing trees of *E. nitens, E. globulus*, and *E. maidenii* in these trials were increment-core sampled for breast-height outerwood density in 30 trees/species/site for the pulping and wood properties study. Their diameter at breast height over-bark (dbhob) was also measured. Ten trees of each species from each site were selected for felling across a range of density, to approximate the 30-tree mean outerwood basic density value. An additional constraint was to select trees of similar dbhob within each species at each site so as to contribute comparable volumes of chips to each species' bulked sample for the kraft pulping study.

Measurements of wood properties from discs of both 8-year-old and 11-year-old trees and from the latter only, of mechanical properties (from 1-m billets), spiral grain and drying characteristics of solid wood, namely shrinkage, collapse, and internal checking (from extra discs), are outlined below. These were aimed at providing a comparative evaluation of the solid-wood-product potential of young material of the three species.

Tree, Log, Disc, and Billet Sampling

Knudsen Road 8-year-old trees

Measurements before felling:

- Basic density, from 5-mm pith-to-bark increment core
- Dbhob

Sampling/measurements after felling:

- Foliage samples collected for species identification and health assessment
- Total tree height
- Diameter over and under bark (dob, dub) measured at heights 0.3 m, 0.7 m, 1.4 m, 5 m, 10 m, 15 m
- Cross-sectional discs cut from base of the butt log, and at consecutive 5-m intervals, down to a small-end diameter (s.e.d.) of 100 mm
- Whole-disc measurements of basic density, moisture content, and heartwood percentage.

Carnation Road 11-year-old trees

Measurements before felling:

- Basic density, from 5-mm pith-to-bark increment core
- Dbhob

Sampling/measurements/ after felling:

- Foliage samples collected for species identification and health assessment
- Total tree height
- Dob, dub measured at 0.3 m, 0.7 m, 1.4 m, 6 m, 11 m, 16 m, and 20 m
- 1-m billet removed from height 5–6 m for assessment of solid wood characteristics
- Cross-sectional discs, cut from the base of the butt log, height 5 m, height 6 m (two discs), and at consecutive 5-m intervals, to s.e.d. 100 mm
- Whole-disc measurements of density, moisture content, and heartwood percentage
- Disc at height 5 m measured for dub, then cut into two diametrically opposed sectors, each divided into inner five rings and remainder, from which rectangular blocks were machined

- Longitudinal, tangential, and radial shrinkage estimated by measurement of dimensions of blocks by calipers at pre-marked measurement points, when green, air-dry to 12% equilibrium moisture content (emc), before and after steam reconditioning (Treloar & Lausberg 1995)
- Radial and tangential "collapse" were calculated as shrinkage before steam reconditioning minus shrinkage after reconditioning (Chafe *et al.* 1992)
- Basic density measured on the same blocks
- Remainder of height 5-m disc used for measuring spiral grain on two diametrically opposed radii, at rings 2, 4, 6, and 8 from the pith (as in Cown *et al.* 1991)
- Extra disc at height 6-m for future SilviScan analysis of tracheid dimensions, density, and microfibril angle (20-mm-wide bark-pith-bark strip) (Evans *et al.* 2000)
- Remainder of disc for assessment of internal checking, by air-drying remaining disc "halves" to 12% emc, cross-cutting, and sanding to provide a clean, smooth surface.

The severity of checking was graded visually, ring by ring on each disc, according to the subjective scoring system of King *et al.* (1993):

No checks in the ring	0
Small checks, entirely within the ring, and with width of 1–2 mm	1
Larger checks, but still entirely within the growth ring	2
A check that crossed one latewood boundary	3
A check that crossed more than one latewood boundary	4
A severe check extending the full radius of the disc	5

One-metre billets from height 5–6 m (11-year-old Carnation Road trial only) were sawn to produce a 30-mm-thick diametral board, including the pith, which was air-dried for several months and then further cut down into three, equal-width, smaller planks from either side of the pith, thus giving two samples, at each ring position. These six planks were then dried to equilibrium moisture content (approximately 14%) and machined to produce six test "sticks" 20 × 20 × 300 mm, three from either side of the pith, for static bending and Janka hardness tests (British Standards Institute 1957). After testing, sticks were oven-dried to obtain moisture content and nominal density for each (defined as oven-dry weight/volume at that moisture content, about 12%). Sticks were culled after testing if they failed at evident imperfections such as knots, bark inclusions, kino, etc.

Log volume, heartwood percentage, bark thickness, moisture content, and green and basic densities for successive log heights were derived from the disc measurements for each tree. The 5-m logs were then chipped to provide bulked chips of each species from each site/age for the kraft pulping study.

Statistical Analysis

The confounding of age, site, and seedlot effects in the 10-tree sample of each species from each site, meant that a within-site analysis of variance model was appropriate. Species were treated as fixed effects and the error term for testing species differences was the among-tree-within-species variance.

The data from standing trees (outerwood and pith-to-bark density, dbhob, and tree height), and wood properties (bark thickness, heartwood percentage, moisture content, green and basic density, from different disc heights, and weighted whole-tree means) were first checked for normality. All properties showed an approximately normal distribution. Analysis within site and within disc-height classes utilised PROC GLM of the SAS software package (SAS Institute 1989). The Tukey's multiple range test option was used to show significant differences between species means within sites and within disc heights. Species was considered a fixed effect.

The process of selection of the sample for a range of outerwood density, and for reduced variation in dbh maximised the within-species variation in density and reduced the variation in tree diameter, without affecting the species/age class means. This was done to improve the chances of detecting significant regressions and correlations within species/age classes between density and other pulping and solid wood traits, e.g., shrinkage and checking. This selection could have effects on the analysis of variance by violating assumptions of normality and randomness. Tests for species differences in diameter will tend to be made over-sensitive, offsetting the effect of competition variance in the multi-tree plots, and tests of differences in density among species and density-related traits will be made under-sensitive.

The mechanical testing data (nominal density, MoE, MoR, and hardness) from sawing the 1-m billet into six test sticks per tree from each of the 10 trees per species at Carnation Road was subjected to analysis of variance at the level of test sticks, to test for differences in mechanical properties between species, trees within species, and pith-to-bark ring position. The ANOVA included the following terms: Species, Tree(Species), Ring position, Ring position × Species, and Ring position × Tree(Species), in addition to the residual error variance. This variance within ring positions, derived in part from variation between two diametrically-opposite test sticks within ring positions. The F-test for species differences used Tree(Species) as the error term, and the tests for Ring position and Ring position × Species, used Position × Tree(Species) as the error.

ANOVAs of test stick data were also performed for each individual species and contained the following random effects: Tree, Position, Position × Tree, and the residual variance, with similar F tests. Least square means were obtained through the SAS procedure GLM, and variance components were estimated with procedure MIXED, to quantify between-tree and within-tree variance.

Correlations were calculated between individual-tree values for selected variables within species/age classes using SAS procedure CORR.

RESULTS AND DISCUSSION

Properties Measured on Standing Trees

Breast-height outerwood and pith-to-bark basic density of *E. maidenii* were over 110 kg/m^3 higher than that of *E. nitens* in both Carnation Road (11-year-old) and Knudsen Road (8-year-old) trials, with *E. globulus* intermediate (Table 1). With greater age at Carnation Road, outerwood densities of *E. globulus* and *E. maidenii* were much higher than at Knudsen Road, but density of *E. nitens* remained the same. The same trends were evident for breast-height pith-to-bark density, though these densities of *E. globulus* and *E. maidenii* were rather lower than the outerwood density, as might be expected. These effects were apparently due to age rather than site, with density in the outer rings of *E. globulus* and

TABLE 1–Mean basic density, dbhob, and tree height of 30 trees per species per site at two Northland sites

Species	Basic density (kg/m^3) Breast height outerwood	Basic density (kg/m^3) Breast height pith-to-bark	Dbhob (cm)	Tree height (m)
Knudsen Road, Kaikohe, age 8 years				
E. nitens	413 b (40)	407 b (19)	23.2 a (1.1)	20.9 a (1.7)
E. globulus	430 b (40)	435 b (36)	19.8 b (1.1)	19.3 a (2.7)
E. maidenii	532 a (40)	520 a (42)	21.1 b (1.2)	21.3 a (1.6)
Carnation Road, Kaikohe, age 11 years				
E. nitens	408 c (34)	412 c (24)	28.3 a (1.9)	25.7 a (1.3)
E. globulus	515 b (38)	470 b (22)	24.4 b (2.3)	23.4 b (0.9)
E. maidenii	572 a (36)	527 a (46)	25.5 b (1.0)	24.1 b (0.9)

Letters following a species mean; from Tukey's multiple range test, within site/disc height. Means not sharing a letter within site/disc height are significantly different (at $p \leq 0.05$); standard deviations provided in parentheses.

E. maidenii rapidly increasing, compared to the flat pith-to-bark gradient in *E. nitens*. The different seedlots of *E. maidenii* and *E. globulus* represented at each site were also likely to have obscured the trends somewhat.

There was also wide variation between individual trees in basic density, with standard deviations in the 8-year-old trees of breast-height outerwood density from 34 to 40 kg/m^3. Outerwood density values for 8-year-old individual trees varied from 368 to 480 kg/m^3 for *E. nitens*, 365 to 484 kg/m^3 for *E. globulus,* and 460 to 603 kg/m^3 for *E. maidenii* (data not shown). A similar amount of variation was shown in the 11-year-old material from Carnation Road.

The rankings for growth traits, diameter at breast height, and height at Knudsen Road (from *E. nitens* to *E. maidenii* and then to *E. globulus*) reflect the basal area growth-ranking reported by Shelbourne *et al.* (2000). However, at Carnation Road *E. nitens* was growing in a separate trial on a part of the site with faster growth than that occupied by *E. globulus* and *E. maidenii*, and the better growth of the *E. nitens* may have been exaggerated. In any case, the selection of only 10 sample trees of each species at each site for similar diameter at breast height, and the small sample size, make any growth comparisons of the species of limited value.

Wood and Bark Properties from Discs

Basic density

Species rankings for disc densities from different heights were similar to those found for breast-height densities at the two sites (Table 2, Fig. 1) and for whole-tree density (Table 3) — i.e., basic density of *E. maidenii* was over 120 kg/m^3 (ca 27%) higher than that of *E. nitens*, with *E. globulus* intermediate but closer to *E. maidenii*. However, disc density increased with increasing height in *E. nitens*, but for *E. maidenii* increased minimally at age 8 years (Knudsen Road) and actually decreased with height at age 11 years (Carnation Road). *Eucalyptus globulus* showed a similar increase in density with height to that shown by

TABLE 2–Species means by disc height for bark thickness, diameter under bark (dub), heartwood, moisture content, green density, and basic density, at Knudsen and Carnation Roads, ages 8 and 11 years

Species	Disc height (m)	Bark thickness (mm)	Dub (mm)	Heart-wood (%)	Moisture content (%)	Green density (kg/m³)	Basic density (kg/m³)	No. of samples
Knudsen Road, Kaikohe, age 8 years								
E. nitens	0	15 b	263 a	49	161 a	1128 ab	435 b	10
E. globulus		11 c	212 b	47	143 a	1111 b	460 b	10
E. maidenii		20 a	216 b	42	110 b	1144 a	548 a	10
E. nitens	5	6 b	183 a	46 a	151 a	1088 b	434 c	10
E. globulus		6 b	148 b	44 ab	132 b	1102 b	479 b	10
E. maidenii		9 a	156 b	34 b	103 c	1150 a	570 a	10
E. nitens	10	5 b	141 a	23	143 a	1096 b	453 c	10
E. globulus		4 c	101 b	12	113 b	1085 b	512 b	10
E. maidenii		7 a	125 b	9	99 b	1168 a	589 a	10
E. nitens	15	4	84	0	123 a	1075	482 b	10
E. globulus		3	80	0	102 b	1094	545 a	4
E. maidenii		4	81	0	88 c	1094	582 a	10
Carnation Road, Kaikohe, age 11 years								
E. nitens	0	18 ab	321 a	60 a	143 a	1123 b	463 c	10
E. globulus		15 b	267 b	56 ab	119 b	1133 ab	519 b	10
E. maidenii		20 a	259 b	50 b	98 c	1144 a	578 a	10
E. nitens	6	8 b	223 a	57 a	152 a	1080 b	430 b	10
E. globulus		9 b	187 b	48 b	108 b	1129 a	546 a	10
E. maidenii		12 a	187 b	44 b	96 b	1122 a	574 a	10
E. nitens	11	6 b	188 a	50 a	141 a	1074 b	448 b	10
E. globulus		7 b	144 b	31 b	104 b	1142 a	562 a	10
E. maidenii		9 a	153 b	27 b	97 b	1123 a	571 a	10
E. nitens	16	5 b	141 a	28 a	131 a	1090	473 b	10
E. globulus		5 b	98 b	1 b	92 b	1093	571 a	10
E. maidenii		6 a	115 b	1 b	92 b	1085	566 a	10
E. nitens	20	4	95	2	118	1071	493	8
E. maidenii		5	79	0	91	1072	561	4

Letters following a species mean; from Tukey's multiple range test, within site/disc height. Means not sharing a letter within site/disc height, significantly different ($p \leq 0.05$). No letters indicate no significant differences.

E. nitens. These changes in density with height are in agreement with those found by Raymond & Muneri (2001) for *E. globulus* and *E. nitens* from five sites for each species in Australia, 10 trees/species/site.

Disc densities at all height positions were significantly lower for *E. nitens* than for *E. globulus* and *E. maidenii* in both trials and density of *E. maidenii* was significantly higher

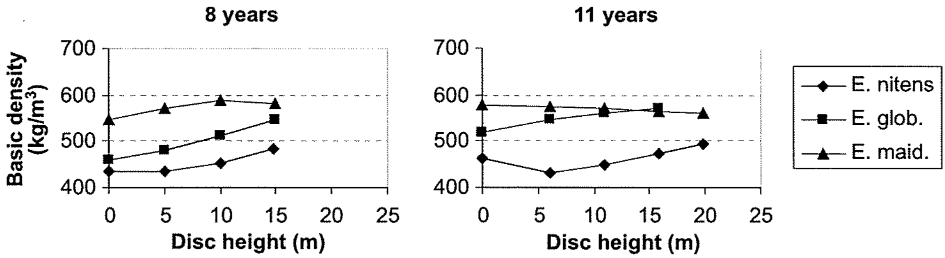

FIG. 1–Basic density changes with disc height at Knudsen Road (age 8 years) and Carnation Road (age 11 years)

TABLE 3–Basal area-weighted whole-tree species mean wood properties, at Knudsen and Carnation Roads, ages 8 and 11 years

Species	Volume (m^3)	Heart-wood (%)	Moisture content (%)	Green density (kg/m^3)	Basic density (kg/m^3)	No. of samples
Knudsen Road, Kaikohe, age 8 years						
E. nitens	0.361 a	41 a	152 a	1104 b	440 b	10
E. globulus	0.211 c	40 a	134 b	1106 b	476 b	10
E. maidenii	0.262 b	29 b	104 c	1149 a	567 a	10
Carnation Road, Kaikohe, age 11 years						
E. nitens	0.676 a	53 a	144 a	1096 b	451 c	10
E. globulus	0.423 b	46 b	111 b	1132 a	540 b	10
E. maidenii	0.440 b	39 c	97 c	1128 a	574 a	10

Letters following a species mean; from Tukey's multiple range test, within site/disc height. Means not sharing a letter within site/disc height, significantly different ($p \leq 0.05$).

than for *E. globulus* at age 8 but not at age 11 years. Whole-tree basic density values for the 8-year-old trees at Knudsen Road (Table 3) averaged 440, 476, and 567 kg/m³ for *E. nitens, E. globulus*, and *E. maidenii*, respectively, and for the older stand at Carnation Road were 451, 540, and 574 kg/m³. Jansen's (1988) earlier study of whole-tree density of five trees/species of the same three species at Knudsen Road (age 6 years) and at Clive (age 10 years) showed similar species differences.

There was large variation among individual-trees in whole-tree density (data not shown) but this was maximised by the selection of 10 trees out of 30 per species/site for a range of density. In the 8-year-old material, the range was 429–477 kg/m³ for *E. nitens*, 402–543 kg/m³ for *E. globulus*, and 520–632 kg/m³ for *E. maidenii*. In the 11-year-old trees from Carnation Road the range was 407–494 kg/m³, 502–585 kg/m³, and 547–630 kg/m³ respectively.

Results from previous studies of *E. nitens* in New Zealand for 10- to 12-year-old trees (Shelbourne *et al.* 2002), showed site mean whole-tree basic densities ranging from 419 kg/m³ in Westland to 483 kg/m³ at Golden Downs Forest in the northern South Island. Average whole-tree density for twenty 15-year-old *E. nitens* trees, grown in Kaingaroa Forest (central North Island) was 467 kg/m³ (Lausberg *et al.* 1995). The whole-tree density of 451 kg/m³ for 11-year-old *E. nitens* at Carnation Road was thus in the middle of the range. Site mean densities for 9-year-old *E. nitens* in Victoria and Tasmania varied from 428 to 563 kg/m^3 and for 5- and 7-year-old *E. globulus* varied from 460 to 570 kg/m^3 (Raymond & Muneri 2001), indicating generally higher densities, age for age, than in New Zealand.

Moisture content

For both age groups, moisture contents were inversely related to basic densities, with *E. nitens* having the highest moisture contents followed by *E. globulus* and *E. maidenii* (Table 2). The basal and 5-m discs generally showed a higher moisture content in the 8-year-old than the 11-year-old trials. Volume-weighted whole-tree values showed the same trends (Table 3). As for basic density, moisture content was more uniform up the stem in both the 8- and 11-year-old trees in *E. maidenii* than for *E. nitens* and *E. globulus*. Analysis of covariance of moisture content on dub showed that, although there were no significant within-species regressions, the apparent significant differences between species (within-site, within-disc height) were open to the interpretation that these were caused by the differences in dub.

Green density

Whole-tree green density of *E. maidenii* was significantly higher than that of *E. nitens* and *E. globulus* in the 8-year-old trial, and both *E. maidenii* and *E. globulus* had significantly higher green density than *E. nitens* in the 11-year-old trial (Table 2). There was a general trend in all species for green density to show a slight reduction with increasing height up the stem.

Diameter-under-bark and volume

For both trials (ages 8 and 11 years), dub of *E. nitens* was significantly larger, irrespective of height position, than those of *E. globulus* and *E. maidenii*, which were similar (Table 2). Mean whole-tree volume (under bark) of the 10-tree samples at Knudsen Road (age 8) averaged 0.36, 0.21, and 0.26 m^3 for *E. nitens, E. globulus*, and *E. maidenii* respectively (Table 3). Basal area of the three species, from the trial assessment at age 7 years, was 40, 21, and 30 m^2/ha respectively (Shelbourne *et al.* 2000). At the Carnation Road trial (age 11), mean tree volume of the 10-tree sample of *E. nitens* was 0.68 m^3 *vs* 0.42 m^3 and 0.44 m^3 for *E. globulus* and *E. maidenii*. By comparison, basal area at Carnation Road (age 11) averaged 46, 27, and 42 m^2/ha respectively (Shelbourne *et al.* 2000). Estimates of mean tree volume differences between species based on these 10-tree samples per site are of limited value because of the small sample size and the selection for uniform diameter. Results of the experiment-wide assessments show that the growth rates of *E. nitens* and *E. globulus* were declining whereas that of *E. maidenii* was improving with age.

Bark thickness

For both 8- and 11-year-old trees, *E. maidenii* had thicker bark than *E. nitens* and *E. globulus*, averaging 20 mm for the basal disc, reducing to 9 mm (age 8) and 12 mm (age 11) at the top of the 5- to 6-m butt log, compared with 6 and 9 mm for *E. nitens* and *E. globulus* (Table 2, Fig. 2). Bark thickness is normally correlated with tree diameter and, as the mean

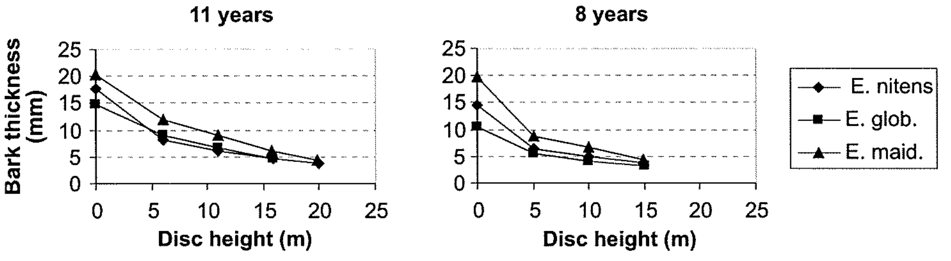

FIG. 2–Bark thickness changes with disc height at Knudsen Road (age 8 years) and Carnation Road (age 11 years)

dub of *E. maidenii* and *E. globulus* was 3–4 cm less than that of *E. nitens*, *E. maidenii*'s bark thickness can be expected to be under-estimated relative to *E. nitens*. With greater age and with increasing height up the tree, the differences in bark thickness between species tended to reduce.

There was appreciable variation between individual trees within each species in bark thickness. For instance, in the 11-year-old trees at height 6 m, bark thickness of *E. nitens* varied from 6.5 to 10 mm, that of *E. globulus* from 6 to 11 mm, and that of *E. maidenii* from 8.5 to 16 mm (data not shown). For the 8-year-old trees at Knudsen Road at height 5 m, the variation in each species was, respectively, 5–8 mm, 4.5–7 mm, and 7.5–11 mm.

Heartwood

Eucalyptus nitens had a slightly greater percentage of heartwood, particularly higher up the tree, than *E. globulus* or *E. maidenii* (Table 2, Fig. 3). All three species had proportionately more heartwood with the increased age at Carnation Road. Volume-weighted whole-tree values show the same trends (Table 3). Analysis of covariance of heartwood percentage on dub showed that, although there was no significant within-species regression, the apparent significant differences between species (within-site, within-disc height) were open to the interpretation that these were caused by the differences in dub.

Lausberg *et al.* (1995) reported whole-tree weighted values of 54% for 15-year-old *E. nitens* trees grown at Kaingaroa compared with 53% at age 11 years at Carnation Road. There was substantial variation in heartwood percentage among individual trees. In the 8-year-old trees at height 5 m, heartwood percentage in *E. nitens* varied from 27% to 56%, in

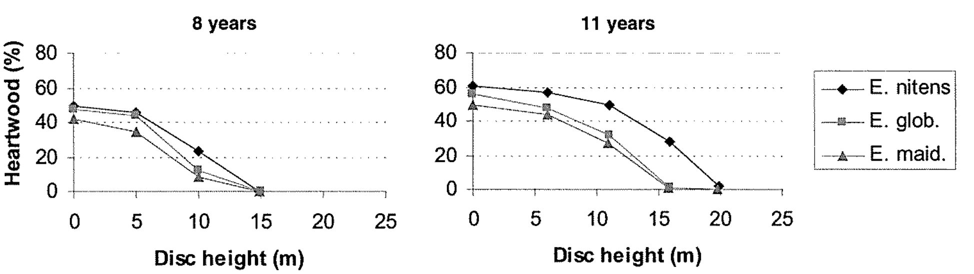

FIG. 3–Heartwood changes with disc height at Knudsen Road (age 8 years) and Carnation Road (age 11 years)

E. globulus from 35% to 65%, and in *E. maidenii* from 16% to 53%. For the 11-year-old material at height 6 m, the range for each species respectively was 47–72%, 34–57%, and 33–55%.

Prediction of Whole-tree Density from Breast-height Pith-to-bark and Outerwood Density

Regression equations were calculated based on 10 trees of each species at each site/age of dependent variable, whole-tree basic density on independent variables, breast-height pith-to-bark and outerwood density, each estimated from a single increment core/tree (Tables 4 and 5).

Breast-height pith-to-bark density proved a fairly good predictor (R^2 0.7–0.9) of whole-tree density within each species in the 8-year-old trial at Knudsen Road (Fig. 4). However, R^2 values were much lower, especially for *E. globulus*, (R^2 0.4–0.6) in the 11-year-old material at Carnation Road, with higher residual standard deviations (Table 4). The addition of more high-density outerwood with age in *E. globulus* and *E. maidenii*, will raise whole-tree density more than breast-height pith-to-bark core density, and this effect and the small sample size of 10 trees/species/site will tend to reduce correlations between pith-to-bark and whole-tree density.

TABLE 4–Within-species, within-site regressions of whole-tree density on breast height pith-to-bark density, 10 trees per species/age

Species	Intercept	Regression slope	R^2	Residual standard deviation
Knudsen Road, age 8 years				
E. nitens	11.3	1.05	0.73	12.5
E. globulus	–5.4	1.11	0.91	13.1
E. maidenii	66.5	0.96	0.89	14.9
Carnation Road, age 11 years				
E. nitens	51.4	0.97	0.59	20.4
E. globulus	163.0	0.80	0.42	22.4
E. maidenii	326.3	0.47	0.59	19.1

TABLE 5–Within-species, within-site regressions of whole-tree density on breast height outerwood density

Species	Intercept	Regression slope	R^2	Residual standard deviation
Knudsen Road age 8 years				
E. nitens	278	0.39	0.48	17.5
E. globulus	54	0.98	0.88	15.4
E. maidenii	143	0.80	0.98	6.9
Carnation Road, age 11 years				
E. nitens	160	0.71	0.65	18.9
E. globulus	289	0.49	0.46	21.5
E. maidenii	364	0.37	0.22	26.2

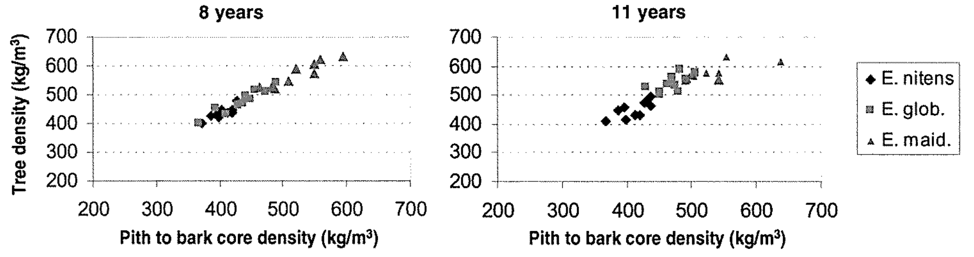

FIG. 4–Relationship between pith-to-bark density and whole-tree density by species/age group at Knudsen Road (age 8 years) and Carnation Road (age 11 years)

Within-site correlation coefficients estimated by Raymond & Muneri (2001) in Australia between whole-tree density and 1.3-m-height "core" density (a diametral strip, equivalent to a bark-to-bark core) varied from 0.57 to 0.91 for *E. globulus* aged 5–7 years, and 0.37 to 0.83 for *E. nitens* aged 7–9 years. These were similar to those estimated in this study from a single pith-to-bark core.

The prediction of whole-tree from outerwood density at breast height (Table 5) was good for *E. globulus* and *E. maidenii* at age 8, but poor for *E. nitens*. However, at age 11, R^2 were 0.46 and 0.22 between these variables for *E. globulus* and *E. maidenii*, while that for *E. nitens* was 0.65. The variable regression slopes and the often low R^2 values for these regressions are likely to be caused by the small number of sample trees, and the use of only a single increment core to sample circumferential variation in density at breast height.

Variation in Basic Density from Pith to Bark

At Carnation Road only, average basic densities of ring groups 1–5 and 6–9 (Table 6), measured on the blocks cut from the height 5-m discs of each species for measuring shrinkage, show no change from inner to outer blocks for *E. nitens*, *vs* an increase of 53 kg/m³ for *E. globulus* and 77 kg/m³ for *E. maidenii*.

These results are at variance with those from densitometry of twenty 15-year-old trees of *E. nitens* by Lausberg *et al.* (1995), which showed a decrease in density to ring 3 in the height

TABLE 6–Mean pith-to-bark basic density trends by ring groups in a 5-m-height disc from 10 trees/species at Carnation Road, age 11 years

Species	Basic density (kg/m³)			No. of samples
	Five-ring groups		Whole disc	
	1–5	6–9		
E. nitens	426 b	422 b	425 b	10
E. globulus	490 a	543 a	517 a	10
E. maidenii	512 a	589 a	541 a	10

Letters following a species mean; from Tukey's multiple range test. Means not sharing a letter within ring group, significantly different ($p \leq 0.05$).

6.1-m discs, followed by a sharp increase to ring 10 from the pith. The difference may be ascribed to the sampling by five-ring groups of this study *vs* the ring-by-ring densitometry study. Evans *et al.* (2000), in their SilviScan study of the same trees as Lausberg *et al.*, did not provide ring-by-ring density from this height level, but predicted whole-tree density at increasing ages.

A recent study on 15-year-old *E. nitens* trees grown at Golden Downs Forest near Nelson (McKenzie, Turner & Shelbourne in press; McKenzie, Shelbourne, Kimberley, McKinley & Britton in press) also showed a decrease in basic density to ring 4 from the pith, followed by an increase up to ring 14.

Species Differences in Shrinkage and Collapse at Carnation Road

Shrinkage percentage after drying to 12% moisture content in longitudinal, radial, and tangential directions, and volumetric shrinkage, were measured on the same blocks as were used to determine pith-to-bark density trends at 5-m stem height in the 11-year-old Carnation Road trees (Table 7). Shrinkage before, minus shrinkage after steam reconditioning, was used to derive "collapse" (Chafe *et al.* 1992). Some collapse was visible in washboarding of the blocks, even after steam reconditioning.

TABLE 7–Average dimensional and volumetric shrinkage, and collapse, by ring groups, from 5-m-height discs at Carnation Road, age 11 years (10 trees per species/age group)

Species	Ring group	Air-dry shrinkage (%) and collapse (%), (adjusted to 12% moisture content)									
		Longitudinal		Radial			Tangential			Volumetric	
		Before reco.	After reco.	Before reco.	After reco.	Collapse	Before reco.	After reco.	Collapse	Before reco.	After reco.
E. nitens	1–5	0.02	−0.18	3.9 b	2.0	1.9 b	16.5 b	6.2	10.3 b	15.1 b	7.7
E. globulus	1–5	−0.02	−0.08	2.7 a	2.4	0.3 a	10.9 a	7.0	3.9 a	11.2 a	8.3
E. maidenii	1–5	−0.02	−0.14	2.2 a	2.1	0.2 a	9.9 a	6.6	3.3 a	11.2 a	8.3
E. nitens	6–9	−0.03	−0.29 b	7.1 b	2.3 a	4.8 c	17.1 b	6.6 a	10.6 c	23.3 b	9.6 a
E. globulus	6–9	0.02	−0.03 a	5.0 a	3.4 b	1.7 b	13.7 a	8.0 b	5.7 b	17.7 a	11.4 b
E. maidenii	6–9	−0.06	−0.03 a	3.9 a	3.5 b	0.4 a	10.4 a	7.7 b	2.7 a	14.6 a	11.6 b

Letters following a mean, from Tukey's multiple range test. Means not sharing a letter within ring group, significantly different ($p \leq 0.05$). Adjustment to 12% mc by: Adjusted shrinkage = shrinkage /(30-mc)*18

Longitudinal shrinkage was negligible, with no significant differences between species. Some minor expansion occurred after steam reconditioning. *Eucalyptus nitens* showed significantly higher levels of radial and tangential shrinkage before steam reconditioning than *E. globulus* and *E. maidenii* — e.g., tangential shrinkage for *E. nitens* averaged 17% in the outer four rings *vs* 14% for *E. globulus* and 10% for *E. maidenii*. Radial shrinkage in those rings was much less — 7, 5, and 4% respectively. After steam reconditioning, radial shrinkage for all species decreased to between 2.0% and 2.4% at rings 1–5 and from 2.3% to 3.5% for rings 6–9; tangential shrinkage decreased to 6–7% for rings 1–5 and 7–8% for rings 6–9.

Collapse for all species (Table 7) was much higher in the tangential than in the radial direction, and was far higher for *E. nitens* (10.6% in rings 6–9) than for *E. globulus* (5.7%) which in turn was much higher than in *E. maidenii* (2.7%).

Between-tree variation was especially large in *E. nitens* in tangential shrinkage before reconditioning. The averaged individual-tree values (of the two samples of rings 1–5 and 6–9) varied from 10% to 23% for *E. nitens*, from 9% to 15% for *E. globulus*, and from 7% to 13% for *E. maidenii*. Tangential shrinkage in 15-year-old *E. nitens* (McKenzie, Turner & Shelbourne in press; McKenzie, Shelbourne, Kimberley, McKinley & Britton in press) showed similar large variation among individual trees and was moderately correlated with checking and collapse, scored subjectively on butt-log boards.

Shrinkage values after steam reconditioning recorded here are comparable with earlier results documented for New Zealand-grown *E. nitens* in which radial and tangential shrinkage after steam reconditioning averaged 3.0% and 5.7% respectively at 12% moisture content (Haslett & Young 1992).

Spiral Grain

Spiral grain was measured on alternate rings from pith to bark on the 5-m disc from 11-year-old Carnation Road trees of each species (Table 8). Absolute rather than directional values have been averaged to calculate species means, as the magnitude of the grain angle is relevant rather than grain direction. For *E. nitens*, nearly every ring measured of each tree showed negative angles. For *E. globulus* and *E.maidenii*, about half the ring/tree values were positive and half were negative angles, and about half the trees showed predominantly positive or negative angles in the four ring positions. The tree with the highest spiral grain angle in *E. nitens* had a mean angle (over four ring positions) of 5.8°, whereas the corresponding highest value for *E. globulus* was 2.8° and for *E. maidenii* was 2.4°. Mean spiral grain angles did not differ significantly between species, and angles for most trees were low compared to those in *Pinus radiata* D.Don corewood (Cown *et al.* 1991). The low levels found for the three species here (in admittedly young trees) indicate that this property is unlikely to have much impact on their utilisation. For *E. nitens*, the angles recorded here agree well with those of earlier studies on 15-year-old trees from Kaingaroa (Lausberg *et al.* 1995) and from Nelson (McKenzie, Turner & Shelbourne in press; McKenzie, Shelbourne, Kimberley, McKinley & Britton in press).

TABLE 8–Average within-tree patterns of spiral grain by species at height 5 m, age 11 years, Carnation Road.

Species	Spiral grain (°) by ring number from the pith				No. of samples
	2	4	6	8	
E. nitens	2.3 a	3.1 a	2.7 a	1.7 a	10
E. globulus	1.3 a	1.3 a	1.2 a	2.9 a	10
E. maidenii	1.5 a	1.7 a	2.3 a	2.1 a	10

Letters following a mean were produced by Tukey's multiple range test. Means not sharing a letter are considered to be significantly different.

Internal Checking

All 10 trees of *E. nitens* were affected by internal checking (Table 9) but showed considerable variation between trees in the number of checks recorded, number of rings affected, and severity score. Numbers ranged from three checks in one growth ring to a maximum of 104 checks contained within four growth rings. Other samples had fewer checks but up to five growth rings affected. The most susceptible growth ring was ring 5 from the pith, located near the heartwood-sapwood boundary. The severity score averaged 2.3 for *E. nitens* (2 = checks greater than 2 mm in width but still contained within the growth ring). Only one tree of *E. globulus* and no trees of *E. maidenii* showed checking.

These results from 11-year-old trees indicate little checking at height 6 m in *E. globulus* and none in *E. maidenii* at this age. However, Washusen *et al.* (2000), in a utilisation study on 15-year-old *E. globulus* grown in the southern Murray-Darling Basin in Victoria, found little prospect for production of high-quality solid wood products, mainly owing to surface checking, internal checking, distortion, and splitting. Personal observation (by Shelbourne) of dried and machined lumber, including laid flooring, sawn from 40-year-old *E. maidenii* grown in Auckland, showed no signs of surface or internal checking.

TABLE 9–Internal checking of 6-m-height discs (checked trees only) at Carnation Road, age 11 years

Species	Tree No.	Total No. of rings affected	Total No. of checks	Ring position (average)	No. of checks/ring (average)	Severity score (average)
E. nitens	31	4	15	4.8	2.5	3.2
	32	1	20	5.0	6.7	2.3
	33	4	55	4.5	6.9	2.0
	34	4	104	4.7	11.6	2.3
	35	4	48	4.8	8.0	1.7
	36	1	3	5.0	1.0	2.7
	37	5	29	5.4	3.6	2.1
	38	3	29	4.3	4.8	2.5
	39	5	44	6.0	7.3	1.8
	40	5	22	4.9	2.4	2.2
	Mean	4	37	4.9	5.5	2.3
E. globulus	44	1	8	5.0	4.0	2.5
E. maidenii	–	–	–	–	–	–

Mechanical Testing of Small Clears for MoE, MoR, and Hardness

Arithmetic, unweighted means of up to six test sticks per tree (from height 5-6 m) were calculated for each species from static bending and hardness tests (Table 10), both at equilibrium moisture content of approximately 14% and after adjustment to 12% mc (Wangaaard 1950). Only an average of 4.4 sticks per tree of each species were tested (instead of six per tree) because many had defects at point of failure, and these data were rejected. Because of the unbalanced numbers of test sticks per tree, the individual test-stick data for nominal density, MoE, MoR, and hardness (unadjusted for moisture content) were analysed to provide least squares means. These were estimated for each species (Table 11), for the three radial positions for each species (Table 12), and the range, mean, and coefficient of variation for individual trees of each species for the outer radial position only (Table 13).

TABLE 10–Arithmetic means of mechanical properties of small-clear test sticks of *E. nitens*, *E. globulus*, and *E. maidenii*

Property	Species means (at emc 14%)			Species means (adjusted to 12% mc)		
	E. nitens	*E. globulus*	*E. maidenii*	*E. nitens*	*E. globulus*	*E. maidenii*
Number of specimens tested	44	44	43	44	44	43
Moisture content (%)	13.8	14.2	14.1	12	12	12
Nominal density (kg/m^3)	496	591	618	500	598	625
Fibre stress at proportional limit (MPa)	46.2	60.6	67.5	49.5	65.9	73.2
Modulus of rupture (MPa)	81.4	110	118	87.3	120	128.1
Modulus of elasticity (GPa)	8.7	12.0	12.6	9.0	12.4	13.0
Work to proportional limit (kJ/m^3)	13.9	17.3	20.5			
Work to maximum load (kJ/m^3)	92	143	174			
Work to total load (kJ/m^3)	190	261	328			
Number of specimens tested	59	58	54			
Hardness on sides (N)	3615	4959	5639	3810	5286	5994

TABLE 11–Least squares species means of nominal density, MoE, MoR, and hardness (at emc)

Species	Density (kg/m^3)	MoE (GPa)	MoR (Mpa)	Hardness (kN)
E. nitens	499 b	8.6 b	82 b	3.61 c
E. globulus	587 a	11.8 a	109 a	4.96 b
E. maidenii	613 a	12.2 a	115 a	5.68 a
5%LSD	38	1.1	10	0.70

Values followed by the same letter do not differ significantly ($p \leq 0.05$)

TABLE 12–Least-squares radial-position means for nominal density and basic mechanical properties (at emc)

Species	Property	Mean radial position 1 (pith)	Mean radial position 2	Mean radial position 3 (bark)
E. nitens	Density (kg/m^3)	482	486	528
	MoE (GPa)	7.8	8.5	9.6
	MoR (MPa)	77.8	79.4	88.1
	Hardness (kN)	3.40	3.39	4.03
E. globulus	Density (kg/m^3)	551	573	636
	MoE (GPa)	10.1	11.6	13.7
	MoR (MPa)	97.8	107.0	122.4
	Hardness (kN)	4.32	4.70	5.86
E. maidenii	Density (kg/m^3)	568	606	664
	MoE (GPa)	10.0	12.0	14.5
	MoR (MPa)	100.3	113.8	130.5
	Hardness (kN)	4.68	5.43	6.92

TABLE 13–Species range, mean, and standard deviation of least squares tree means of test sticks for the outer radial position (rings 7–9) (at emc)

		Nominal density (kg/m^3)	MoE (GPa)	MoR (MPa)	Hardness (kN)
E. nitens	Maximum	582	10.9	101	5.3
	Minimum	471	7.7	71	3.1
	Mean	528	9.6	88.1	4.03
	Std dev.	31.9	1.0	9.2	0.66
E. globulus	Maximum	712	15.2	135	6.7
	Minimum	609	11.4	109	5.1
	Mean	636	13.7	122.4	5.86
	Std dev.	40.8	1.2	10.2	0.69
E. maidenii	Maximum	761	17.0	157	8.5
	Minimum	601	12.4	115	5.9
	Mean	664	14.5	130.5	6.92
	Std dev.	47.1	1.3	13.0	0.90

Relativities for different strength properties closely paralleled the arithmetic and least squares mean nominal densities of *E. nitens, E. globulus*, and *E. maidenii* of 499, 587, and 613 kg/m^3, respectively (Tables 10, 11). Both *E. globulus* and *E. maidenii* were substantially stiffer, stronger, and harder than *E. nitens*. Corresponding MoE values were 8.6, 11.8, and 12.2 GPa. The nominal density values are an approximate function of mean basic densities of the height 6-m discs, which were 430, 546, and 574 kg/m^3 respectively (Table 2). Arithmetic mean MoE of all test sticks of this 11-year-old *E. nitens*, after adjustment to 12% mc, was 8.95 GPa, which compared with 9.9 GPa for 15-year-old trees from Golden Downs (McKenzie, Turner & Shelbourne in press; McKenzie, Shelbourne, Kimberley, McKinley & Britton in press), sampled similarly at height 6 m.

The three radial positions, from which the test sticks were taken, correspond approximately to rings 1–3, rings 4–6, and rings 7–9 from the pith, at height 5–6 m. The least-squares radial position means of the three mechanical properties MoE, MoR, and hardness (Table 12) showed a substantial pith-to-bark increase over this small number of growth rings. *Eucalyptus nitens* showed a smaller increase in nominal density (9.5%) than *E. maidenii* (17%) and a smaller relative increase in mechanical properties. All radial positions could be regarded as lying within the corewood zone but the outermost position would give strength properties closest to those of sawn timber from logs of mature trees. Mean MoEs for this position were 9.6 GPa for *E. nitens*, 13.7 GPa for *E. globulus*, and 14.5 GPa for *E. maidenii*. Corresponding MoR values were 88, 122, and 131 MPa, respectively. By comparison, in a *P. radiata* family test in Kinleith Forest, small clears removed from rings 9 and 10 from the pith at breast height had a mean MoE of 6.3 GPa and mean MoR of 63 MPa (S. Kumar & J. Lee unpubl. data).

The variability in mechanical properties among trees of each species can be appreciated from the maximum and minimum values, and standard deviations in Table 13. Differences between species mean values for *E. nitens* and *E. maidenii* generally exceeded the range within species.

Estimates of percentage variance components from analysis of variance (Table 14) and the range of individual-tree values for each species showed that, for *E. globulus* and *E. maidenii*, the variance due to radial position was greater than among-tree variance for all properties, and particularly so in the case of MoE. For *E. nitens*, variance due to radial position for density, MoR, and hardness was much smaller than among-tree variance, and for MoE it was roughly equal to that between trees. This reflects the rather small increase in density from pith to bark in the trees of this species. The variation "within radial position × tree" was substantial for each species for all properties, reflecting real circumferential variation as well as minor "noise". If these traits are heritable, and wood density has shown moderate to high heritabilities (Muneri & Raymond 2000; Kube *et al.* 2001; Gea *et al.* 1997), gains from genetic selection should be possible. However, the within-species correlations of height 6-m disc density and MoE for *E. nitens*, *E. globulus*, and *E. maidenii* respectively were 0.72, 0.66, and 0.87, and with MoR were 0.74, 0.27, and 0.77. Density was thus far from being a perfect predictor of MoE or MoR.

TABLE 14–Variance component estimates from analyses by species, as a percentage of total variance

Species	Property	Variance component (%)			
		Between trees	Between radial positions	Tree × radial position	Within radial position × tree
E. nitens	Density (kg/m^3)	38**	27**	0	36
	MoE (Gpa)	25*	28*	0	47
	MoR (Mpa)	43**	17*	0	40
	Hardness (kN)	56**	17**	5	22
E. globulus	Density (kg/m^3)	21*	33**	0	46
	MoE (Gpa)	11	46**	13	30
	MoR (Mpa)	18**	40**	13	30
	Hardness (kN)	24**	42**	10	24
E. maidenii	Density (kg/m^3)	28**	35**	10	27
	MoE (Gpa)	7*	57**	14	22
	MoR (Mpa)	22*	42**	7	30
	Hardness (kN)	27**	50**	7	16

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

Relationships Between Shrinkage, Density, and Checking

The possibility of predictive relationships between wood properties (basic density and heartwood percentage) and wood-drying characteristics (shrinkage, collapse, and checking) was investigated. Correlations were estimated for each species (based on only 10 trees / species) for air-dry shrinkage and radial and tangential collapse with density, for ring groups 1–5 and 6–9. Most correlations of density with longitudinal, radial, and tangential shrinkage, before and after reconditioning, were weak and non-significant except for *Eucalyptus maidenii* correlations of density with radial shrinkage before and after reconditioning in rings 6–9, and likewise for tangential shrinkage (0.65 to 0.73, significant at $p \leq 0.05$). Thus, within

E. maidenii the higher density trees showed greatest shrinkage. Correlations within *E. nitens* of radial and tangential collapse with disc density were 0.72 and 0.67 respectively (significant at $p \leq 0.05$).

For *E. nitens* only, correlations were also estimated between internal checking and heartwood percentage, basic density, and longitudinal, radial, tangential, and volumetric shrinkage before reconditioning, and with radial and tangential collapse (Table 15). Internal checking was characterised by number of rings with checking and total number of checks. The only significant ($p \leq 0.05$) correlations between checking and longitudinal shrinkage before steam reconditioning, were between number of rings with checks and longitudinal shrinkage ($r = 0.72$) and between number of rings with checks and heartwood percentage ($r = 0.66$). Neither checking measure was significantly correlated with whole-tree density or with radial and tangential collapse.

TABLE 15–Simple correlation coefficients between selected wood properties and internal checking in *E. nitens*

Internal checking	Heart-wood (%)	Basic density (kg/m^3)	Shrinkage before reconditioning				Collapse	
			Long.	Radial	Tang.	Vol.	Tang.	Radial
No. of rings with checks	0.66*	–0.23	0.72*	0.19	0.43	0.58	0.43	0.29
Total No. of checks/disc	0.51	–0.37	0.22	–0.17	0.31	0.18	0.33	0.04

* significant at $p \leq 0.05$

These results (based on only 10 trees) were somewhat at variance with those on 15-year-old *E. nitens* of McKenzie, Turner & Shelbourne (in press) and McKenzie, Shelbourne, Kimberley, McKinley & Britton (in press). In that study of 15 trees, collapse, subjectively scored in butt log boards, showed moderate correlations with cross-sectional area shrinkage in boards and tangential and radial shrinkage in disc blocks. Checking in discs was strongly correlated with collapse in boards and weakly with tangential and radial shrinkage in outerwood.

CONCLUSIONS

The principal conclusions that can be drawn from this study are that young, New Zealand plantation-grown *E. maidenii* has wood properties, drying properties, and mechanical properties that are superior to those of *E. nitens* and *E. globulus*. These results indicate that *E. maidenii* shows considerable promise for production of high-quality structural- and appearance-grade lumber. Results from a limited number of comparative field trials of these species, including those from which the material for this study were taken, give some confidence that on warmer sites in the North Island, where *E. nitens* and *E. globulus* are destined to fail, *E. maidenii* shows good health and acceptable growth and form.

Some specific findings for the 11-year-old trees were:

- Whole-tree basic density of *E. maidenii*, grown in Northland, averaging 574 kg/m^3, was over 120 kg/m^3 higher than for *E. nitens* and 34 kg/m^3 higher than *E. globulus*.
- Wood basic density decreased slightly with increasing height up the tree in *E. maidenii* and increased in *E. nitens* and *E. globulus*.

- Tangential shrinkage from green to air-dry, measured from blocks cut from discs at height 5 m, averaged 17% for *E. nitens*, 12% for *E. globulus*, and 10% for *E. maidenii*.
- Corresponding tangential collapse averaged 11% for *E. nitens*, 5% for *E. globulus*, and 3% for *E. maidenii*.
- Spiral grain angles in the 5-m height discs were so low for all three species as to be unlikely to cause distortion on drying.
- Internal checking of *E. nitens* was widespread and often severe in the discs from height 6 m. Checking was confined to one tree out of 10 in *E. globulus* and was completely absent in *E. maidenii*.
- Mechanical properties measured on 20 × 20 × 300-mm test sticks from height 5 to 6 m, showed that strength and stiffness paralleled basic density differences between species, with average MoE values for outerwood of 9.6 GPa for *E. nitens*, 13.7 GPa for *E. globulus*, and 14.5 GPa for *E. maidenii*. Corresponding MoR values were 88, 122, and 131 MPa.
- Bark was thicker in *E. maidenii* than in *E. nitens*, especially at the base of the tree, and bark of *E. nitens* was a little thicker than that of *E. globulus*.
- *Eucalyptus nitens* has an appreciably larger proportion of heartwood than *E. maidenii* and a little more than *E. globulus*.

Previous studies on *E. nitens* and *E. globulus* in New Zealand and in Australia have shown growth-stress-related "sawability" problems and severe checking on drying. Severe drying degrade of appearance grade timber has been shown in *E. globulus* in Australia. The continued good growth and health of *E. maidenii* in New Zealand, combined with its lack of checking, low spiral grain angle, low shrinkage, and excellent strength and stiffness, indicate its potential suitability for solid-wood products. Longitudinal growth stresses that are found in most hardwoods, and which have been demonstrated as a serious problem in other utilisation studies of *E. globulus* and *E. nitens*, need to be evaluated as part of a future sawing study in *E. maidenii*. Its natural durability also needs to be assessed in long-term graveyard tests. It is planned to include this species in large-plot, long-term trials of eucalypts for solid-wood uses.

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