Forestry *An International Journal of Forest Research*

Institute of Chartered Foresters

Forestry 2022; **95**, 504–517, https://doi.org/10.1093/forestry/cpac007
Advance Access publication 2 April 2022

Effects of thinning on the longitudinal and radial variation in wood properties of *Eucalyptus nitens*

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Received 3 November 2021

Eucalypt plantations in Tasmania have been managed predominantly for fibre production, but there is also growing interest in the production of solid wood products. For solid wood production, stiffness and basic density are key wood properties as they define the suitability of the timber for particular products and ultimately value. To inform processing options available for targeting high value wood products there is a need to understand how wood properties vary within a tree and how thinning impacts wood quality to foster efficient processing. Three thinning trials of 20–22-year-old plantation grown *Eucalyptus nitens* were used to assess stiffness and basic density longitudinally from the base to 20 m height in the tree and radially at a fixed height of 2.5 m. Longitudinally and radially, wood properties varied more within the tree than the variation which arose as a result of thinning. Stiffness was lowest at the bottom of the tree irrespective of thinning treatment and the highest stiffness was located from 7.5 to 15 m height depending on thinning and site. Commercial thinning to 300 trees ha^{-1} had no effect on stiffness in the bottom of the tree but resulted in lower stiffness in the upper logs. Trees in thinned stands had slightly lower basic density and that reduction was consistent within the tree and across sites. Thinning resulted in significant radial change in wood properties and the thinning effect was apparent soon after the thinning treatment. The results demonstrate that thinning has an adverse impact on wood properties, but not to a degree that hinders the benefits thinning brings to maximizing wood growth. However, the high variation in wood quality within the tree suggests that it would be valuable segregating logs within a tree to maximize solid wood product value.

Introduction

Eucalyptus nitens is commonly planted in cool temperate zones (Forrester et al. 2013). Most plantations are established to produce pulpwood, but this species is also considered to have potential for solid wood products (Hamilton et al. 2011; Forrester et al. 2013). A substantial plantation resource of around 18 000 ha of *E. nitens* has been established in Tasmania and is being managed for solid-wood products (Sustainable Timber Tasmania 2019). Managing eucalypt plantations for the production of solid wood on short rotations requires their planting at high stand densities to establish good form and then selective thinning to increase individual tree size and a greater volume of sawlogs suitable for processing (Gerrand et al. 1997; Nolan et al. 2005; Wood et al. 2011; Forrester et al. 2013). In Tasmania, commercial thinning is done in ages of 7–12 years when trees are large enough to allow a commercial pulpwood harvest and an early financial return (Candy and Gerrand 1997; Wood et al. 2009; Beadle et al. 2011; Sustainable Timber Tasmania 2019) with the objective of achieving suitable log size for the remaining trees within the planned 20–25 years rotation (Gerrand et al. 1997; Wood et al. 2009).

There are several wood properties that are important for grading and pricing of eucalypt timber. These include dimensional stability, log end splitting, warp and drying collapse (McKenzie et al. 2003; Washusen et al. 2008). Stiffness is also an important property for grading eucalypt timber (Dickson et al. 2003; Farrell et al. 2012; Blackburn et al. 2018) and basic density is an important indicator of stiffness, as well as hardness, strength and workability (Baillères et al. 2008).

Handling Editor: Dr. David Auty

Wood properties are known to change radially from the pith to the outside of the tree, and longitudinally with height. As this variation can be large in fast-growing plantation trees, knowledge of how wood properties vary within trees is critical for the optimal utilization of wood as a raw material (Zobel and Van Buijtenen 1989). An ability to estimate the proportion of fit-for-purpose wood properties in a stand, tree or log can be used to manage wood harvesting and maximize forest value (Lachenbruch et al. 2011; McGavin et al. 2014; West 2014). To create an understanding of how to best exploit harvested logs, this study examines the longitudinal variation in basic density and stiffness in 2.5 m log lengths to 20 m height; it also examines the radial variation in these properties at 2.5 m height.

Two crucial properties of solid wood, basic density and stiffness are a function of the growing environment, silvicultural management and genetics (Zobel and Van Buijtenen 1989; Downes et al. 1997; Blackburn et al. 2014; Vega et al. 2020; Balasso et al. 2021; Rocha-Sepúlveda et al. 2021; Vega et al. 2021). Wood stiffness is the limiting factor that determines veneer sheet F-grade according to AS/NZS 2269.0:2012 (Standards Australia 2012) and structural timber standard AS/NZS 1720.1-2010 (Standards Australia 2010). For *E. nitens*, studies have shown that basic density first decreases and then increases with height up the stem (Purnell 1988; Lausberg et al. 1995; Beadle et al. 1996; Downes et al. 1997; Raymond and MacDonald 1998; Raymond and Muneri 2001; Shelbourne et al. 2002; McKenzie et al. 2003), and that stiffness increases with increasing height; consequently the upper logs tend to have higher stiffness (McKenzie et al. 2003; Valencia 2008; Washusen et al. 2009; Blakemore et al. 2010; Farrell et al. 2012; Balasso et al. 2019). In some studies (McKimm and Ilic 1987; Lausberg et al. 1995; McKenzie et al. 2003), basic density decreased radially from the pith until ring 4 and then increased with distance through the outer wood, in others there was no initial decrease but stiffness increased continuously from the pith to the outer wood (Blakemore et al. 2010; Medhurst et al. 2012; McGavin et al. 2015; Vega et al. 2020). This study extends this knowledge by examining these changes to much greater heights in the stem in stands that have also been subjected to thinning. Earlier studies indicated that thinning has no effect on basic density in *E. nitens* (Munoz et al. 2010; Bravo et al. 2012; Medhurst et al. 2012; Gendvilas et al. 2021a) but that it can reduce wood stiffness (Bravo et al. 2012; Gendvilas et al. 2021a). An understanding of how thinning influences the pattern of within-tree variation of basic density and stiffness remains limited so far, particularly in eucalypts.

The aim of this study was to examine the variation in basic density and stiffness of *E. nitens* within the tree and the impacts of thinning on those same wood properties at three contrasting sites in Tasmania, to inform wood processing strategies based on wood quality.

The specific objectives of this study were to:

1. Examine the longitudinal variation in wood property traits and whether this is impacted by commercial thinning within the tree from the base to 20 m height, and to
2. Examine how commercial thinning affects radial variation within the tree from the pith to the outer wood at a height above ground of 2.5 m.

Methods

Site description and experimental design

Three 20–22-year-old stands of *E. nitens* at Urana, Florentine and Gads in Tasmania, Australia were selected for this study (Table 1) (Gendvilas et al. 2021a). *E. nitens* grown in Tasmania originate from a single region on mainland Australia, the Central Highlands of Victoria (Hamilton et al. 2008). The plantations were established using standard nursery stock from an open pollinated seed source. The stocking at planting was 1100 trees ha $^{-1}$, and the best formed dominant and codominant trees (300 trees ha $^{-1}$) at all three sites had been pruned in three stages to a maximum height of 6.5 m between ages 3 and 5 years (Gendvilas et al. 2021a).

At either age 8 or 9 years, a commercial thinning treatment was performed 'from below' where small trees were removed to reduce the stand density to a target final stocking of 300 trees ha^{-1} (Table 1). Mortality in the unthinned control treatment at Urana was greater than in the control treatments at Florentine and Gads (Table 1 and Appendix 1). On all three sites, there were four replicates for the control and thinned treatments except for the thinning treatment at Florentine which had three replicates.

Tree selection

The pruned trees within each replicate were ranked in order from the smallest to largest DBH (diameter at breast height, 1.3 m above ground level) and split into three size classes (small, medium, large) based on DBH. A stratified, random sampling approach was then used to select two trees for felling within each size class, totalling six trees per replicate. As the Florentine thinning treatment had three replicates, eight trees were selected from each, two small, four medium and two large in order to have a balanced number of 24 trees from all treatments. The stratified random sampling ensured that the full range of tree diameters were included. Size class itself was not a variable of interest but used as a co-variate in the analysis.

Work in forest

All trees were felled manually with a chainsaw in June–July 2019, delimbed and cut into up to 13 2.5-m logs per tree. To ensure consistency across the experiment, eight logs were assessed from each tree. Stump height averaged 300 mm. Log lengths were remeasured to centimetre accuracy. A Director HM-200 'Hitman' (Fibregen, Christchurch, New Zealand) was used to assess log acoustic wave velocity (AWV) within 1 week of felling; the average temperature during these measurements was 6.4°C, 6.0°C and 5.3°C at Urana, Florentine and Gads, respectively.

For the longitudinal wood property assessments (Figure 1), a cross-sectional 50 mm thick disc was cut at stump height, at 2.5 m height, and then at successive 2.5 m intervals up the tree. Two extra discs at 2.5 m height were cut for radial wood property assessments (Figure 1). To avoid moisture loss, each disc was numbered and sealed in a plastic bag immediately after cross-cutting. Within 4 days of felling, the diameter of each disc was measured with and without bark. All discs, except the two for radial assessments, were split with an axe into four

Table 1 Site and treatment description of *Eucalyptus nitens* thinning trials in Tasmania.

	Urana		Florentine		Gads	
Location	41°20′57.0″S 148°02′54.8″E		42°36′22.0″S 146°28′09.5″E		41°34′22.9″S 146°12′13.8″E	
Elevation (m, asl.)	400		400		700	
Rainfall (mm yr^{-1})*	1101		1332		1556	
Mean annual temperature °C*	11.4		10.3		9.4	
Coupe planted (year)	1997		1999		1999	
Thinning code	Control	EC300	Control	EC300	Control	EC300
Replicates	4	4	4	3	4	4
Thinning age (year)	N/A	8	N/A	8	N/A	9
Stocking in 2019 (trees ha^{-1})	579 (36)	316 (28)	941 (6)	283 (30)	1045 (24)	315 (14)
Mortality up to 2019 (%)	44 (7)	16 (4)	15 (9)	5 (2)	7 (4)	6 (9)
Height (m)	33.5 (0.5)	32 (0.5)	34.8 (0.7)	36.5 (0.5)	30.7 (0.6)	29.4 (0.5)
DBH (cm)	32.2 (0.4)	37.1 (0.6)	30.2 (0.3)	38.7 (0.7)	27.1 (0.3)	35.8 (0.5)
H/DBH (m m^{-1})	106 (3)	89 (3)	118 (3)	96 (3)	115 (2)	83 (2)

*Temperature and precipitation data from trial planting date until 2018 were extracted for the trial site using the 'BgetAWAP' function of the 'AUSclim' package (P.A. Harrison unpublished R package); Standard error in brackets; EC300 is commercial thinning to 300 trees ha^{-1}.

quarters (Figure 1). One quarter of each split disc was weighed to 1 g accuracy using portable scales. The split disc quarters were subsequently stored in sealed plastic bags in a cold room at 5°C for up to 3 weeks (longitudinal assessments) and the two full discs for 2 months (radial assessments).

Basic and green density, log MOE measurements

Disc quarter (wedge) basic density was determined as described in AS/NZS 1080.3:2000 (Standards Australia 2000), and wedge green volume by water displacement (Heinrichs and Lassen 1970). Dry mass was measured after oven drying at 103 ± 2°C until the wedge reached constant mass. Basic density was calculated as the ratio of oven dry mass (kg) to green volume (m^3), and green density as the ratio of green mass (kg, measured in the forest) to green volume (m^3).

To account for taper when calculating log density, more weight should be given to the density of the disc at the large end; average wedge densities were therefore calculated using formula (1) (Kimberley et al. 2015):

$$D_{log} = WD_{wedge,L} + (1 - W)\, D_{wedge,S} \quad (1)$$

where $WD_{wedge,L}$ and $D_{wedge,S}$ are wedge basic density or green density at the large and small ends of the log, respectively, and W is the weighting factor which is a function of the ratio of the large- to small-end diameter of the log (Kimberley et al. 2015).

The MOE in GPa of logs was estimated using Equation (2) (Lai et al. 2019):

$$MOE = \rho\, v^2 \quad (2)$$

where ρ (kg m^{-3}) is the mean green density and v (km s^{-1}) is the AWV of the log.

Wood sample preparation for radial measurements

From one of each of the two discs for the radial assessment, a full diameter 50 mm-wide and 50-mm thick strip passing through the pith was cut and given a unique identification number. To minimize splitting and checking, strips were air-dried for 4 weeks in a ventilated room at 15°C. The strips were then fumigated and sent to Scion, Rotorua, New Zealand where they were conditioned for 2 months in a controlled environment at ~65 per cent relative humidity and 20°C to reach an equilibrium moisture content of ~12 per cent. The surfaces were then cut with a miter saw to create smooth and straight surfaces and an even thickness of 30 mm.

Annual ring width measurement

Each strip was scanned with an optical scanner at a resolution of 600 pixels per inch. Image J software (Schneider et al. 2012) was used to define ring boundaries based on the latewood ring and each ring width in millimetres calculated and expressed in terms of ring number from the pith.

Radial acoustic measurements and adjustment to annual rings

Ultrasonic time of flight AWV was used to assess stiffness (Mason et al. 2017; Dahlen et al. 2019; Schimleck et al. 2019). Ultrasonic time of flight AWV was measured in the longitudinal direction on the strips with a pair of transducers using the DiscBot machine (Scion, New Zealand). The strip was mounted in a frame that moved past the sensors and precisely recorded each scan position every 5 mm from the pith. A series of parallel paths 5 mm apart was traced across the sample to provide complete coverage. To avoid damage to the machine, the 10 mm-length at either end of each strip was not scanned. In total, 140 out of the 144 samples were successfully scanned.

The AWV measurements were fitted to a generalized additive model (GAM) using the *mgcv* R package (Wood 2011) with a fixed

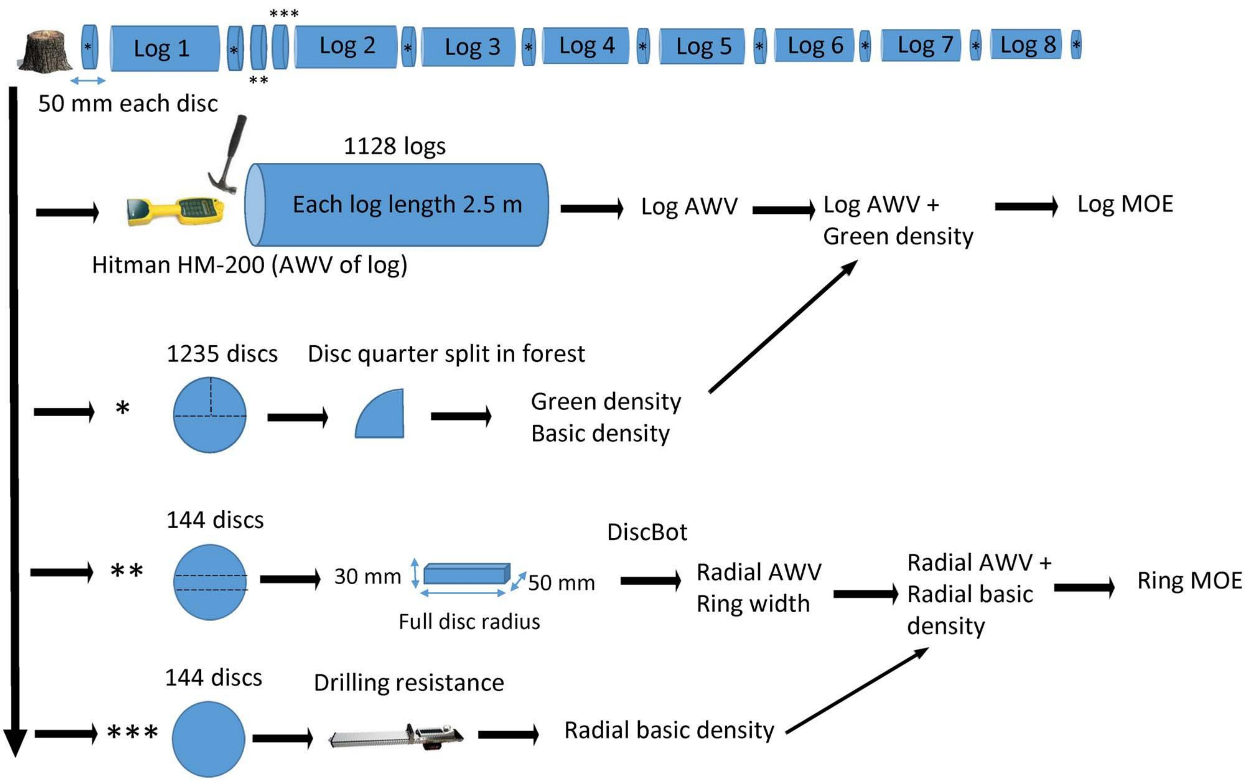

Figure 1 Tree processing description of three *Eucalyptus nitens* thinning trials.

smoothing parameter for all strips (Appendix 2). As the distance from the pith until the beginning and end of each ring was known, it was possible to allocate AWV values for each ring. The mean AWV value was calculated from the GAM model estimates for each annual ring in both directions of the strip and expressed by ring number from pith. As the edges of the strips were not scanned, there was not a complete representation of all of the outer rings. Therefore, data were truncated at ring position 16 to achieve balance for all treatments. The ring AWV values for each ring from both sides of the strip were averaged.

Annual ring basic density and MOE measurement

Drilling resistance can be used for tree-ring analyses (Rinn et al. 1996; Chantre and Rozenberg 1997; Wang and Lin 2001; Wang et al. 2003; Guller et al. 2012), but to obtain accurate basic density measurements radially when using drilling resistance, the friction effect has to be accounted for (Sharapov et al. 2017; Downes et al. 2018; Fundova et al. 2018; Gendvilas et al. 2021b). Drilling resistance of green discs from cambium to pith was obtained from a single cross-sectional trace using an IML-RESI PowerDrill © PD 400 (Resi) (IML System GmbH, Wiesloch, Germany) fitted with a new needle. Sampling conditions were 1.5 m min^{-1} speed of forward feed and 3500 rpm. The drag as the needle travels through the disc was accounted for using the semi-non-linear friction correction (Gendvilas et al. 2021b). Basic density for each ring was calculated using custom software written in R and available at: https://forestquality.shinyapps.io/FQ_ResiProcessor/. The parameters for basic density prediction, slope (6.6) and intercept (207.3), were used (Gendvilas et al. 2021a). The annual ring MOE (MPa) was estimated using equation (2), where ρ is the basic density obtained from Resi (kg m^{-3}) and v is the mean AWV (km s^{-1}) derived from the fitted GAM model from the annual rings measured using DiscBot.

Statistical analysis

Differences in radial and longitudinal variation in wood properties between thinning treatments were examined using a mixed linear model. The model had the following terms:

$$\begin{aligned} Y = \mu &+ \text{Site} + \text{Thinning} + \text{Position} + \text{Size class} \\ &+ (\text{Site} \times \text{Thinning}) + (\text{Site} \times \text{Position}) \\ &+ (\text{Thinning} \times \text{Position}) + (\text{Site} \times \text{Thinning} \times \text{Position}) \\ &+ \text{Block} : \text{Site} + \text{Plot} : \text{Block} \\ &+ \text{Tree} : \text{Site} + \text{spl}\,(\text{Position} : \text{Site} : \text{Thinning}) + \text{error} \end{aligned}$$

where Y is the observed response for longitudinal (log basic density, log AWV, log MOE and log small end diameter) and radial (ring basic density, ring AWV, ring MOE and ring width) variation, and μ is the overall mean. Site, Thinning, Position and their interactions were fixed effects. Size class was treated as a co-variate by being included as a fixed effect term only, and not included in the interaction terms. Random terms were Block nested within

Table 2 Statistics for the longitudinal and radial variation of each dependent variable in *Eucalyptus nitens* thinning trials in Tasmania. DBH class was considered as co-variate and was not included in interaction term. F-tests for fixed effects from Wald's table

Fixed effects and interactions	Longitudinal				Radial			
	Basic density	AWV	MOE	SED	Basic density	AWV	MOE	Ring width
Position	604.2***	896.9***	441.8***	6777.0***	156.0***	33856.9***	549.6***	1207.0***
Thinning	14.2***	52.6***	29.7***	115.4***	5.5*	27.6***	4.4*	42.6***
Site	20.2***	12.9**	29.6***	7.5*	16.9**	1.4 ns	3.4*	3.0 ns
Size class	0.3 ns	3.9*	2.4 ns	122.9***	1.2 ns	10.5***	0.6 ns	35.3***
Site x Thinning	0.4 ns	4.3*	2.4 ns	10.6***	0.7 ns	7.5**	1.5 ns	1.5 ns
Site x Position	2.2 ns	66.8***	76.7***	15.0***	276.8***	246.8***	12.5***	20.6***
Thinning x Position	3.3 ns	127.3***	149.0***	89.5***	9.5**	1067.5***	29.0***	94.0***
Site x Thinning x Position	2.9 ns	7.3**	1.4 ns	10.2***	1.4 ns	182.0***	1.6 ns	3.1*

Note: $*P \leq 0.05$, $**P \leq 0.01$, $***P \leq 0.001$, ns – not significant. AWV—acoustic wave velocity; MOE—modulus of elasticity; SED—log small end diameter. 'Position' for longitudinal variation is log number from bottom of the tree and 'Position' for radial variation is ring number from the pith.

Site, Plot nested within Block and Tree nested within Site. An spl (Position:Site:Treatment) is the random log or ring position trend, nested within the site and treatment, and approximated by a cubic spline (Apiolaza and Garrick 2001; Apiolaza 2009; Butler et al. 2009; Ivković et al. 2013). A spline was used to account for the nature of the non-linear trend for both radial and longitudinal variation. The spl (Position:Site:Treatment) random term significantly improved all models as found by likelihood ratio tests. As within-tree error is auto-correlated (Apiolaza 2009), in the selected model a first-order autoregressive correlation structure (AR(1)) was applied among successive annual ring or log positions to allow separate correlations and residual error variances for each site (Jordan et al. 2005; Auty et al. 2013; Moore et al. 2014). The assumptions of normality and heterogeneity for each variable were tested by visually assessing residual plots and where assumptions were not met, the log (for ring AWV and width) and square root (for ring basic density and MOE) transformations were applied. Statistical significance of the fixed effects was assessed using a Wald F-test. Analyses were undertaken with ASReml-R package version 4.1 (Butler et al. 2017) within the R environment (R Core Team 2020).

Results

Longitudinal variation

We observed significant longitudinal variation in basic density; the highest values were observed in the upper logs and the lowest most commonly in the third log (5–7.5 m) (Table 2 and Figure 2a). The difference between the lowest and highest values of basic density with position varied between 50 and 68 kg m^{-3}. Thinning was associated with a significant reduction in basic density, on average by 15 kg m^{-3}. The response patterns of basic density to position and thinning were consistent across sites. The significant differences in basic density across sites were associated with the highest value at Urana (518 kg m^{-3}), then Florentine (484 kg m^{-3}) and then Gads (459 kg m^{-3}).

There was also significant longitudinal variation in AWV. In general, AWV was highest between the third and sixth log (5–15 m) and lowest in logs one and two (0–5 m). Thinning led to a significant reduction in AWV, and this increased with log position (Table 2 and Figure 2b). The reduction was not evident until log position 7 (15 m) at Urana and Florentine and position 2 (5 m) at Gads and the reduction was greatest at Gads.

Similarly, the highest MOE was located in the mid-section of the tree between log 3 and log 6 (5–15 m). This significant longitudinal variation in MOE was influenced by thinning (Table 2 and Figure 2c), however, the reduction was not evident until log position 7 (15 m) at Urana and Florentine and position 3 (5 m) at Gads and was greatest at Gads. There was also a significant effect of site on the longitudinal variation in MOE; the increase up to the mid-positions was greatest at Urana and lowest at Gads (Table 2 and Figure 2c).

Thinning significantly increased log size (expressed as small end diameter; SED), however, the effect was a function of position and not consistent across the sites (Table 2, Figure 2d). In response to thinning, this increase diminished in the upper logs at Urana and Gads, but remained significant at all positions at Florentine (Figure 2d). The smallest incremental response at log position 1 was at Urana (27 mm) and greatest at Gads (78 mm) followed by Florentine (69 mm) and the response decreased with increasing log position, the rate depending on site (Figure 2d).

Radial variation

There was significant radial variation in basic density with position (Table 2; Figure 3). At all sites the lowest values were observed between rings 4 and 6 but the patterns towards the pith and edge differed between sites; at Urana, there was a steeper increase in radial density from ring 4 to 16 but a much smaller increase from ring 4 to ring 1, than at Florentine and Gads. Radial variation in basic density was impacted by thinning, but a significant reduction was only evident from ring position 9 to 11 at Florentine and 9 to 15 at Gads (Figure 3a). At ring 16, the mean basic densities were 522, 470 and 437 kg m^{-3} at Urana, Florentine and Gads, respectively.

Across sites, there was significant radial variation in AWV with position (Table 2); in the unthinned treatment it varied between 4.5 and 4.7 km s^{-1} at the pith and 6.0 and 6.3 km s^{-1} at the outermost rings (Table 2, Figure 3b). AWV was influenced

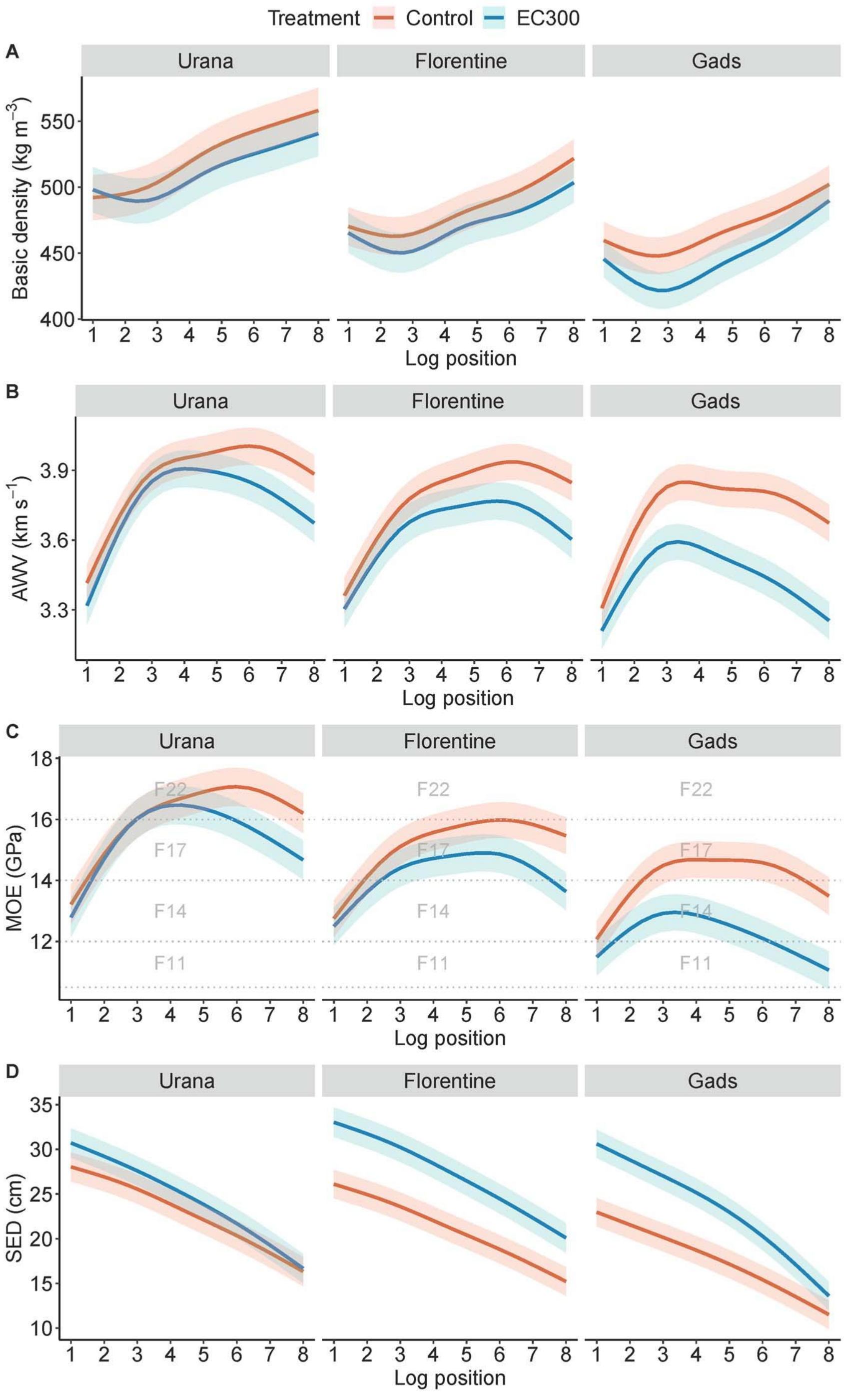

Figure 2 Longitudinal variation of wood property traits of *Eucalyptus nitens* from the stump to a height of 20 m. Red line: unthinned; and blue: thinned. Shaded line is 95 per cent confidence interval estimated from the fitted model. (A) basic density; (B) acoustic wave velocity (AWV); (C) modulus of elasticity (MOE), F-grade assigned based on MOE values according to AS/NZS 2269.0:2012 and AS/NZS 1720.1-2010 standards (Standards Australia 2010; Standards Australia 2012); (D) log small end diameter (SED).

by thinning but these effects were not consistent across sites (Table 2 and Figure 3b). A significant decrease in AWV was evident between rings 8 and 16 at Florentine and rings 4 and 16 at Gads and this decrease became greater with ring position particularly at Gads where the AWV at ring position 16 was 6.3 and 5.5 km s^{-1} in the unthinned and thinned treatments, respectively (Figure 3b). Thinning had no effect on radial AWV at Urana (Figure 3b).

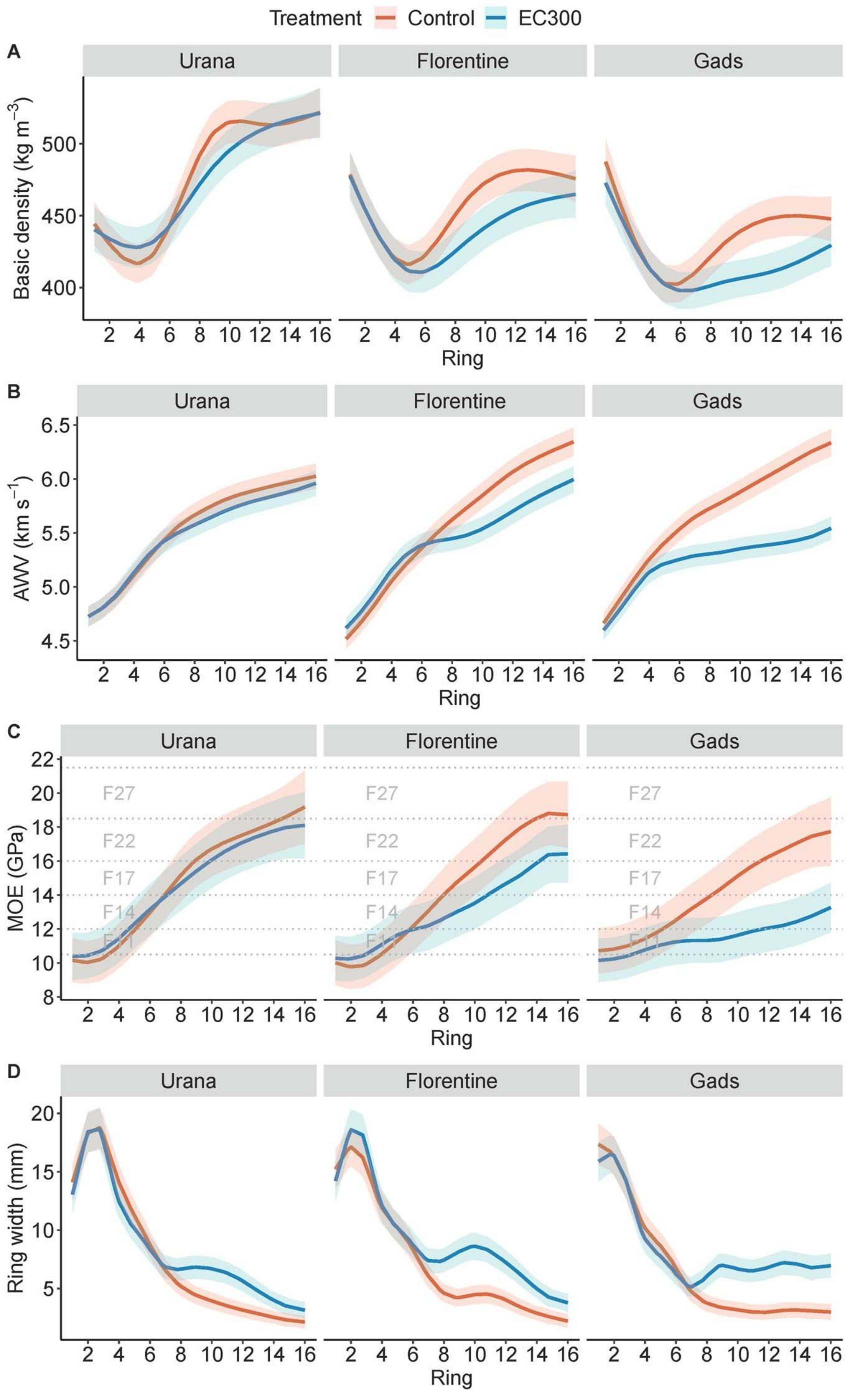

Figure 3 Radial variation of *Eucalyptus nitens* thinning trials in Tasmania. The red line is unthinned and blue thinned. Shaded line is 95 per cent confidence interval estimated from the fitted model. (A) basic density; (B) acoustic wave velocity (AWV); (C) modulus of elasticity (MOE), F-grade assigned based on MOE values according to AS/NZS 2269.0:2012 and AS/NZS 1720.1-2010 standards (Standards Australia 2010, Standards Australia 2012); (D) Ring width. Thinning treatment was imposed at the stage of formation of the eighth ring position from the pith at a height of 2.5 m.

There were significant differences in the radial variation of MOE with position (Table 2, Figure 3c). At all sites, MOE increased with ring position and in the unthinned treatment from between 10.0 and 10.7 GPa at ring 1 to 17.7 and 19.2 GPa at ring 16. Thinning affected this pattern and a significant reduction in MOE was evident at Gads between rings 9 and 16; there was no reduction with radial position at Urana and apparent reductions at Florentine beyond ring 8 were not significant (Table 2 and Figure 3c).

As expected, thinning significantly increased ring width (Table 2), the response coinciding with the silvicultural intervention when the stand was aged 8–9 years (eighth-ninth ring). However, this effect was not consistent across sites, and greater at Florentine and Gads than at Urana, and sustained for longer at Gads than Florentine (Table 2 and Figure 3d).

Discussion

This study has shown that thinning significantly affects basic density, AWV and MOE, and that the magnitude of the effect varies longitudinally and radially within the tree and is generally not consistent across sites. Changes in the longitudinal and radial values of these wood properties were always greater than in response to thinning. Thinning reduced AWV and MOE to a much greater extent than basic density, and the response was more marked in the upper than the lower log sections. Understanding this within-tree variation in wood quality traits has implications for forest growers, wood processors and timber users, and the consequences of the adopted thinning strategy on solid-wood properties and log quality are discussed further below.

The longitudinal variation in MOE indicated first an increase and then a decrease in stiffness with increasing tree height (log position). A steep increase in stiffness towards the mid-section of the tree followed by a shallower decrease in *Pinus radiata* (Waghorn et al. 2007; Watt et al. 2011), *Picea sitchensis* (Simic et al. 2019), *Cryptomeria japonica* (Yamashita et al. 2009) and *Populus* hybrids (Himes et al. 2021) suggests that this pattern is common to a wide variety of commercially grown tree species. A number of previous studies of *E. nitens* using either two, three or four logs of between 2.5 and 5.5 m in length have reported that MOE was greater in the upper than lower log(s) (McKenzie et al. 2003; Valencia 2008; Washusen et al. 2009; Blakemore et al. 2010; Farrell et al. 2012; Balasso et al. 2019), as was the case in *Pinus taeda* (Antony et al. 2012), and *Picea glauca* and *Populus tremuloides* (Sattler et al. 2013). The much greater number (eight) of 2.5 m logs used in this study showed that maximum stiffness was generally present between the third and sixth log (5 and 15 m), and that the patterns closely matched those for AWV. Microfibril angle (MFA) is inversely related to stiffness and in *E. nitens* and *Eucalyptus fastigata* it has been shown to be lowest in the mid-section of the stem at 40–60 per cent tree height (Kibblewhite et al. 2004). That the longitudinal changes in MOE were dependent on site may in part be related to differences in tree height and therefore mid-height from the ground.

Radially at 2.5 m height, MOE increased with ring position and there was some indication that the rate of increase accelerated in ages 6–8 years and then slowed in the outer rings. Other studies of *E. nitens* have found that changes in MOE or, inversely, MFA followed a similar pattern (Medhurst et al. 2012; Vega et al. 2020). For softwoods the region adjacent to the pith with low MOE prior to an increase towards the outer wood is related to its anatomical properties as ‘corewood’ or ‘juvenile wood’ (Burdon et al. 2004; Moore and Cown 2017). It has been suggested that ontogenetic changes in wood structure from pith to bark may be linked to gene expression that responds to changing hydraulic and mechanical support requirements (Lachenbruch et al. 2011).

Most commonly, basic density first decreased with height up the stem (log position) and then increased. This pattern where basic density reaches its lowest values at 20–30 per cent stem height and then increases appears common for fast-growing hardwoods such as *E. nitens* (Purnell 1988; Lausberg et al. 1995; Beadle et al. 1996; Downes et al. 1997; Raymond and MacDonald 1998; Raymond and Muneri 2001; Kube and Raymond 2002; Shelbourne et al. 2002; McKenzie et al. 2003; Kibblewhite et al. 2004), *Eucalyptus globulus* (Downes et al. 1997; Raymond and MacDonald 1998; Raymond and Muneri 2001), *Eucalyptus grandis* (Sette Jr et al. 2012; Trevisan et al. 2012), as well as *Betula pendula* (Liepiņš and Liepiņš 2017), *Populus tremula* (Heräjärvi and Junkkonen 2006; Liepiņš et al. 2017), *P. tremula x tremuloides* (Heräjärvi and Junkkonen 2006) and *Populus* hybrids (Himes et al. 2021). Basic density is a function of the relative amounts of low-density early and high-density late wood in the annual rings (Zobel and Van Buijtenen 1989; Evans et al. 2000). In this study, basic density at 2.5 m height was higher near the pith and the outer rings than in the fourth to sixth rings. While this pattern of radial variation appears consistent across tree height (Heräjärvi and Junkkonen 2006), annual ring width is not. This study indicates that the very fast early growth rates of *E. nitens* appear to be associated with the highest widths and lowest densities in rings 2–6 that result in the lower logs containing a higher proportion of low-density wood than the upper logs.

Thinning had no effect on MOE in the bottom logs. The trees had been thinned at ages 8–9 years and this lack of thinning effect on stiffness in this region may be explained by the amount of wood formed before and after thinning at various heights in the tree. The bottom logs contained at least eight rings that were formed prior to thinning and that are associated with high rates of diameter growth. Two other studies on a 22-year-old plantation stand of *E. nitens* showed that thinning at age 6 years had no effect on the MOE of sawn boards up to 5.7 m (Washusen et al. 2009) and at 1.3 m (Medhurst et al. 2012) height. That thinning has no effect on stiffness of the bottom logs offers a valuable resource from the largest diameter harvestable logs, albeit of lower than average stiffness.

In contrast, the upper logs in both the unthinned and thinned treatments had a higher MOE and stiffness associated with the larger proportion of wood formed from rings that developed later in the growth cycle. However, reductions in MOE in response to thinning occurred in upper log sections, and the magnitude was dependent on site. The greatest reduction and greatest number of log positions affected were at Gads, the high elevation site with the lowest mean annual temperature and highest rainfall and the significant reductions in AWV per log position in response to thinning matched those for MOE. Other studies (Vega 2016; Blackburn et al. 2018; Balasso et al. 2021; Vega et al. 2021) have shown that increasing elevation is associated with lower stiffness and basic densities in planted *E. nitens*; this study has shown that the thinning response is more associated with lower stiffness. A decrease in the proportion of latewood which has higher stiffness and density (Bouriaud et al. 2005; Downes and Drew 2008; Wagner et al. 2013; Knapic et al. 2014; Kharrat et al. 2019) on cooler and wetter sites (Cown and Ball 2001) coupled with greater growth post thinning will also result in reduced MOE. In addition, Watt et al. (2011) also observed that reductions in stiffness as a result of different stocking increased radially with tree height, and this may also explain why thinning had a greater effect in the upper parts of the tree in this study. Another contributing factor is tree slenderness. Thinning leads to a reduction in slenderness and lower MOE (Watt and Zoric 2010; Caballé et al. 2020; Balasso et al. 2021); trees with high slenderness have greater stiffness to prevent stem buckling (Watt et al. 2006). Greater exposure to wind load on higher elevation sites also reduces slenderness (Jacobs 1936; Wood et al. 2008; Nicoll et al. 2019) in a way that results in a greater reduction in stiffness.

The effect of thinning on log basic density was small and did not exceed 15 kg m^{-3}. That thinning has no significant effect on log basic density has been found previously for *E. nitens* (Washusen et al. 2009; Munoz et al. 2010; Medhurst et al. 2012; Gendvilas et al. 2021a) and other species (Zobel and Van Buijtenen 1989; Schneider et al. 2008; Moore et al. 2009; Hegazy et al. 2014; Mäkinen et al. 2015; Krajnc et al. 2019). In the context of this study, growing environment was the dominant factor determining log basic density.

Except at Urana where there had been poor survival in the control treatment, although not always significant, the effect of thinning at Florentine and Gads on all radial wood properties generally became visible immediately after thinning and increased with age. A similar pattern of annual increase in basic density and stiffness due to difference in stocking was observed for radiata pine (Lasserre et al. 2009; Watt et al. 2011) and basic density in *Acacia salicina* (Hegazy et al. 2014). The thinning response on wood growth radially appears to be inversely related to wood quality. For example, the largest response in wood growth radially due to thinning was at Gads where annual rings after thinning continued to be widest, while at the other sites ring width started to decrease. However, while thinning results in lower stiffness, it also makes these wood properties less variable radially. Lower variability radially results in more uniform wood which is better for solid wood processing (Beadle et al. 2011; Washusen 2011; McGavin et al. 2015).

For both plywood and structural timber based on AS/NZS 2269.0:2012 and AS/NZS 1720.1-2010, respectively (Standards Australia 2010; Standards Australia 2012), at the upper log positions thinning reduced MOE by less than a single F-grade; however, the difference between the bottom log which had the lowest MOE and those with highest MOE was three F-grade classes, from F14 to F22 or F11 to F17 (Figure 2c). Because radial variation in MOE was greater than longitudinal variation, F-grades moving from pith to edge changed by as much as five grades, from F11 to F24; however, the difference due to thinning was only one F-grade. Such high variation of MOE within a tree suggests that log segregation at harvesting offers the best means of creating greater product value as logs that do not meet the requirement for high stress-grade products can be processed for other purposes (Blackburn et al. 2018). This study shows that the bottom logs, that is, those of greatest diameter can fall into this category. In addition, further improvements in product value could be achieved by segregating products based on stiffness within log. That would influence the way logs are processed, for example cutting or peeling around the lower stiffness core.

The low stiffness in the bottom log suggests that when trees are grown for solid wood production and where the structural grade is crucial, it may be economically advantageous to cut a 2.5–5 m log from the base for appearance product like furniture. If this bottom part of the tree is pruned, the knot-free wood offers a valuable appearance product. The remaining section of the tree could then be used for purposes where knots are not critical but higher stiffness required, for example for engineered timber products. Given that wood products require different threshold requirements for size and quality, the information gained in this study can be used by wood processors to guide log allocation and wood-processing strategies.

Conclusion

This study explored the longitudinal and radial variation patterns of wood properties and the influence of commercial thinning from *E. nitens* plantations grown specifically to produce solid-wood products. This work found significant within-tree variation in wood quality and that thinning of *E. nitens* plantations is an important tool for manipulation of wood quantity and quality that influences both suitability and value of different solid-wood products. The findings of this study show that highest stiffness was located mid-section in the tree, while basic density was lowest at 20–30 per cent and then increased with tree height. Thinning reduced stiffness more than basic density but thinning had no effect at the bottom of the tree. However, the variation in both stiffness and density was far greater within the tree than due to thinning, suggesting opportunities might be advantageous for within-tree log segregation based on wood quality.

Acknowledgements

We would like to thank Hugh Fitzgerald, Rose Brinkhoff, Carlos Novoa Plaza, Ibrahim Bourbia for the assistance in the field, Thomas Baker for assistance in the field and statistical support, Brad Potts, Peter Harrison and Greg Dutkowski for statistical advice, Sustainable Timbers Tasmania's staff Crispen Marunda and Kennedy Kurwaisimba for providing information for the research trials and forest managers John McNamara and David White provided access to the trials, Rodney McCauley for felling and processing logs, John Lee and Jonathan Harrington for scanning wood strips using DiscBot machine and Chris Beadle for comments which helped to improve the manuscript. Thank you to three anonymous reviewers and editors who helped further improve the manuscript.

Data Availability

The data underlying this article will be shared on reasonable request to the corresponding author.

Conflict of interest statement

None declared.

Funding

This research was supported by the Australian Research Council Industrial Transformation Training Centre for Forest Value (grant no. IC150100004).

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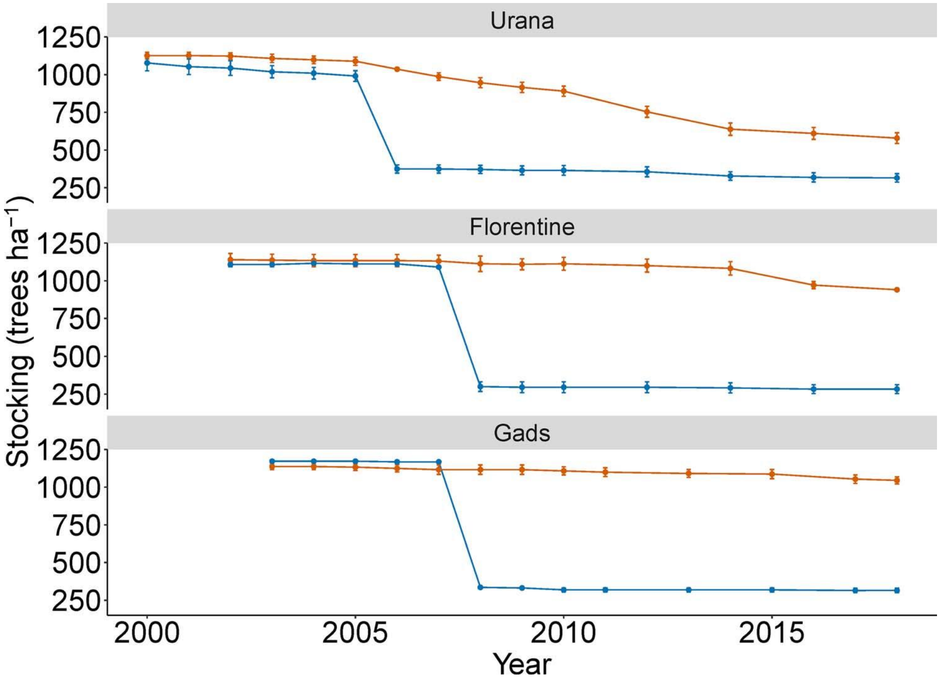
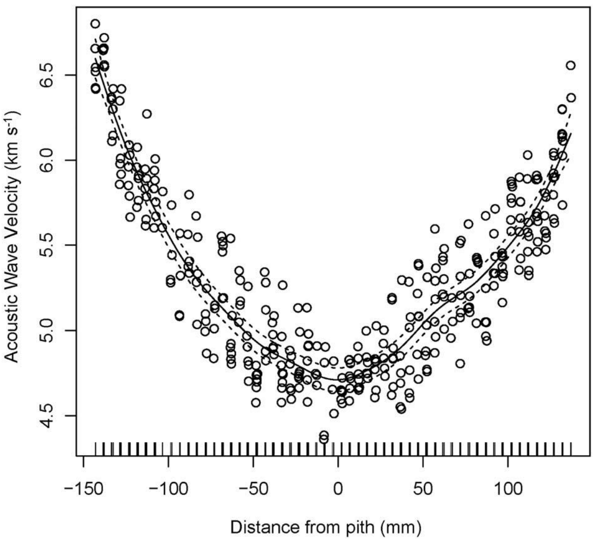


Appendix 1. Stocking rates at the three thinning trials in Tasmania, Australia, from 2000 to 2019. Each line corresponds to a different thinning treatment: Control – unthinned (red); EC300 – early commercial thinning to 300 trees ha^{-1} at age of 8–9 years (blue).



Appendix 2. An example of one out of the 140 *E. nitens* wood strips that has been scanned for ultrasonic acoustic wave velocity using the DiscBot machine. Each individual point represents a single scan point which is measured in distance from the pith. A GAM was fitted to the raw data where later predictions from the model were used to define mean value for each annual ring from known ring boundaries in distance from pith. Solid line is the mean and dashed lines are standard error of the mean from the GAM model.