The influence of heartwood extractives on wood density patterns in tree stems

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Case Report

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Abstract

Context:

Wood density varies within stems from pith to bark and base to top. Wood density is the combination of cell walls and extractives, each factor controlling different wood properties. Understanding the distribution of heartwood extractives is critical for species grown for their heartwood.

Aims:

Heartwood compounds are resource intensive to quantify by chemical extraction and have been rarely considered in studies of within stem wood density patterns. The objective was to disentangle the contributions of cell walls and extractives to within stem density patterns without the need for extraction.

Methods:

By sampling *Eucalyptus bosistoana* F.Muell. and *Eucalyptus globoidea* Blakely trees across a wide age-range, wood density of heartwood and sapwood was measured for all within-stem positions. Statistical modelling allowed to quantify the contributions of cell walls and heartwood extractives to specie-specific within-stem density patterns.

Results:

Heartwood extractives had a significant effect on wood density for the two species. The within-stem patterns differed between species and were complex.

Conclusion

Strategically sampling wood density for a wide age-range of trees allows to deduce the complex specie-specific within stem patterns of heartwood extractives and cell walls, without the laborious task of wood extraction. This improves our understanding of wood quality.

Key message

Cell walls and extractives contribute independently to wood density. The two components control different wood properties, such as strength or durability, respectively. However, extractive measurements are laborious hindering studying typical within-stem distributions. Strategic sampling of heartwood and sapwood density allowed the determination of the individual contributions to the complex within-stem wood density patterns without the need for chemical extraction.

1. Introduction

The density of wood can range from less than 100 kg m^{-3} to more than 1300 kg m^{-3} (Zanne, Lopez-Gonzalez et al., 2009). Variation is not only found between species but also within a specie. Typical species-specific radial and axial wood density gradients have been described (Schimleck, Dahlen et al., 2025). For example wood density doubles in *Eucalyptus robusta* Sm. from less than 400 kg m^{-3} at the centre base of the stem to over 800 kg m^{-3} at the periphery of the top log (Skolmen, 1972).

Wood density is in the first instant controlled by the volume of pores, i.e. cell lumen, as the cell wall material is of almost constant density (Kellogg and Wangaard, 1969). The deposition of plant cell walls is controlled by the cambium during xylem formation. For trees which form heartwood, in an independent secondary process extractives can be deposited into the porous wood structure (Hillis, 1987). As in some timber species heartwood extractives can make up close to 30% of the mass (Hillis, 1987; Fengel, 1991) the density of their sapwood, predominantly made up of cell walls, will differ from that of their heartwood, a mixture of cell walls and secondarily deposited extractives.

The two independent contributions to wood density, cell walls and extractives, affect different wood properties and consequently wood utilisation. For example, mechanical and pulp properties should be mainly affected by cell walls (Hillis, 1978; Ona, Sonoda et al., 1997), while wood features such as colour, natural durability or heating value are mainly under the control of extractives (Taylor, Gartner et al., 2002; Telmo and Lousada, 2011). Carbon sequestration is affected by both.

Separating these two independent biological processes' contributions to wood density is useful for species with higher extractive content when investigating wood quality (Hillis, 1978; Lehnebach, Bossu et al., 2019). Cell wall density was assessed for mapping pulp properties (Ona, Sonoda et al., 1997; Ona, Sonoda et al., 1998) or extractive content when investigating natural durability (Nelson and Heather, 1972). Regarding typical species-specific density patterns, this was either achieved by removing extractives by solvent extraction (Nelson and Heather, 1972; Wilkins and Horne, 1991; Ona, Sonoda et al., 1997; Ona, Sonoda et al., 1998) or focusing on young trees where heartwood formation had not started (Gonçalves, Lorensani et al., 2019). While the former is labour intensive, the latter cannot be used for older, heartwood-containing trees.

As the contribution of extractives is the difference of sapwood and heartwood density, it should, however, be possible to deduce the individual contributions of cell walls and heartwood extractives from density data. This will require local density measurements of sapwood and heartwood on all positions across the stems. These can be obtained if a wide range of tree sizes/ages is sampled for wood density and the wood type is recorded. Such a sample set became available in the course of a biomass study of *Eucalyptus bosistoana* F.Muell. and *Eucalyptus globoidea* Blakely. The objective of this study was to demonstrate that typical specie-specific patterns for cell walls and extractive content can be obtained without labour intensive solvent extraction by statistical modelling of local heartwood and sapwood density data from trees spanning a wide age/size range.

Within stem patterns of heartwood extractives have been documented (Sherrard and Kurth, 1933) and have been described to typically increase from the pith to the heartwood-sapwood boundary and being more abundant further up the stem (Hillis, 1987). Radial gradients in heartwood extractives have also been found in branches (Terrasse, Brancheriau et al., 2021). Heartwood extractives are associated with decay resistance (Hawley, Fleck et al., 1924) and durability standards regard inner heartwood as less durable than outer heartwood from old-growth trees (AS5604, 2005). It appears that these typical specie-specific heartwood extractive content patterns have not been quantitatively modelled.

Eucalyptus globoidea and *E. bosistoana* are emerging plantation species with fast-growth (Boczniewicz, Mason et al., 2022). Their dens and ground-durable heartwood (Poynton, 1979; Poynton, 1979; Bootle, 2005) is suited for structural (Guo and Altaner, 2018), out-door (Millen, Altaner et al., 2018) and biomass products. Extractive contents of up to 15% were reported for *E. globoidea* and *E. bosistoana* in their heartwood (Li and Altaner, 2019). Considering their applications, cell wall, extractive and total density are relevant properties. However, little is known about the wood density variations of these species.

2. Material and methods

2.1. Material

Stem discs of *E. bosistoana* and *E. globoidea* trees were obtained during biomass and taper studies of the species. A detailed description of the sites, trees and field sampling procedures is available elsewhere (Boczniewicz, Mason et al., 2022; Mason, Millen et al., under review). This study was based on stem discs from 74 *E. bosistoana* originating from eight sites felled when 2- to 20-years-old, and 63 *E. globoidea* trees originating from five sites felled when 7- to 29-years-old (Table 1). Stem discs were cut at variable height depending on taper increments (Boczniewicz, Mason et al., 2022) and oven-dried. Heartwood was highlighted by applying methyl orange pH indicator.

Table 1
Sites information and summary statistics of wood density data for *E. bosistoana* and *E. globoidea*. Different letters indicate Tukey HSD significance (P = 0.01) between wood types in each site.

E. bosistoana					
Sites *Coordinates*	**Number of trees**	**Tree age (years)**	**Wood type**	**Number of blocks**	**Mean wood density (sd) (kg/m^3)**
Cravens *41°26’S* *173°56’E*	12	14	SW	126	880.4 (61.0)[a]
			HW	70	952.2 (48.2)[b]
			Mix	132	945.0 (51.8)[b]
Dillon *41°66'S* *173°67'E*	3	5	SW	20	837.1 (41.0)
			HW	0	-
			Mix	0	-
Flemming *43°11’S* *172°39’E*	17	20	SW	139	849.7 (54.0)[a]
			HW	31	940.2 (46.0)[b]
			Mix	80	898.0 (53.5)[c]
Holdaway *41°39’S* *173°18’E*	7	2	SW	24	757.6 (118.7)
			HW	0	-
			Mix	0	-
Lawsons *41°43’S* *174°02’E*	15	14	SW	166	888.2 (47.8)[a]
			HW	22	985.3 (58.6)[b]
			Mix	98	957.4 (48.9)[c]
MacBeth *42°47’S* *173°11’E*	1	9	SW	10	893.6 (52.0)
			HW	0	-
			Mix	0	-
Pukaka *41°24’S* *174°00’E*	13	20	SW	157	895.1 (58.9)[a]
			HW	136	971.2 (44.7)[b]
			Mix	182	945.4 (45.1)[c]
Waikakaho *41°25’S*	6	18	SW	89	827.2 (57.1)[a]

E. bosistoana					
173°54'E			HW	80	910.9 (69.3)[b]
			Mix	91	884.5 (54.6)[c]
Total	74	2 to 20	SW	731	868.0 (65.9)[a]
			HW	339	951.1 (58.5)[b]
			Mix	582	931.3 (56.6)[c]
E. globoidea					
Sites *Coordinates*	**Number of trees**	**Tree age (years)**	**Wood type**	**Number of blocks**	
Avery *41°46'S* *174°08'E*	8	12	SW	54	639.2 (48.5)[a]
			HW	23	831.2 (43.9)[b]
			Mix	89	727.6 (78.0)[c]
Ettrick *43°47'32.0"S* *172°50'20.8"E*	26	29	SW	322	618.6 (73.3)[a]
			HW	1005	664.5 (87.4)[b]
			Mix	262	696.0 (76.4)[c]
JNL *41°02'42.7"S* *175°52'37.2"E*	5	7	SW	106	568.8 (61.2)[a]
			HW	33	701.3 (46.6)[b]
			Mix	12	644.7 (41.2)[c]
MacBeth *42°47'S* *173°11'E*	11	9	SW	118	610.5 (62.1)[a]
			HW	6	771.7 (72.9)[b]
			Mix	118	685.4 (65.3)[c]
Pukaka *41°24'S* *174°00'E*	13	17	SW	234	645.5 (51.4)[a]
			HW	330	712.6 (59.0)[b]
			Mix	220	688.1 (60.6)[c]
Total	63	7 to 29	SW	834	620.0 (67.3)[a]

E. bosistoana			
	HW	1397	679.9 (85.3)^{b}
	Mix	626	696.0 (71.6)^{c}

2.2. Density

A 2.5 cm wide full diameter strip including the pith was split from each of the 3–5 cm thick stem disc. These strips were further split into wood blocks, 2.5 x 2.5 cm in cross-section, starting with a block centred over the pith. Wood blocks were dried at 103°C before each block was weighed and the heartwood percentage of each block was estimated to the nearest 10%. The volume of each block was then determined by immersion weighing in water. Dry density was calculated as the ratio of dry mass and dry volume.

2.3. Data analysis

Data was analysed with the R software (R Core Team, 2022). For analysing the site effect on heartwood density without confounding of tree age, only heartwood samples centred at the pith within the first 0.5 m stem height were considered. Tukey HSD tests were used to test significance ($p = 0.01$) of differences between groups. Linear mixed effect models were calculated with the lmer function of the lme4 package (Bates, Mächler et al., 2015). The model for dry wood density of each species considered distance from the pith (cm), disc height (m) and heartwood (%) as well as their two-way interactions, and site as fixed effects. Potential correlations in observations taken from the same tree were accounted for by including tree as a random effect.

3. Results

The mean dry heartwood density of the *E. bosistoana* tress in this study was 951 kg m^{-3} (Table 1). Considering the published tangential movement of 0.42% per % change in moisture content (MC) (AS1720.2, 2006) and a radial to tangential movement ratio of 1 : 2, this equated to approximately 1000 kg m^{-3} at 12% MC. The mean dry sapwood density of 868 kg m^{-3} (Table 1) equated to ~900 kg m^{-3} at 12% MC.

Dry density of the *E. globoidea* heartwood was 680 kg m^{-3} (Table 1) or approximately 710 kg m^{-3} at 12% (MC) considering 0.36% per % MC change (AS1720.2, 2006). The average sapwood dry density of the *E. globoidea* trees was 620 kg m^{-3} (Table 1), equating to approximately 640 kg m^{-3} at 12% MC.

3.1. Site effect

Site means of heartwood dry density at the centre base of the stem, that is within 13 mm of the pith and below 0.5 m stem height, ranged between 902 and 1006 kg m^{-3} for *E. bosistoana* and 689 and 843 kg m^{-}

[3] for *E. globoidea*, respectively (Fig. 1). The difference among sites was statistically significant (P = 0.01) for both species.

The same analysis for sapwood suffered from limited observations at a given stem position across sites, giving low confidence in the results.

3.2. Radial and axial density patterns

The data allowed to investigate the effects of height, distance from the pith, heartwood extractives and site on dry wood density for *E. bosistoana* and *E. globoidea*. All effects including the two-way interactions between stem height, distance from the pith and extractive content were significant (Table 2). The models revealed complex typical specie-specific density patterns within the stem. Individual contributions of cell walls and extractives differed between the two species.

For *E. bosistoana* the sapwood density, i.e. the contribution of the cell walls, had negative coefficients for stem height and distance from the pith and a positive interaction term between the two (Table 2), resulting in a saddle like pattern with lower density at the top of the stem and the outer stem base (Fig. 2). The contribution of heartwood extractives increased with distance from the centre base of the stem, i.e. terms for stem height, distance to the pith and their interaction were positive (Table 2). The resulting heartwood density pattern within the stems, i.e. the combination of cell walls and heartwood extractives, was complex with the radial density gradient dependent on the height (Fig. 2).

The within stem wood density patterns of *E. globoidea* differed from those of *E. bosistoana* (Fig. 3). Sapwood density, i.e. the contribution of cell walls, increased with distance from the centre base of the stem, i.e. had positive terms for height, distance from the pith as well as their interaction (Table 2). Also, in contrast to *E. bosistoana*, heartwood extractives decreased with stem height and distance from the pith, ie heartwood related terms were negative (Table 2).

For both species, the significance of site on wood density described in section 3.1 was also reflected in the significance of site terms in this model (Table 2).

Table 2 Fixed effect estimates on within stem dry density of *E. bosistoana* and *E. globoidea*. Significance levels: * $p < 0.05$; ** $p < 0.01$ and *** $p < 0.001$.

Fixed effects	*E. bosistoana*		*E. globoidea*	
Intercept (kg m^{-3})	931***		648***	
Radius (kg m^{-3} cm^{-1})	-4.43***		7.17***	
Disk height (kg m^{-3} m^{-1})	-5.40***		3.97***	
Interaction of radius and disk height (kg m^{-3} cm^{-2} m^{-1})	0.888***		0.244***	
Heartwood (kg m^{-3})	37***		118***	
Interaction of heartwood and radius (kg m^{-3} cm^{-1})	5.43***		-2.33***	
Interaction of heartwood and disk height (kg m^{-3} m^{-1})	3.84***		-1.68***	
Site (kg m^{-3})	MacBeth	-23.6	MacBeth	-47.3*
	Pukaka	6.6	Pukaka	-69.4**
	Waikakaho	-52.0**	Ettrick	-125***
	Dillon	-88.1***	JNL	-101***
	Flemming	-52.4***		
	Holdaway	-166***		
	Lawsons	-7.65		

4. Discussion

Densities at 12% MC have been published for *E. bosistoana* heartwood from old-growth Australian forests (1100 kg m^{-3}) (AS1720.2, 2006) and heartwood from 42-year-old trees grown in Urugay (942 kg m^{-3}) (Mantero, O’Neill et al., 2014). The less than 20-year-old NZ-grown *E. bosistoana* tress in this study were with a heartwood density of ~ 1000 kg m^{-3} (section 3) denser than the timber grown in Urugay. The mean sapwood density (~ 900 kg m^{-3} at 12% MC) was higher than the reported 816 kg m^{-3} for 2-year-old seedings of this species (Davies, 2019).

Density of the *E. globoidea* heartwood was with 710 kg m^{-3} at 12% MC considerably lower than the 850 kg m^{-3} reported for heartwood sourced from old-growth Australian forests (AS1720.2 2006). It, however, fell in the reported range (640 to 830 kg m^{-3}) for the species by Ilic (2002) and NZ-grown plantation trees aged 30-year-old (690 kg m^{-3}) (Guo and Altaner, 2018), 28-year-old (720 kg m^{-3}) (Scown, Lim et al., 2023), or 25-year-old (655 kg m^{-3}) (Jones, McConnochie et al., 2010). Sapwood density of approximately 640 kg m^{-3} at 12% MC, was similar to that reported for tops of 7-year-old trees (600–630 kg m^{-3}) but was lower than that of 2-year-old coppice (660 kg m^{-3}) (Iyiola, 2021). It should be noted that the differences discussed above are a combination of both, site and tree age.

In average. heartwood for both species was denser than its sapwood (Tabel 1). The 83 kg m^{-3} and 60 kg m^{-3} for *E. bosistoana* and *E. globoidea*, respectively. Ignoring radial or axial gradients described below, this suggested an extractive content of ~ 9% in the heartwood. This was plausible, as the ethanol soluble extractive fraction made up ~ 5% (ranging up to 14%) of the heartwood in young 7-year-old *E. bosistoana* and 5- to 80-year-old *E. globoidea* trees (Li, Apiolaza et al., 2018).

4.1. Site effect

Site and tree age was confounded in this data set. However, in contrast to previous studies reporting whole tree density (McKinley, Shelbourne et al., 2000), by comparing wood density at a fixed position in the stem, it was possible to remove the confounding age effect and test for site effects. The site effect on heartwood density at the centre base of the stem was significant in this study (Fig. 1). Site effects on wood density are well known for other tree species (Raymond and Muneri, 2001; Kimberley, Cown et al., 2015; Hein, Chaix et al., 2016; Vega, Hamilton et al., 2020), but had not been confirmed for *E. bosistoana* and *E. globoidea*.

It was not possible to differentiate the contributions of cell walls and heartwood extractives, as the study lacked sapwood data for this within stem location. It is likely that both factors are site dependent. Site difference in heartwood extractive contents for replicated breeding trials of *E. bosistoana* have been detected (Li, Apiolaza et al., 2018) and are relevant for spices grown for their durable heartwood. The available data did not allow to investigate environmental variables influencing wood density in these species.

4.2. Radial and axial density patterns within stems

Axial and radial gradients of wood density have been reported for eucalypts (Hillis, 1978). Consistent with this study, Frederick, Madgwick et al. (1982) reported distinct radial profiles at different heights of the stem for heartwood of 17-year-old *E. regnans* F.Muell. trees but contributions of cell walls and heartwood extractives were not separated. Complex within stem sapwood density patterns have also been recorded for young *Eucalyptus grandis* W.Hill ex Maiden and its hybrid with *Eucalyptus urophylla* S.T.Blake (Wilkins and Horne, 1991; Hein, Chaix et al., 2016). But these studies did not quantified the effects of stem height and distance from the pith. Typical specie-specific radial density patters in heartwood of some eucalypt species have been quantified as relevant wood property for rotary peeled veneer (McGavin, Bailleres et al., 2015; Vega, Hamilton et al., 2020). Neiter study quantified the effect of heartwood extractives.

It is worth mentioning that the linear nature of the used mixed effect model in this study does not allow extrapolation to larger trees, as density gradients approach a maximum asymptote in mature trees. The developed models are applicable for short-rotation plantations, but more complex function such as the sigmoidal functions used by McGavin, Bailleres et al. (2015) might be needed for larger trees.

4.3. Within stem heartwood extractive patterns

The with distance from the centre base of the stem observed increasing heartwood extractive content in *E. bosistoana* matched the commonly described pattern for a range of tree species (Hillis, 1987). Higher amounts of extractives were reported for outer than inner heartwood of *Eucalyptus marginata* Sm. (Hillis, 1956), or *E. grandis* (Bamber, Floyd et al., 1969). It appears that no decreasing radial or axial gradients in heartwood extractives have been reported in literature and in this sense *E. globoidea* seems to be unique. But the polyphenol content in heartwood of *E. grandis* was found to be not affected by sampling height in the 5 innermost annual rings (Bamber, Floyd et al., 1969).

The radially decreasing resin content in softwoods (Uprichard and Lloyd, 1980) is unrelated to heartwood extractives as softwood resins are synthesised in epithelial cells able to flow through the stem in the resin canal network (Govina, Apiolaza et al., 2021) and not fixed in space like heartwood extractives after deposition in the cell walls when sapwood transforms into heartwood in the transition zone.

Site was also reported to affect the amount of heartwood extractives of *Eucalyptus globulus* Labill. (Pereira, 1988; Morais and Pereira, 2012).

5. Conclusion

The study demonstrated the complexity of within-stem wood density patterns in *E. bosistoana* and *E. globoidea*. Heartwood extractives significantly influence density variations, with distinct radial and axial gradients differing between species. Site effects further shape these patterns. Contributions of cell walls and heartwood extractives and can be deduced from sapwood and heartwood density without the need for chemical extraction, if both data are available across the stem.

Wood properties related to cell walls such as strength, and those related to heartwood extractives such as durability are expected to correlate better with the individual density contributions rather than the commonly reported heartwood patterns. If wood density maps are used to predict wood properties for species featuring high extractive contents, the individual contributions should be considered.

Declarations

Competing Interests

The author has no financial interests to disclose. Clemens Altaner is a director of New Zealand Dryland Forests IP Limited.

Author Contribution

C.A. conceived the study, analyzed the data and wrote the manuscript.

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Data Availability

Data is provided within the manuscript or supplementary information files.

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Figures

Fig. 1

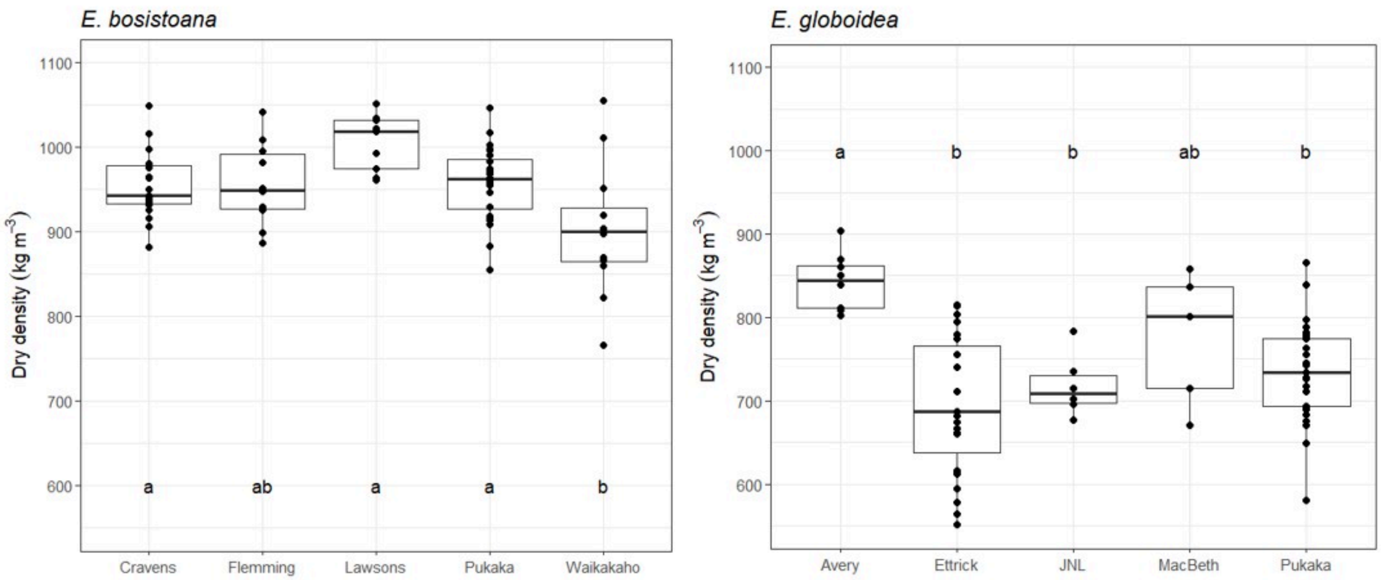

Figure 1

Box plots of heartwood dry density at the center (within 13 mm of the pith) base (below 0.5 m stem height) of for *E. bosistoana*and *E. globoidea* at different sites. Different letters indicate Tukey HSD significance (P = 0.01) between sites for each species.

Fig. 2

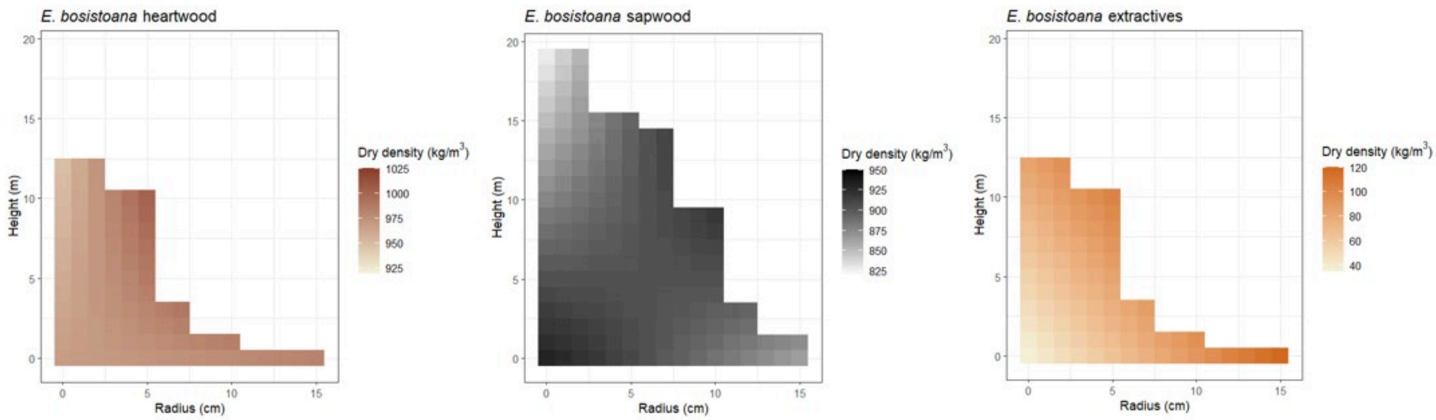

Figure 2

Within stem dry density patterns for *E. bosistoana* for heartwood, sapwood and heartwood extractives.

Fig. 3

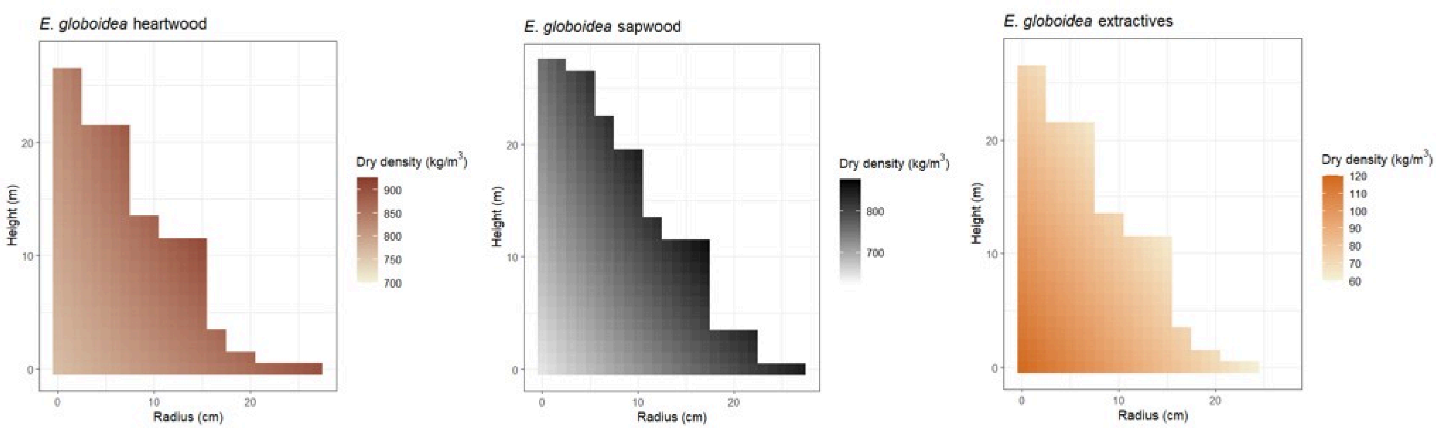

Figure 3

Within stem dry density patterns for *E. globoidea*for heartwood, sapwood and heartwood extractives.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- WoodDryDensity.xlsx