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ORIGINAL ARTICLE

Basic density and shrinkage of Scots pine (*Pinus sylvestris* L.) thinning wood

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Abstract

The basic density and shrinkage properties of Scots pine wood from commercial first and second thinning-stage forests were studied in eastern Finland with a reference from final-felling forests. Linear mixed model analysis was applied, indicating statistically significant differences in basic density between stand types and forest site types, with significant effects of cambial age and height position. Additionally, the 2-level interaction terms between site type, cambial age and height position were significant. In *Myrtillus* type sites, the basic density was 380 kg/m^3 for first-thinning wood, and 407 kg/m^3 and 406 kg/m^3 for second-thinning and final-felling wood, respectively. Young thinning trees showed, on average, wider growth rings (2.83 mm) compared to mature trees (2.04 mm). Density and latewood proportions increased with tree age, particularly in poor site types, whereas the growth ring width had opposite effects. Significant differences were observed in radial, tangential and volumetric shrinkage across stand types, height positions and radial positions, while the longitudinal shrinkage model indicated statistically significant differences between radial positions only. The radial shrinkage was 4.04% in the first thinnings and 4.44% in the second thinnings, while the tangential shrinkage was 6.98% and 7.16%, respectively. The substantial variation in properties, particularly in the first thinnings, likely reflected the presence of juvenile wood, stem form defects and reaction wood in the harvested material, making it less suitable for mechanical processing. The results confirmed that the properties of second-thinning wood enable its use in applications requiring higher density and allowing reasonable shrinkage.

1 Introduction

The size and quantity of structural wood constituents determine the density of wood (Kollmann and Côté 1984; Fengel and Wegener 1989). The inherited properties, along with physiological, mechanical and environmental factors, affect those constituents, their spatial variation and the perceived overall density of timber among other wood properties (Cown 1974; Kollmann and Côté 1984; Gort-Oromi 2010). Within a tree, density varies in the radial and longitudinal directions, the degree, type and direction of this variation differing between species (Zobel and van Buijtenen 1989).

The density of Scots pine (*Pinus sylvestris* L.) and most other conifers increases from pith to bark. Additionally, it decreases with a slowing rate from the tree base to the top. In the radial direction, density varies with cambial age, earlywood and latewood proportions, growth rate, and the differences between juvenile and mature wood (e.g., Cown 1974; Grekin and Verkasalo 2010; Guller et al. 2012). The decrease of density towards the top is typically most intensive in the stem base, due to the younger average age of wood and a higher proportion of juvenile wood in the top (Uusvaara 1974, 1991; Kollmann and Côté 1984; Zobel and van Buijtenen 1989; Repola 2006; Kärkkäinen 2007; Auty et al. 2014).

Wood density is significantly influenced by growth conditions within a forest stand. Factors such as site fertility, the spatial distribution of trees and a tree's position within the stand affect both the growth rate and the proportion of stem wood in the total growth (Kellomäki 1981; Uusvaara 1991).

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Thinning, drainage and similar changes in the growth environment typically lead to accelerated growth, which subsequently decreases wood density (Cown 1973; Kollmann and Côté 1984; Rikala 2003; Varhimo et al. 2003; Richter 2015).

Accelerated growth alters the anatomical structure of wood, impacting both the fibre width and the proportion of cell wall within the cross-section of the growth ring. This process especially promotes the formation of earlywood, leading to a lower overall density of wood (Uusvaara 1974; Mäkinen et al. 2002). The properties of coniferous wood tissue are markedly different depending on the season of formation, as the density of latewood surpasses that of earlywood due to its thick, lignin-rich tracheid walls, compressed cells and small lumens (Fengel and Wegener 1989; Bowyer et al. 2007; Fries and Ericsson 2009; Forest Products Laboratory 2010; Richter 2015). The site conditions affect the density of latewood more than that of earlywood, and to a larger extent, the properties of earlywood depend on the genetic variation between individual trees (Fernandes et al. 2017).

Growth rings become thinner as their distance to the pith increases. Additionally, increased crown competition within forests begins to limit tree growth (Richter 2015). Thus, the growth rings tend to be thicker in young trees and within the juvenile wood area compared to those in mature trees and the mature wood. The first 5–20 growth rings from the pith are considered to form the juvenile wood zone in conifers (Zobel and van Buijtenen 1989; Thörnqvist 1990; Bowyer et al. 2007; Gryc et al. 2007; Kärkkäinen 2007; Forest Products Laboratory 2010). Regarding Scots pine, both early transition of 10–15 rings from the pith (Wilhelmsson et al. 2002) and late transition of 22 rings, on average (Sauter et al. 1999; Mutz et al. 2004), were reported from juvenile wood to mature wood. It has also been suggested that, rather than defining the juvenile wood area by growth rings, a threshold value of wood density could be used to differentiate between juvenile wood and mature wood (Cown 1992). Covering a conical area in the central core of a stem from base to top, the proportion of juvenile wood in the total tree volume is higher in young trees than in adult trees and this proportion increases towards the top (Zobel and van Buijtenen 1989; Zobel and Sprague 1998; Pereira et al. 2003; Gryc et al. 2007). The tracheid cell walls of juvenile wood are thin and the latewood proportion is low, resulting in markedly lower density and strength compared to mature wood (Thörnqvist 1990; Zobel and Sprague 1998; Burdon et al. 2004; Bowyer et al. 2007; Gryc et al. 2007; Forest Products Laboratory 2010). The high content of juvenile wood significantly limits the usability of wood material, particularly in mechanical processing and for products requiring high strength (Cown 1992; Dumail and Castera 1997; Zobel and Sprague 1998). Additionally, it can have negative effects in certain pulping processes.

The shrinkage of wood due to drying is anisotropic, being the most extensive in the tangential direction and about half of that in the radial direction, whereas the longitudinal shrinkage is of minor magnitude (Forest Products Laboratory 2010; Pang 2002). The shrinkage of the earlywood tracheid cells is anisotropic whereas the latewood tends to shrink relatively evenly in different directions (Watanabe et al. 1998; Kärkkäinen 2007). Thus, the anisotropy of shrinkage usually decreases with increasing density (Kärkkäinen 2007; Grekin and Verkasalo 2010). High transverse shrinkage generally correlates with high density, while longitudinal shrinkage decreases as density increases (Pang 2002; Calvo et al. 2006; Gryc et al. 2007; Kärkkäinen 2007; Forest Products Laboratory 2010; Grekin and Verkasalo 2010). However, the transverse shrinkage is lower in juvenile wood than in mature wood. Conversely, longitudinal shrinkage is higher, due to the high microfibril angle of the secondary wall S_2 and the associated compression wood and spiral grain (Boutelje 1973; Cown 1974; Ying et al. 1994; Pereira et al. 2003; Bowyer et al. 2007; Riesco Muñoz and Díaz González 2007; Grekin and Verkasalo 2010; Ruano et al. 2022). The sapwood of mature trees tends to shrink more than heartwood due to its higher density, and this shrinkage is primarily influenced by the properties of latewood tracheids (Gao et al. 2022). Calvo et al. (2006) noted that wood material farthest from the pith, despite its higher density and better mechanical properties, exhibits many unfavourable characteristics, including lower dimensional stability. The shrinkage and swelling characteristics, along with the resulting dimensional stability, are crucial from an industrial perspective. Uneven shrinkage in different directions can lead to checking, warping, and drying deformations. Therefore, the anisotropic nature of wood might be one of its most disadvantageous characteristics as a material (Pang 2002).

First thinnings and the following, intermediate cuttings are part of the forest management practices in the Nordic countries. The thinning methods in Finland, Sweden and Norway have been described in the forest management guidelines (Yrjölä 2002). Thinnings primarily aim to improve the future growth potential, dimensions and quality of the forests. However, the yield of merchantable timber, saw logs and pulpwood from the first thinnings is low. Overall, thinnings account for 25–30% of the total cutting income for forest owners during the forest rotation period, underlining the significance of intermediate cuttings as a source of raw material for the wood processing industry in Finland (Äijälä et al. 2019). In 2019, first thinnings produced 5%, and later thinnings 36%, of the total yield of roundwood from standing sales of all tree species. Specifically for Scots pine from standing sales, 27% of logs and 66% of pulpwood were harvested from thinning forests (Torvelainen et al. 2021).

In the Nordic countries, the wood products industries utilise mainly standard saw logs from final fellings as well as from second and later thinnings. The small-diameter logs or short logs, i.e. small-sized timber from thinnings or the uppermost parts of final felling trees, are less common in sawmilling. Small-sized timber is primarily used in selected outdoor applications, environmental construction, less demanding construction, and packaging (Wall et al. 2005; Mauno 2021; Toikka 2024). Additionally, it is often processed into bioenergy. Earlier research has identified alternative uses for small-sized timber, such as advanced biofuels and in innovations based on lignin valorisation (Mauno 2021). In the production of cross-laminated timber (CLT) or glue-laminated timber (GLT), using small-sized timber can improve material efficiency, especially with more advanced processing methods (Hernandez et al. 2005; Fredriksson et al. 2015). Information about critical wood properties and their variation is important from an industry perspective. It may also be valuable for the forest owners during timber sales and in forest management planning.

The data were collected from eastern Finland, which is an important region for the growing and utilisation of Scots pine. The objective of this study was to assess the basic density and shrinkage properties of Scots pine wood from commercial first and second thinning stage forests in eastern Finland. We hypothesised that these properties differ significantly from those of pine wood from final felling forests. As the direct and indirect effects of age on wood properties are well-known, both internal and external factors, such as the cambial age of tree and forest site type, respectively, were used as predictive factors in the statistical analyses. Previous research on the properties of young wood material, especially from thinnings and the pulpwood section of trees, is plentiful. In contrast, there are fewer published studies focusing on the second thinning removal and the wood properties that are most significant for wood products (Hakkila et al. 1995, 2020; Varhimo et al. 2003; Wall et al. 2005; Kask and Pikk 2009).

Table 1 Properties of the study stands by stand type and site type before harvesting

Stand type	Site type (number of stands)	Trees/ha	Age (years)	Breast-height diameter (cm)	Height (m)
First thinning	*Myrtillus* type (2)	1,800	33	13.8	12.6
	Vaccinium type (2)	2,300	44	12.9	13.9
	Vaccinium vitis-idaea transformed type (2)	1,353	43	14.0	13.4
	Average	1,818	40	13.6	13.3
Second thinning	*Myrtillus* type (1)	1,500	68	22.4	21.3
	Vaccinium type (1)	1,100	66	20.9	21.6
	Calluna type (1)	1,600	70	14.6	15.4
	Dwarf-shrub transformed type (1)	1,833	90	15.5	14.6
	Average	1,508	74	18.4	18.2
Final felling	*Myrtillus* type (2)	478	80	28.4	25.2

2 Materials and methods

2.1 Wood specimens

The data for the study were collected from 10 Scots pine-dominated first-thinning and second-thinning forest stands in eastern Finland (62–63° N, 30° E), and the reference material was collected from two final-felling stands in the same area (Table 1). The stands were mainly located in the state forests. The availability of stands was limited due to the relatively strict selection criteria based on the properties of the stands. Thus, the dataset did not include all possible combinations of stand and site types in the area. The study stands were from mineral soils, including *Myrtillus*, *Vaccinium* and *Calluna* types, and from transformed types of drained peatlands, *Vaccinium vitis-idaea* and dwarf-shrub transformed types. The site types and other stand properties were verified through forest management plans, which were available for all study stands.

Ten sample trees were felled from each study stand and the complete dataset of 121 felled sample trees was utilised to measure basic density, shrinkage and average of growth ring width, while a subset of 64 trees was taken for a detailed measurement of growth rings. The sample trees were required to have at least one 2-m-long section of stem which met the quality and size specifications for saw timber, specifically for saw logs, small-sized logs, or balks. The trees were cut into 1.4–3.5 m logs down to the minimum top diameter of 8 cm, which, on average, was located at the height of 12 m in the standing trees (70% of the tree height). One approximately 30-mm thick disc was sawn from the lower end of each log, including the top, which was left in the forest. The total number of discs in the study was 838.

The discs were further cut in the laboratory so that either three or five clear-wood specimens were made from each disc, following the south-north line marked in them in the forest (Fig. 1). The positioning of specimens aimed at obtaining information from the assumed juvenile-wood (20 first growth rings from the pith outwards) and mature-wood areas (from the 21 st growth ring outwards); thus, when

possible, one specimen was prepared from the pith ('P'), two from the middle of the disc radius ('N1', 'S1'), and further two more close to the edges ('N2', 'S2'). The total number of specimens in the study was 3,560.

The dimensions of the specimens were 20 mm in the radial and tangential directions and approximately 30 mm in the longitudinal direction.

Out of 3,560 specimens, 2,350 were included in the linear mixed model for basic density. These comprised specimens with known radial position (all the specimens located in the pith (P) and N1/S1 and N2/S2 specimens in the subset of 64 trees.

Of the 3,560 specimens, 3,515 were included in the linear mixed model for radial shrinkage, 2,720 for tangential shrinkage, 3,512 for longitudinal shrinkage and 2,706 for volumetric shrinkage. The tangential shrinkage was not measured from the pith-enclosed specimens, because both specimen dimensions in the cross-sectional surface were radial, while the tangential dimension was absent. Outliers identified in the radial, tangential and longitudinal measurements were excluded from the dataset, as they were most likely attributable to measurement errors. The volumetric shrinkage model included only those samples for which valid measurements were available in the radial, tangential and longitudinal directions.

2.2 Methods

The basic density (henceforth referred to briefly as density) of wood was determined using the oven-dry method according to the standard ISO 3131 (International Organization for Standardization 1975). The mean density of the specimens represented the density of the disc from which the specimens were sawn.

The average basic density (kg/m^3) of a stem was calculated applying the equation for the area-weighted wood density (AWD) presented by Hannrup and Ekberg (1998):

$$AWD = \frac{\Sigma\, a_i d_i}{\Sigma\, a_i}, \tag{1}$$

where a_i = cross-sectional area of the disc i and d_i = density of the disc i.

The total shrinkage values (β_m, %) in radial (r), tangential (t) and longitudinal (a) direction were assessed according to the standard ISO 4469 (International Organization for Standardization 1981) and calculated as follows:

$$\beta_m = \frac{l_{m\,max} - l_{m\,min}}{l_{m\,max}} \bullet 100, \tag{2}$$

where $l_{m\,max}$ = dimension (mm) of specimen measured above the fibre saturation point in direction m and $l_{m\,min}$ = dimension (mm) measured as oven dry in direction m.

The maximal volumetric shrinkage β_V, % was assessed according to the standard ISO 4858 (International Organization for Standardization 1982), and calculated as follows:

$$\beta_V = \frac{l_{r\,max}\, l_{t\,max}\, l_{a\,max} - l_{r\,min}\, l_{t\,min}\, l_{a\,min}}{l_{r\,max}\, l_{t\,max}\, l_{a\,max}} \bullet 100. \tag{3}$$

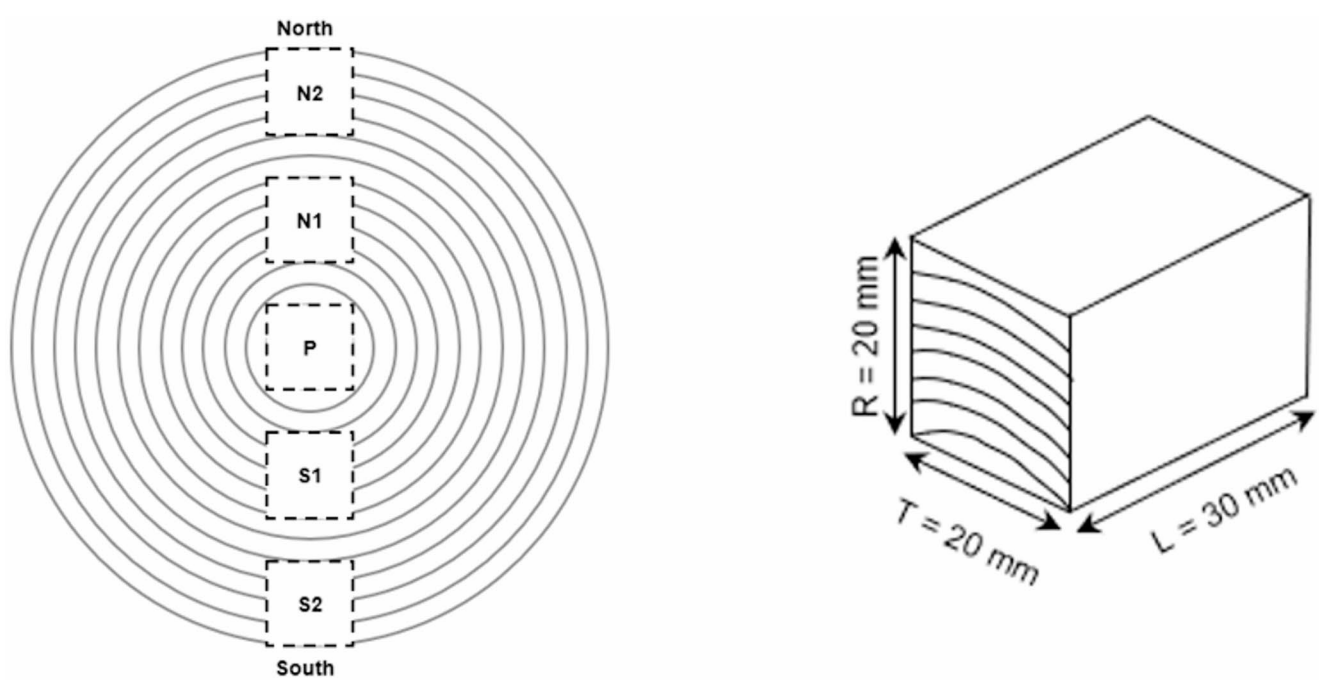

Fig. 1 Locations of the specimens in the discs, and a specimen for the basic density and shrinkage measurements

The growth ring width was measured from the discs with a light microscope and the earlywood and latewood proportions using an image analysis system (WinDENDRO™, Régent Instruments Inc., Québec, Canada). The tree-wise growth ring width and earlywood/latewood proportions were calculated as the mean values of all discs sawn from each tree in Chap. 3.1.

2.3 Statistical analyses

Descriptive statistics on basic density, shrinkage, growth ring width and latewood proportion were presented separately for the stand and site types. Due to the data structure, the statistical comparisons between all stand types were possible in *Myrtillus* type only, whereas *Vaccinium* type enabled comparisons between the first and second thinnings. The within-tree variation of density and shrinkage were assessed both in the radial direction, from pith to bark and in the longitudinal direction, from the tree base to the top. The radial and vertical within-tree variations of density and shrinkage were further studied using logarithmic, exponential and linear models.

The generalized linear mixed model (GENLINMIXED) procedure in IBM SPSS Statistics was used to analyse the significance of potential predictor variables for the basic density and shrinkage and to fit the models to the data. Pairwise contrasts of categorical values were calculated with least significant difference (LSD) test.

The analysis of variance (ANOVA) was employed to compare the juvenile wood growth rates (20 first year rings from the pith outwards) across the stand types in Chap. 3.2.4.

The R-square values between basic density and the tree-level variables were calculated to identify predictors for the model. A linear mixed model was developed to analyse the basic density of trees (Eq. 4). The stand-level and tree-level variables and their transformations were used as predictors. The data had a hierarchical structure, which was considered by including the random effects of stand, tree and log in the variance component model. Forest site type, stand type, cambial age and a common logarithm ($\log_{10}$) transformation of vertical position were included as variables.

Basic density was modelled by fitting the square root transformation of a linear mixed model

$$\sqrt{\rho} = b_0 + site_j + stand_k + cmbage + \log_{10}(h) + site_j * cmbage + site_j * \log_{10}(h) + cmbage * \log_{10}(h) + u_s + u_{ts} + u_{lts} + \epsilon\,, \quad (4)$$

where ρ = basic density (kg/m^3), b_0 = intercept, $site_j$ = forest site type, $stand_k$ = stand type, $cmbage$ = cambial age (years), h = height position (m), u_s = random stand effect, u_{ts} = random tree effect, u_{lts} = random log effect, ε = random error term.

Square root transformation was performed to reduce heteroscedasticity of the residuals. The cut-off p-value for the variables was 0.05. The model selection was based on the likelihood-ratio test; thus, the model with the lowest −2 log-likelihood value was chosen. Overfitting of the model was prevented by including only 2-level interaction terms to the model but excluding all the 2-level interaction terms with the development class of the stand.

Radial, tangential, longitudinal and volumetric shrinkage was modelled using a linear mixed model

$$\beta_M = b_0 + stand_k + rpos_n + h + u_{ts} + u_{lts} + \epsilon\,, \quad (5)$$

where β_M = shrinkage (%), radial, tangential, longitudinal or volumetric, b_0 = intercept, $stand_k$ = stand type, $rpos_n$ = radial position, h = height position (m), u_{ts} = random tree effect, u_{lts} = random log effect, ε = random error term.

In tangential shrinkage u_{ts} was omitted to avoid overparameterization of the model.

3 Results and discussion

3.1 Growth ring width and latewood proportion

The analysis of growth ring width using descriptive statistics indicated notable variations in growth rates across different site types. Where comparisons were possible, such as in the *Myrtillus* and *Vaccinium* site types, differences were also observed between the stand types (Table 2). The widest growth rings were measured in *Myrtillus* type, while the narrowest were found in the dwarf-shrub transformed type. Results showed a decreasing growth rate when moving towards less fertile site types. Numerous previous studies have shown that soil nutrient levels significantly influence the growth rate and wood density of Scots pine, as well as properties such as branchiness, (e.g., Cown 1974; Uusvaara 1981; Lämsä et al. 1990; Huuskonen et al. 2014). These factors, in turn, influence the quality and potential applications of sawn timber. In Scots pine, the correlation between fast growth and wood density is usually negative (Hakkila 1966; Repola 2006; Hakkila et al. 2020). The effect of growth rate on density is most pronounced in young stands (Björklund and Walfridsson 1993). The results by Lämsä et al. (1990) on young Scots pine indicated that the fertile site type and wide spacing resulted in fast growth and thick branches, thus decreasing the quality of sawn timber due to large knots visible in the wood material. Varmola (1996) observed that on the most fertile site types, i.e., *Myrtillus* type and better, even a substantial increase in the stand density does not mitigate the negative effects of fast growth on quality, especially those caused by the large branch diameter.

Table 2 Mean values and standard deviations of the growth ring width (mm) and latewood proportion (%) of trees by site type and stand type

Site type	First thinning	Second thinning	Final felling
	Growth ring width (mm)		
Myrtillus	2.83 ± 0.57 (*n* = 20)	2.00 ± 0.23 (*n* = 10)	2.04 ± 0.35 (*n* = 20)
Vaccinium	1.78 ± 0.54 (*n* = 21)	1.95 ± 0.31 (*n* = 10)	–
Calluna	–	1.16 ± 0.29 (*n* = 10)	–
Vaccinium vitis-idaea	2.24 ± 0.52 (*n* = 20)	–	–
Dwarf-shrub	–	1.01 ± 0.27 (*n* = 10)	–
	Latewood proportion (%)		
Myrtillus	33.2 ± 2.4 (*n* = 14)	33.2 ± 1.2 (*n* = 5)	34.7 ± 2.2 (*n* = 10)
Vaccinium	34.4 ± 3.1 (*n* = 10)	34.2 ± 1.3 (*n* = 5)	–
Calluna	–	36.8 ± 2.4 (*n* = 5)	–
Vaccinium vitis-idaea	35.7 ± 3.6 (*n* = 10)	–	–
Dwarf-shrub	–	36.3 ± 0.7 (*n* = 5)	–

In this data, stand type had a complex effect on growth ring width. When comparing materials from *Myrtillus* sites, the growth ring width of trees was higher in the first thinnings than in the second thinnings or final fellings, on average (Table 2). Where the *Vaccinium* type was concerned, the difference between first and second thinnings was marginal. The order of second thinnings and final fellings may indicate notable differences in the other growth conditions of sample trees. The factors such as minimal shading due to the low stand density or dominant position of a tree are known to promote the growth of trees which, in turn, is negatively correlated with the latewood proportion and further, with wood density (Kellomäki 1981; Butterfield 2003). In our study, the final-felling trees likely benefited from the growth impulse provided by the previous thinning, or thinnings, and the subsequent wider spacing. This probably increased the width of growth rings formed after thinning, compared to the second-thinning forests where the number of trees per hectare was relatively high, thus suppressing the growth of individual trees. The results on growth rate followed the findings by Kärenlampi and Riekkinen (2004) on the decreasing growth rate along with the tree age. Similarly, Knapic and Pereira (2005) noted that the growth rate of maritime pine (*Pinus pinaster* Ait.) decreases along with the cambial age.

The descriptive statistics indicated minor differences in the latewood proportions between the stand types and the site types (Table 2). The differences between stand types were small but with relatively high standard deviations. Sarkhad et al. (2022) studied pine species and noted that for Scots pine, the latewood percentage increased from pith outwards and stabilised when approaching bark, but where *Pinus obovata* and *Pinus sibirica* were concerned, the increment of latewood proportion from pith to bark was gradual. Vargas-Hernandez et al. (1994) reported an increase in the latewood proportion of Douglas fir (*Pseudotsuga menziesii*) with age, although the increase was irregular during the initial years. As the latewood formation starts only when the elongation of the leading shoot has ended, the latewood proportion markedly depends on the length of its formation period (Vargas-Hernandez and Adams 1991). The proximity of foliage organs favours the formation of earlywood, hence usually resulting in low latewood proportion in young trees (Larson 1969).

In general, the wood material from sites with high or medium fertility (*Myrtillus* type and *Vaccinium* type) had a lower latewood proportion than the wood from sites with low fertility (*Calluna* type, *Vaccinium vitis-idaea* transformed type and dwarf-shrub transformed type). As an exception, the latewood percentage on *Vaccinium vitis-idaea* transformed type was at the same level with the sites of high or medium fertility. The standard deviation of latewood proportion was relatively consistent across the site types, except for the dwarf-shrub transformed type, where the variation was notably lower. The results were consistent with earlier studies on Scots pine in which high site fertility was associated with accelerated growth, resulting in wider earlywood area of growth rings in boreal conditions (e.g., Hakkila 1966; Hakkila et al. 2020). A potential explanation is that wide growth rings are linked to high levels of photosynthesis, which require greater water transportation capacity, as in softwoods, water primarily moves through the earlywood (Kärkkäinen 2007).

3.2 Basic density

3.2.1 Average stem density

The average basic density of individual sample trees was 414 kg/m^3, with a standard deviation of 30 kg/m^3. This value was calculated as the area-weighted stem density. Basic density and its tree-to-tree variation were the highest in second thinning trees, 435 kg/m^3 (std. dev. 29 kg/m^3), the values being lower in first-thinning trees 404 kg/m^3 (std. dev. 28 kg/m^3) and in final-felling trees 406 kg/m^3 (std. dev. 17 kg/m^3). The positive effect of tree age on the average basic density of a stem is illustrated in Fig. 2a. Even though the trend is clear (R^2 = 0.245), there is considerable variation in area-weighted stem density in all stand types.

In the first-thinning and final-felling trees, the average basic density of a stem was at the same level as in other studies on Scots pine. It should be noted that in most of the

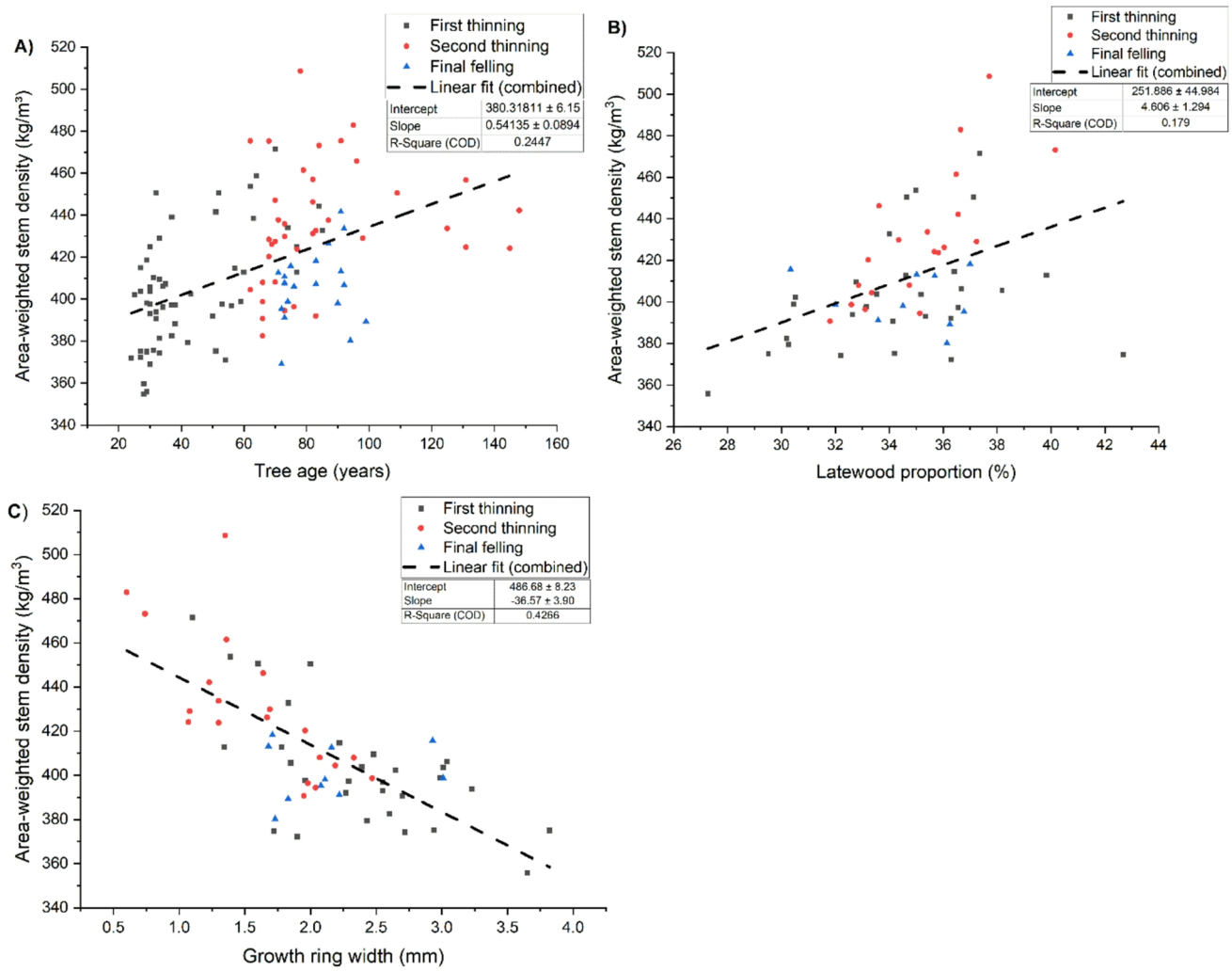

Fig. 2 (**a**) Age (years), (**b**) latewood proportion (%) and (**c**) growth ring width (mm) of sample trees versus area-weighted stem density (kg/m^3) by stand type

former research, before and during the 1960's, the results were obtained from naturally regenerated forests which, due to their slower growth and presumably more inconsistent forest management, were expected to hold somewhat higher basic density than the current commercial forests in Finland (e.g., Hakkila 1966; Hakkila 1979). More recently, Kankare et al. (2022) studied wood properties of Scots pines approaching the second thinning stage and reported somewhat higher mean densities than those in our study.

In contrast to the Finnish studies, very high average ring density values, 588 kg/m^3, were reported in Portugal for mature trees with the average age of 46–66 years, thus indicating a good suitability of Scots pine for reforestation especially in the mountain areas (Fernandes et al. 2017). Our study focused on thinning forests and therefore the final-felling trees, which usually have the highest wood density, were less present in this data than in the reference studies.

The latewood proportion and growth ring width had opposite effects on the average basic density of a stem. Specifically, the basic density increased with higher latewood proportions, whereas an increase in the growth ring width corresponded to lower basic density values (Fig. 2b and c). In addition, the R^2 value between growth ring width and area-weighted stem density was considerably higher (0.427) than the corresponding value between latewood proportion and area-weighted stem density (0.179). The results illustrated in Fig. 2b and c were expected based on the higher density of latewood and the findings that latewood width remains relatively constant while the earlywood width is more affected by the increase in the growth rate (e.g., Mäkinen et al. 2002; Bowyer et al. 2007; Kärkkäinen 2007; Richter 2015). The correlation between ring width and wood density is influenced by climatic patterns. Sites that experience spring drought but subsequently enjoy favourable growth conditions during the later growing season may

exhibit a positive relationship between growth ring width and wood density. However, it is more likely that the majority of the growth increment occurs in spring, resulting in a negative correlation between density and growth ring width (Wimmer and Downes 2003).

3.2.2 Variation of average stem density according to stand type and site type

Based on the descriptive statistics, the site type and stand type markedly affected the basic density (Table 3). Among the site types, the wood density was lowest in the first thinnings of *Myrtillus* type and *Vaccinium vitis-idaea* transformed type. Wood from *Vaccinium* type, dwarf-shrub transformed type and *Calluna* type had higher density and the differences between site types were notable. Similarly, Hakkila (1966) reported a statistically significant difference in the basic density of first-thinning wood between fertile and poor mineral soil site types in Finland. Instead, Aleinikovas and Grigaliūnas (2006) found no statistically significant differences in the wood density between three forest site types with different fertility levels in Lithuania. Guller et al. (2012) observed that while the radial growth of young Calabrian pine (*Pinus brutia*) trees was dependent on the forest site properties, the wood density did not vary statistically significantly between the site types. According to Carson et al. (2014), the growth rate as such had a weak correlation with wood density while the stand density and the silvicultural manipulation of trees by pruning had a greater effect.

The results indicated that in *Myrtillus* type the density was higher in the second thinnings and final fellings than in the first thinnings. In the second thinnings, the density in *Myrtillus* type was at the same level with that of the *Vaccinium* type. Moreover, the difference in the *Vaccinium* type between the first and second thinnings was small. In our study, the second-thinning stands originated mostly from site types which were poor in nutrients and with relatively high age, whereas the final-felling forests were from *Myrtillus* type. Riesco Muñoz and Díaz González (2007) noted that the density of Scots pine was lower in young trees from thinnings than in mature trees, probably due to the presumably higher juvenile wood proportion of young trees in their data on Scots pine from the mountain areas in Galicia, in the north-western Spain. Hakkila et al. (2020) concluded that owing to the higher latewood proportion, the basic density of mature trees is higher than the density of young trees.

Table 3 Mean values and standard deviations of the average stem density (kg/m^3) by site type and stand type

Site type	First thinning	Second thinning	Final felling
	Average stem density (kg/m^3)		
Myrtillus	380 ± 30 (n = 20)	407 ± 41 (n = 10)	406 ± 17 (n = 20)
Vaccinium	425 ± 37 (n = 21)	420 ± 17 (n = 10)	–
Calluna	–	471 ± 40 (n = 10)	–
Vaccinium vitis-idaea	400 ± 24 (n = 20)	–	–
Dwarf-shrub	–	n	–

3.2.3 Vertical and radial variation of density

Wood density varied within the trees, decreasing from base to top in all stand types (Fig. 3), as typical for Scots pine and other species with increasing density from pith to bark (e.g., Uusvaara 1974; Calvo et al. 2006; Auty et al. 2014). The change in density along with the height is due to the lower average cambial age of wood and the increase in relative proportion of juvenile wood in the upper parts of stem (Jalava 1945; Kollmann and Côté 1984; Zobel and van Buijtenen 1989; Uusvaara 1991; Kärkkäinen 2007). Supporting the findings by Uusvaara (1974) and Repola (2006), Fig. 3 illustrated that the longitudinal decrease in density was the most intensive in the stem base and levelled towards the top. At all heights, the wood density was the lowest in first thinnings, whereas the difference between final fellings and second thinnings was negligible. Similarly to our study, Deng et al. (2014) found for Chinese red pine (*Pinus massoniana* L.) that independent of the height position within a tree, the density of mature trees surpassed that of young trees.

In the vertical direction, density was the highest in the stem base, i.e., at the relative height of 10% or lower, and the lowest density was found at the top of the merchantable stem. The difference between the lowest and highest stem parts was approximately 80 kg/m^3 and the gap increased along with the age of the trees. The vertical variation in density in our study was smaller than that in, for instance, Repola (2006), Deng et al. (2014) and Hakkila et al. (2020), as they recorded differences of over 100 kg/m^3 between the tree base and the top for Scots pine and Chinese red pine. More in detail, Hakkila et al. (2020) reported the basic density of 409, 447 and 465 kg/m^3 for 5-meter butt logs of Scots pine in first thinnings, second or third thinnings and final fellings, respectively. In upper logs, the corresponding values of basic density were 373, 399 and 393 kg/m^3. According to Hakkila et al. (1995), the density at stump height of the first-thinning trees was approximately 15% higher than that at the top. Riesco Muñoz and Díaz González (2007) observed for thinning-stage Scots pine only a 5% decrease in basic density from the stem base to the height of five metres, the basic density of a 5-meter butt log being 470 kg/m^3, on average. They concluded that the density had less effect on the number of merchantable timber assortments obtained from a tree than the stem diameter at different heights. Moreover, based on the modest vertical decrease

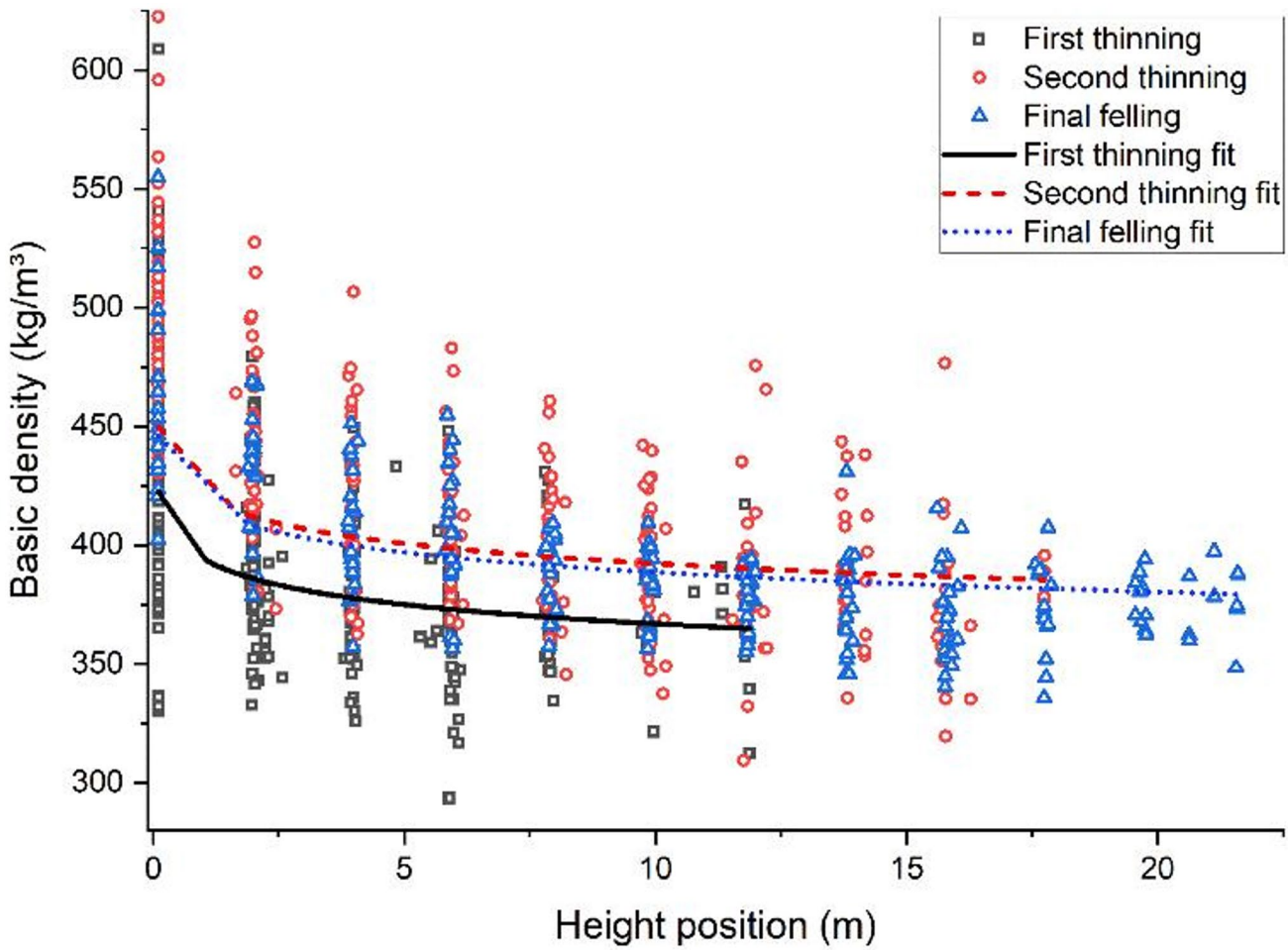

Fig. 3 Vertical variation of the basic density (kg/m^3) within a stem by stand type. Fit curves: *Myrtillus* type, cambial age of 15 years

in density, Riesco Muñoz et al. (2008) suggested that the second and even the third logs of the thinned trees could be utilised as raw material for the timber industry. In our study the sample discs at the diameter of 8 cm represented the tree top whereas for instance Repola's (2006) study included there the full unmerchantable top sections and Hakkila et al. (1995) considered the top section beyond the diameter of 7 cm.

The wood density increased in the radial direction from pith to bark (Figs. 4, 5, 6). The density was clearly lower in the core, including the pith, than close to the bark, thus increasing along with the tree age. In southern Finnish conditions, the density of mature Scots pine trees was noted to reach its highest value at the tree age of 80 years (Hakkila 1979). Moreover, several studies reported the increment of wood density from pith outwards and its stabilisation after 20–30 growth rings, as well as a decrease over the first growth rings followed by an increase towards the bark (e.g., Hakkila 1966; Riesco Muñoz et al. 2008; Auty et al. 2014; Kimberley et al. 2015; Dias et al. 2018). In this study, the sample trees were mainly from thinning forests, with the maximum cambial age around 90 years found in the mature trees and none of the studied strata indicated a clear culmination or a downward-turning trend for density in the radial direction.

Where the site types were concerned, at all radial locations from the pith and at the 5-m height, density was higher in the poorest mineral soil site type, i.e., *Calluna* type, than in *Myrtillus* and *Vaccinium* types (Fig. 4a). Instead, there was a constant difference in the density between dwarf-shrub and *Vaccinium vitis-idaea* transformed types in drained peatlands (Fig. 4b). According to Uusvaara (1974), an exceptionally high nutrient content of forest soil emphasises the effect of site type on wood density. In our study this kind of pronounced effect was not noticed as *Myrtillus* type was the most fertile site type. As presented in Fig. 4c for *Myrtillus* type forests, the average density was very similar in all stand types in terms of location from the pith.

In our study, the difference in wood density between pith and close to bark was at its highest at the relative height-position of 10–20%. The wood density of conifers generally increases outwards from pith at all height-positions, the

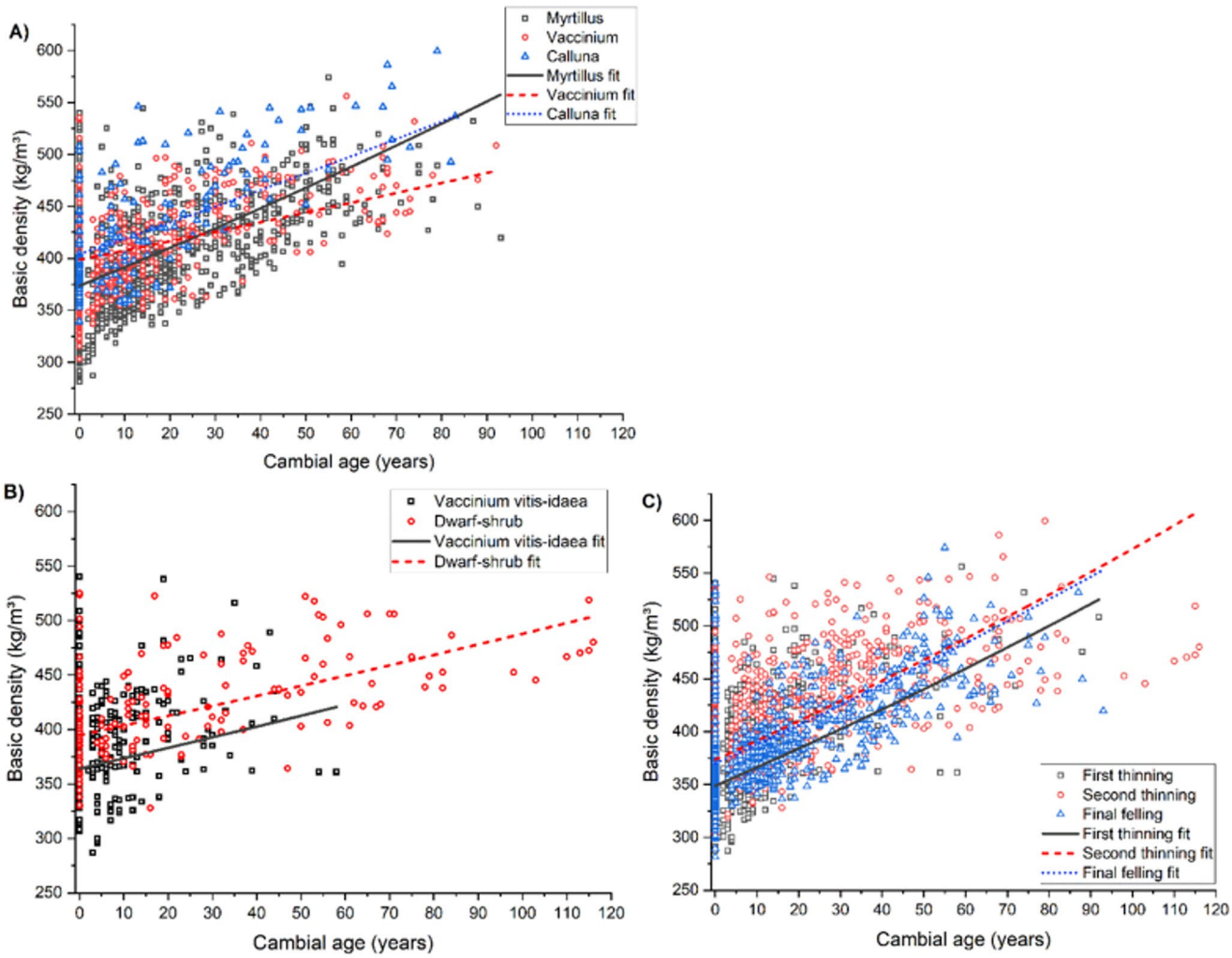

Fig. 4 (**a**) Radial variation of basic density (kg/m^3) within a stem by site type in mineral soils in second thinnings. (**b**) Radial variation of the basic density (kg/m^3) within a stem by site type in peatlands. Linear fits: *Vaccinum vitis-idaea* type in first thinning and dwarf-shrub type in second thinning. (**c**) Radial variation of the basic density (kg/m^3) within a stem by the stand type. Linear fits: *Myrtillus* type. In all Figures the linear fits were presented for the height position of 5 m

difference being largest at the relative height of 10% and diminishing above that towards the top of the tree (e.g., Cown 1974; Uusvaara 1974). Guller et al. (2012) reported that the increase in wood density of Calabrian pine (*Pinus brutia*) from pith to bark was primarily due to the higher latewood proportion close to the bark. A similar conclusion could be made in our study based on the increasing radial trend of latewood proportion and density.

3.2.4 Linear mixed model for basic density

According to the square root transformation of the linear mixed model for basic density, the differences between site types, cambial age and the logarithm of height position were very significant ($p<0.001$) (Table 4). Furthermore, differences between stand types were significant ($p<0.05$). All the 2-level interaction terms between site type, cambial age and height position were very significant ($p<0.001$).

In pairwise comparisons between the site types, a significant difference was observed between *Myrtillus* and *Calluna* types ($p=0.033$) (Table 5). The parameter estimates indicated that the soil nutrient levels markedly affected the basic density of wood, resulting in the highest densities in the poorest site types of this study, both in mineral soils (*Calluna* type) and in drained peatlands (dwarf-shrub transformed type). Similarly, in the study by Kask et al. (2021), the site characteristics were concluded to affect the basic density so that less fertile site types produced higher wood density in comparison to *Myrtillus* type.

Significant differences were observed between stand types in the pairwise comparison of the first and second thinnings ($p=0.018$), indicating that the basic density was higher in older stands (second thinning) compared to

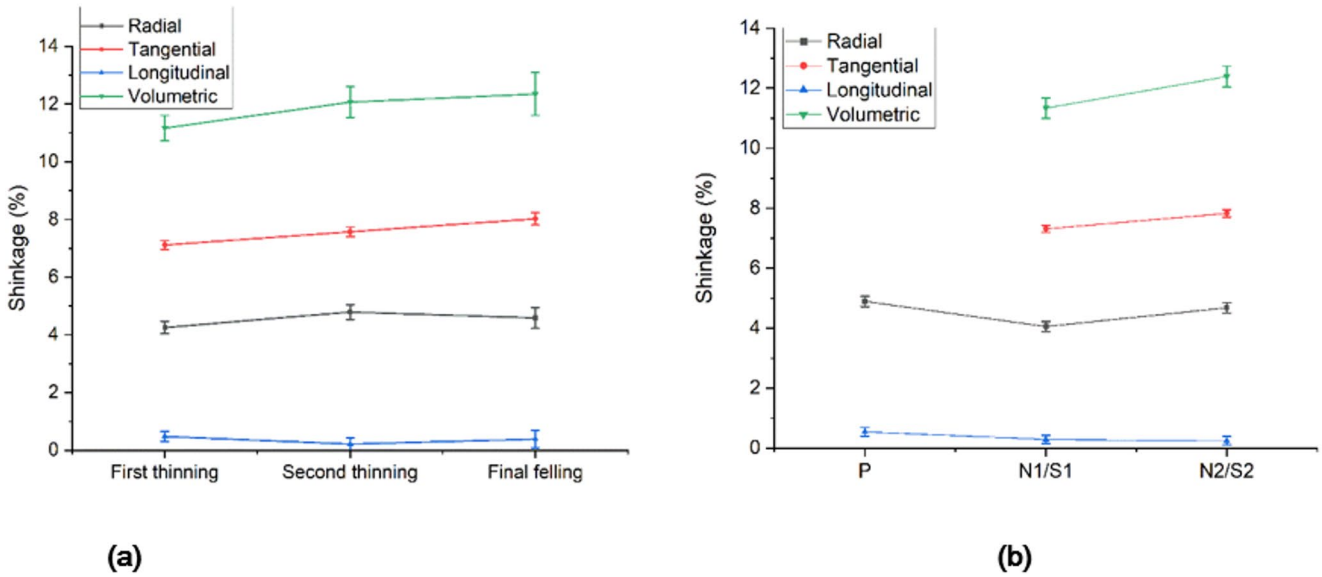

Fig. 5 Radial, tangential, longitudinal and volumetric shrinkages (mean values ± 95% confidence interval) according to the (**a**) stand type and (**b**) the radial position of a specimen. The data points were presented for the height position of 3 m

Table 4 Fixed effects in the linear mixed model for the basic density (kg/m^3)

Source	F	df1	df2	*p*
Site type	6.139	4	2332	< 0.001
Stand type	3.441	2	2332	0.032
Cambial age	41.943	1	2332	< 0.001
Height position $\log_{10}$	975.526	1	2332	< 0.001
Site type * Cambial age	22.182	4	2332	< 0.001
Site type * Height position $\log_{10}$	24.738	4	2332	< 0.001
Cambial age * Height position $\log_{10}$	428.633	1	2332	< 0.001

younger stands (first thinnings). The difference between the first thinnings and final fellings was not significant but, however, relatively close to the limit of significance ($p = 0.068$). These results are consistent with the findings of Auty et al. (2014), who observed a decreasing proportion of low-density wood with increasing tree age. Their study compared wood material from trees harvested at 70 years and 100 years, demonstrating this trend. The results suggest potential changes in wood material as sapwood transitions to heartwood, which is characterised by a higher content of extractives (Kärkkäinen 2007). It should be noted, however, that only two final-felling stands were included in the present study, which contributes to the uncertainty of the results.

In Scots pine, the juvenile wood section can be roughly represented by the first 20 growth rings from pith outwards: Mutz et al. (2004) modelled the transition between the juvenile and mature wood to approximately 22 years. In our data from *Myrtillus* type, the cumulative widths of the first 20 growth rings in the butt logs of the first thinnings, second thinnings and final fellings were 56, 24 and 34 mm, respectively. In *Vaccinium* type, the corresponding values for the first and second thinnings were only 24 mm and 12 mm, respectively. Thus, based on our assessment, the 'P' specimens predominantly represent juvenile wood, while the 'N1/S1' specimens likely consist of both juvenile wood and mature wood – or solely mature wood depending on growth rate – and the N2/S2 specimens correspond to mature wood. The cumulative width was counted as the average of two opposite measurements from the pith outwards. In the analysis of variance, the differences in growth rate between the different stand types were statistically significant in *Myrtillus* type ($F(2,58) = 17.542$; $p < 0.001$), but not in *Vaccinium* type ($F(1,29) = 2.796$; $p = 0.105$).

In *Myrtillus* type forests, the higher growth rate of juvenile wood in the first-thinning stands compared to the older stands accounts for the observed differences in basic density. The growth of Scots pine trees is usually slowing down with the age (Kärenlampi and Riekkinen 2004; Knapic and Pereira 2005). In addition, the faster growth of the first-thinning trees may be due to the current, more intensive silvicultural practices, such as tending of sapling stands. We assume that regarding the proportions of juvenile wood, a difference between the first-thinning and second-thinning stands would have been observed also in drained peatlands. In drained peatlands, the first-thinning trees were relatively young at the time of this study and thus, the accelerated growth due to the drainage had started early, maybe even in the sapling phase of the forest. The second-thinning trees were markedly older and their growth had been very slow before the drainage, due to which the absolute volumetric proportion of juvenile wood could be expected to be lower in the second thinnings than in the first thinnings.

Table 5 Fixed coefficients of the square root transformation in the linear mixed model for the basic density (kg/m^3). Normal probability distribution is assumed

Variable	Estimate	Std. Error	95% Confidence Interval	
			Lower	Upper
Intercept	21.253	0.472	20.326	22.179
Site type (ref: Dwarf-shrub)				
Myrtillus	–1.243	0.419	–2.064	–0.422
Vaccinium	–0.143	0.421	–0.969	0.683
Calluna type	0.276	0.465	–0.635	1.188
Vaccinium vitis-idaea	–0.626	0.488	–1.582	0.331
Stand type (ref: Final felling)				
First thinning	–0.558	0.306	–1.157	0.041
Second thinning	0.094	0.339	–0.571	0.759
Cambial age	0.003	0.003	–0.002	0.008
Height position $\log_{10}$	–2.116	0.152	–2.415	–1.818
Interaction of site type and cambial age (ref: Dwarf-shrub * Cambial age)				
Myrtillus * Cambial age	0.024	0.003	0.018	0.030
Vaccinium * Cambial age	0.000	0.004	–0.007	0.007
Calluna * Cambial age	0.015	0.005	0.006	0.024
Vaccinium vitis-idaea * Cambial age	0.002	0.007	–0.011	0.016
Interaction of site type and height position $\log_{10}$ (ref: Dwarf-shrub * Height position $\log_{10}$)				
Myrtillus * Height position $\log_{10}$	1.006	0.159	0.694	1.318
Vaccinium * Height position $\log_{10}$	0.347	0.171	0.012	0.681
Calluna * Height position $\log_{10}$	–0.061	0.206	–0.465	0.343
Vaccinium vitis-idaea * Height position $\log_{10}$	0.701	0.193	0.323	1.079
Cambial age * Heigh position $\log_{10}$	0.027	0.001	0.025	0.030

Higher heartwood content in older stands might also explain the increase in density to some extent. According to Edvardsson et al. (2022), median age for the first heartwood ring formed in Scots pine is between 25 and 40 years in certain regions in Sweden. Uusitalo (2004) concluded that in southern Finland, the heartwood formation of Scots pine starts approximately at the cambial age of 20 years. Since the proportions of extractives such as pinosylvin, resin acids and free fatty acids increase during the heartwood formation, this may change not only the chemical properties but also the mechanical properties of wood (Bergström 2003; Pereira et al. 2003; Kärkkäinen 2007).

Table 6 Variation of random effects in linear mixed model for the basic density (kg/m^3)

Random effect	Variance	Fitting statistics	
Stand	0.057	R^2	0.471
Tree	0.346	Bias	0.06 (0.3%)
Log	0.245	RMSE	1.05 (5.3%)
Residual	0.566		

In our study, both the horizontal and vertical positions within a tree had a very significant effect on basic density. The coefficients for cambial age and height position indicated that the density increased along with the age from pith to bark and decreased from base to top. The results echoed the findings on Scots pine by Uusvaara (1974), where the tree age and height position within a tree were observed as significant factors when modelling the basic density. Auty et al. (2014) studied the within-tree variation of basic density in Scots pine using a mixed-effects model similarly to our study and proved that the wood density can be modelled with the factors such as the cambial age, growth ring width and the height position in the stem.

We observed that the interaction term of site type and cambial age was significant for basic density, thus implying a decrease in relative differences in basic density between the site types as cambial age increased. The corresponding trend was clearly noticeable in vertical position: in fertile site types, basic density decreased more slowly from the stump towards the top than in the less fertile site types. Moreover, there was a significant interaction between cambial age and height position, with density increasing more rapidly at higher positions for a given distance from the pith towards the bark.

Most of the unexplained variation was observed at the residual level (Table 6). Furthermore, unexplained variation at the tree and log levels was relatively high. This might be, i.e., due to the previous silvicultural actions in the stands or the spatial distribution of trees and its effects on root competition and light conditions. At the stand level the variance was relatively low. R^2 value, which describes how well the model explains the variability of observed data, is relatively good (0.471).

3.3 Shrinkage

The shrinkage of Scots pine wood was roughly 4% in the radial, 7% in the tangential and 0.3% in the longitudinal direction, while the volumetric shrinkage was 11%, on average (Table 7). The results were either comparable to or slightly lower than those reported in earlier studies. In the data from mature and later thinning stage Scots pines from Finland and Sweden, the radial shrinkage varied between 2% and 5% and the tangential shrinkage between 5.5% and 8.5%, depending on the cambial age, height position within

a tree and the geographical region (Grekin and Verkasalo 2010). In Czech Republic, Scots pine wood exhibited radial shrinkage ranging from 4.9 to 5.7% and tangential shrinkage ranging from 7.2 to 8.1%, in a study which compared two cutting regimes, the shelterwood method and clearcutting (Schönfelder et al. 2018).

Significant positive correlations were observed between radial shrinkage and density (0.161, $p<0.001$), tangential shrinkage and density (0.258, $p<0.001$), as well as volumetric shrinkage and density (0.296, $p<0.001$). According to general understanding, there is a positive relationship between density and the aforementioned shrinkage properties, but the relationship between longitudinal shrinkage and density is negative (Yao 1969; Dumail and Castera 1997; Calvo et al. 2006; Kärkkäinen 2007; Riesco Muñoz et al. 2008; Schönfelder et al. 2018; Hara et al. 2023). As an exception to the previous statement, compression wood, despite its higher density, is more prone to longitudinal shrinkage due to the deviating, high microfibril angle of the S_2 layer (e.g., Saranpää 1997; Bowyer et al. 2007). Moreover, compression wood is often linked with juvenile wood, as well as with high microfibril angle and spiral grain and therefore, it usually has a higher tendency for longitudinal shrinkage than the normal wood (Bowyer et al. 2007; Forest Products Laboratory 2010). In our data, however, the correlation of density and longitudinal shrinkage was not statistically significant ($p=0.839$). Statistically significant correlations were noted between the radial and tangential shrinkage (0.286, $p<0.001$), radial and longitudinal shrinkage (0.343, $p<0.001$) and tangential and longitudinal shrinkage (0.090, $p<0.001$).

Linear mixed models were constructed for the different shrinkage properties (Table 8). Based on the fixed coefficients, the stand type and original height position of a specimen significantly affected the radial, tangential and volumetric shrinkage values. All studied shrinkage properties, including the longitudinal shrinkage, varied markedly according to the radial position of a specimen.

The linear mixed models indicated the lowest radial, tangential and volumetric shrinkage values in the wood from the first thinnings (Table 9; Fig. 5a). Pairwise comparisons revealed significant differences in radial shrinkage between the first and second thinnings, with the second thinnings exhibiting a markedly higher shrinkage ($p=0.002$). The parameter estimates for radial shrinkage indicated 0.33% points lower value for the first-thinning wood than for the final-felling wood, while the shrinkage of the second thinning wood was 0.20% points higher than the final-felling reference. The differences between the first thinnings and final fellings ($p=0.118$), as well as between the second thinnings and final fellings ($p=0.362$) were not significant.

In the case of tangential shrinkage, all pairwise comparisons between the stand types were statistically significant ($p<0.001$), the first thinnings having the lowest and the final fellings the highest shrinkage. Based on the parameter estimates, the tangential shrinkage was 0.91% points smaller in the first thinnings than in the final fellings.

The differences in transverse shrinkage between the first thinnings and other stand types can be attributed to variations in wood density, the rapid growth of young, first-thinning-stage trees and the presence of juvenile wood. The radial and tangential shrinkages were positively correlated with density, which in turn, was significantly lower in the first thinnings than in more mature stand types (Tables 3 and 4). The low density is explained by the rapid growth rate of the first-thinning trees of this study, which leads to a higher proportion of earlywood rather than high-density latewood (Uusvaara 1974; Mäkinen et al. 2002). Due to its higher relative density, latewood tends to shrink more than

Table 7 Mean values and standard deviations of relative radial, tangential, longitudinal and volumetric shrinkages by the stand type in clear wood specimens

Stand type	Radial shrinkage	Tangential shrinkage	Longitudinal shrinkage	Volumetric shrinkage
	Mean ± Std. dev. (% ± %-points)			
First thinning	4.038 ± 1.291 (n = 1183)	6.981 ± 1.554 (n = 882)	0.430 ± 0.952 (n = 1187)	10.825 ± 2.283 (n = 877)
Second thinning	4.442 ± 1.329 (n = 1322)	7.158 ± 1.583 (n = 1017)	0.137 ± 0.964 (n = 1315)	11.249 ± 2.422 (n = 1011)
Final felling	4.195 ± 1.367 (n = 1010)	7.431 ± 1.606 (n = 821)	0.286 ± 0.762 (n = 1010)	11.414 ± 2.520 (n = 818)

Table 8 Fixed effects in the linear mixed models for radial, tangential, longitudinal and volumetric shrinkage (%)

Dimension	Radial				Tangential			
Source	F	df1	df2	p	F	df1	df2	p
Stand type	5.142	2	3509	0.006	24.516	2	2715	<0.001
Radial position	256.420	2	3509	<0.001	167.959	1	2715	<0.001
Height position	71.504	1	3509	<0.001	90.356	1	2715	<0.001
Dimension	Longitudinal				Volumetric			
Source	F	df1	df2	p	F	df1	df2	p
Stand type	1.883	2	3506	0.152	5.043	2	2701	0.007
Radial position	74.108	2	3506	<0.001	312.910	1	2701	<0.001
Height position	2.134	1	3506	0.144	198.060	1	2701	<0.001

Table 9 Fixed coefficients in the linear mixed model for radial, tangential, longitudinal and volumetric shrinkage (%). Normal probability distribution is assumed

Dimension	Radial				Tangential			
Variable	Estimate	Std. Error	t-Value	Sig.	Estimate	Std. Error	t-Value	Sig.
Intercept	4.833	0.185	26.057	<0.001	8.552	0.128	66.887	<0.001
Stand type (ref: Final felling)								
First thinning	–0.331	0.212	–1.564	0.118	–0.911	0.130	–6.992	<0.001
Second thinning	0.203	0.222	0.911	0.362	–0.454	0.117	–3.866	<0.001
Radial position (ref: N2/S2)								
P	0.219	0.046	4.749	<0.001	–	–	–	–
N1/S1	–0.623	0.039	–16.034	<0.001	–0.515	0.040	–12.960	<0.001
Height position	–0.037	0.004	–8.456	<0.001	–0.090	0.009	–9.506	<0.001
Dimension	Longitudinal				Volumetric			
Variable	Estimate	Std. Error	t-Value	Sig.	Estimate	Std. Error	t-Value	Sig.
Intercept	0.289	0.155	1.863	0.063	13.265	0.387	34.238	<0.001
Stand type (ref: Final felling)								
First thinning	0.092	0.178	0.517	0.605	–1.179	0.444	–2.658	0.008
Second thinning	–0.182	0.187	–0.970	0.332	–0.285	0.466	–0.611	0.541
Radial position (ref: N2/S2)								
P	0.300	0.027	11.116	<0.001	–	–	–	–
N1/S1	0.044	0.023	1.931	0.054	–1.054	0.060	–17.689	<0.001
Height position	–0.005	0.003	–1.461	0.144	–0.129	0.009	–14.073	<0.001

earlywood, with tangential shrinkage being particularly influenced by latewood (Kärkkäinen 2007). Based on the cumulative width of juvenile wood in different stand types, its proportion was markedly larger in the first thinnings than in the second thinnings or final fellings. Thus, the greater microfibril angle of the secondary wall in the juvenile wood area decreases the transverse shrinkage of the first-thinning wood (Bowyer et al. 2007; Kärkkäinen 2007).

For the longitudinal shrinkage, difference between the first and second thinnings was close to the significance limit ($p=0.053$), but statistically significant differences were not detected between any of the stand types, i.e., first thinnings and final fellings ($p=0.605$), or second thinnings and final fellings ($p=0.332$).

Where the volumetric shrinkage was concerned, statistically significant differences were detected between the first thinnings and second thinnings ($p=0.011$), as well as between the first thinnings and final fellings ($p=0.008$). The difference between second thinnings and final fellings was not statistically significant ($p=0.539$).

Within the stem cross-section only N1/S1 and N2/S2 specimens were included in the analyses of tangential and volumetric shrinkages (Table 9). Both in the radial and tangential directions, all pairwise differences between the radial sample positions were statistically significant ($p<0.001$). The model estimate for radial shrinkage was the highest in the pith-enclosed samples and the lowest in the N1/S1 samples, compared to the reference level of N2/S2 (Fig. 5b). The data was verified to eliminate potential measurement errors that could explain the unexpected shrinkage behaviour of P and N1/S1 samples. Kantieva et al. (2023) observed the lowest radial shrinkage of Scots pine between the pith and the medium of the tree radius, the most substantial differences being in the top part of the trunk. A similar pattern of radial shrinkage, with the highest values near the pith and followed by a rapid decline, was observed by Ruano et al. (2022) in a small dataset of black pine (*Pinus nigra*). In contrast to the results in this study, radial shrinkage remained stable in outer part of the tree after the rapid drop. In the models for Scots pine, radial shrinkage increased from the pith outwards and then stabilized, which was largely due to the composition of the sample from mature or close to mature forests (Grekin and Verkasalo 2010).

For the longitudinal shrinkage, the differences between P and N1/S1 as well as between P and N2/S2 were significant ($p<0.001$). In addition, the difference between N1/S1 and N2/S2 in the longitudinal shrinkage was close to the significance limit ($p=0.054$). These results were aligned with earlier studies, as the longitudinal shrinkage usually is markedly higher in the juvenile wood area than in the outer parts of the cross section, (e.g., Bowyer et al. 2007; Riesco Muñoz and Díaz González 2007). Ivković et al. (2009) noted similar trends for radiata pine, characterised with a

Table 10 Variation of random effects in linear mixed model for shrinkage and fitting statistics (in %-points)

Random effect	Radial	Tangential	Longitudinal	Volumetric
Tree	0.620	–	0.448	2.723
Log	0.102	1.404	0.088	0.760
Residual	0.905	0.872	0.305	1.998
Fitting statistics				
R^2	0.10.8	0.33.9	0.038	0.341
Bias	–0.08 (–1.8%)	–0.02 (–0.2%)	–0.03 (–10.4%)	–0.15 (–1.3%)
RMSE	1.27 (29.3%)	1.50 (20.8%)	0.90 (288.4%)	2.27 (20.1%)

steep decrease of longitudinal shrinkage from the juvenile wood area outwards.

For the volumetric shrinkage the differences between N1/S1 and N2/S2 samples were statistically significant ($p<0.001$) and the largest shrinkage was noted in the outermost samples. Similarly, for instance Riesco Muñoz et al. (2008) and Hara et al. (2023) reported a positive correlation between volumetric shrinkage and cambial age.

The parameter estimates indicated decreasing wood shrinkage upwards from the tree base. The radial shrinkage decreased by 0.037% points per metre, while the tangential and volumetric shrinkage decreased by 0.090 and 0.129% points, respectively. These results were in line with earlier research, confirming the effect of the height position (Yao 1969; Dumail and Castera 1997; Calvo et al. 2006; Riesco Muñoz et al. 2008; Schönfelder et al. 2018; Grekin and Verkasalo 2010; Hara et al. 2023). However, minor or insignificant effects of height position have also been reported (e.g., Ruano et al. 2022).

Variation of random effects and fitting statistics of the models are presented in Table 10. In radial shrinkage model, residual variation was the most substantial source of random variation. In tangential shrinkage model, variance on the log level was higher than the residual variation. Approximately 50% of the total random variation of longitudinal and volumetric shrinkages were on the tree level. R^2 values are the highest in tangential and volumetric shrinkage models. In longitudinal shrinkage, both bias and RMSE values were very high and R^2 value very low, which was most probably explained by the random inaccuracy of longitudinal shrinkage measurements as well as the low absolute shrinkage values in comparison to radial and tangential shrinkages.

The stem form defects and related reaction wood present in the harvested material may partly explain the variation in shrinkage values. However, a detailed analysis of the factors would require more information about the growth conditions and the external properties of the trees. Although clear wood specimens are expected to be free from defects, the simple visual inspection conducted in this study may have somewhat failed to detect the presence of reaction wood in the specimens.

4 Conclusion

The linear mixed model proved to be an effective method for assessing the impacts of multiple factors on basic density and the shrinkage properties of Scots pine wood. The results confirmed that wood with moderate or even relatively high basic density and acceptable shrinkage could be harvested from both final fellings and second thinnings.

The densities of second-thinning and final-felling wood were comparable. The relatively high age of the second-thinning trees likely explained their higher density. This may be attributed to a significant proportion of latewood and a low proportion of juvenile wood in the mature wood material. As a Scots-pine forest reaches the second-thinning stage, tree growth begins to stabilise. This leads to a steady increase in the proportion of latewood and the commencement of heartwood formation.

The linear mixed models indicated clear differences between the stand types in radial, tangential and volumetric shrinkage at a given distance to the pith. According to the model parameters, the lowest shrinkage values were observed in first thinnings. This may be attributed to the presence of juvenile wood, as well as changes in silvicultural practices over the decades. The initial growth of the current first-thinning forests has likely been accelerated by intensive forest management practices such as tree breeding, tending of sapling stands and drainage of peatlands. Consequently, these practices lead to lower wood density and a reduced tendency for shrinkage, particularly in the radial and tangential directions.

The significant residual variation observed in the shrinkage models can be partly attributed to random measurement errors, particularly in the case of longitudinal shrinkage. The data did not reveal any systematic errors. In general, the first-thinning wood showed a wider variation in the studied properties compared to other stand development classes, which may be due to the characteristics of immature wood material, such as juvenile wood. Furthermore, defects and the formation of compression wood diminish the suitability of wood for further processing and applications that require high quality standards. The stem form and other technical defects are especially prevalent in the thinning removal.

Our study highlighted the sensitivity of Scots pine wood properties to the effects of forest stands. Based on the observed density and shrinkage properties, raw material suitable for the wood products industry would be available from carefully selected first thinning forests. The differences between second thinnings and final fellings were mostly

insignificant, and the results confirmed that the properties of second-thinning wood are more consistent than those of first-thinning wood, enabling its use in applications requiring high density and reasonable shrinkage behaviour.

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Author contributions The project was initiated by Erkki Verkasalo. Reeta Stöd was responsible for coordinating data collection, laboratory measurements and drafting the initial versions of the manuscript. Juhani Marttila and Reeta Stöd analysed the data and prepared the final manuscript where Antti Haapala designed and created the figures. Writing the final manuscript was supervised by Erkki Verkasalo, Laura Tomppo and Antti Haapala. All authors contributed to the final manuscript and approved it.

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Data availability Data supporting the findings of this study are available from the corresponding author upon request.

Declarations

Competing interests The authors declare no competing interests.

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References

Äijälä O, Koistinen A, Sved J, Vanhatalo K, Väisänen P (2019) Metsänhoidon suositukset. https://metsanhoidonsuositukset.fi/fi. Accessed 3 July 2023

Aleinikovas M, Grigaliūnas J (2006) Differences of pine (*Pinus sylvestris* L.) wood physical and mechanical properties from different forest site types in Lithuania. Baltic for 12(1):9–13

Auty D, Achim A, Macdonald E, Cameron AD, Gardiner BA (2014) Models for predicting wood density variation in Scots pine. Forestry 87(3):449–458. https://doi.org/10.1093/forestry/cpu005

Bergström B (2003) Chemical and structural changes during heartwood formation in *Pinus sylvestris*. Forestry 76:45–53. https://doi.org/10.1093/forestry/76.1.45

Björklund L, Walfridsson E (1993) Tallvedens Egenskaper i Sverige – Torr-rådensitet, kärnvedhalt, Fuktighet och Barkhalt [Properties of pine wood in sweden: basic density, Heartwood content, moisture and bark content]. Swedish University of Agricultural Sciences, Department of Forest Products. Report 234. Swedish

Boutelje J (1973) On the relationship between structure and the shrinkage and swelling of the wood in Swedish pine (*Pinus sylvestris*) and spruce (*Picea abies*). Svensk Papperstidn 76(3):78–83

Bowyer JL, Shmulsky R, Haygreen JG (2007) Forest products & wood science. An introduction, 5th edn. Blackwell Publishing, Hoboken

Burdon R, Walker J, Megraw B, Evans R, Cown D (2004) Juvenile wood (*sensu novo*) in pine: conflicts and possible opportunities for growing, processing and utilization. N Z J for 49(3):24–31

Butterfield B (2003) Wood anatomy in relation to wood quality. In: Barnett JR, Jeronimidis G (eds) Wood quality and its biological basis. Blackwell Publishing Ltd, Hoboken, pp 30–52

Calvo CF, Cotrina AD, Cuffré AG, Piter JC, Stefani PM, Torrán EA (2006) Variación radial y axial del hinchamiento, del factor anisotrópico y de la densidad, en el *Eucalyptus grandis* de Argentina [Radial and axial variation of swelling, anisotropy and density, in Argentinean *Eucalyptus grandis*]. Maderas Cienc Tecnol 8(3):159–168. https://doi.org/10.4067/S0718-221X2006000300003

Carson S, Cown D, Mckinley R, Moore J (2014) Effects of site, silviculture and seedlot on wood density and estimated wood stiffness in radiata pine at mid-rotation. N Z J For Sci. https://doi.org/10.1186/s40490-014-0026-3

Cown DJ (1973) Effects of severe thinning and pruning treatments on the intrinsic wood properties of young radiata pine. N Z J for 3(3):379–389

Cown DJ (1974) Wood density of radiata pine: its variation and manipulation. N Z J Sci 19(1):84–92

Cown DJ (1992) Corewood (juvenile wood) in *Pinus radiata* – should we be concerned? N Z J Sci 22(1):87–95

Deng X, Zhang L, Lei P, Xiang W, Yan W (2014) Variations of wood basic density with tree age and social classes in the axial direction within *Pinus massoniana* stems in southern China. Ann Sci 71(4):505–516. https://doi.org/10.1007/s13595-013-0356-y

Dias A, Gaspar MJ, Carvalho A, Pires J, Lima-Brito J, Silva ME, Louzada JL (2018) Within- and between-tree variation of wood density components in *Pinus Nigra* at six sites in Portugal. Ann For Sci 75:58. https://doi.org/10.1007/s13595-018-0734-6

Dumail JF, Castera P (1997) Transverse shrinkage in maritime pine juvenile wood. Wood Sci Technol 31:251–264. https://doi.org/10.1007/BF00702613

Edvardsson J, Rögnvaldsson K, Helgadóttir EÞ, Linderson H, Hrafnkelsson B (2022) A statistical model for the prediction of the number of sapwood rings in Scots pine (*Pinus sylvestris* L). Dendrochronologia 74:1–11. https://doi.org/10.1016/j.dendro.2022.125963

Fengel D, Wegener G (1989) Wood: chemistry, ultrastructure, reactions. Walter de Gruyter, Berlin-New York, p p 613

Fernandes C, Gaspar MJ, Pires J, Silva ME, Carvalho A, Brito JL, Lousada JL (2017) Within and between-tree variation of wood density components in *Pinus sylvestris* at five sites in Portugal. Eur J Wood Prod 75:511–526. https://doi.org/10.1007/s00107-016-1130-2

Forest Products Laboratory, United States Department of Agriculture Forest Service (2010) Wood Handbook. Madison, Wisconsin. www.fpl.fs.fed.us. https://doi.org/10.2737/FPL-GTR-190

Fredriksson M, Bomark P, Broman O, Grönlund A (2015) Using small diameter logs for cross-laminated timber production. BioResources. https://doi.org/10.15376/biores.10.1.1477-1486

Fries A, Ericsson T (2009) Genetic parameters for earlywood and latewood densities and development with increasing age in Scots pine. Ann Sci 66:404. https://doi-org.ezproxy.uef.fi: https://doi.org/10.1051/forest/2009019

Gao Y, Fu Z, Zhou Y, Gao X, Zhou F, Cao H (2022) Moisture-related shrinkage behavior of wood at macroscale and cellular level. Polymers 5045. https://doi.org/10.3390/polym14225045

Gort-Oromi J (2010) Effects of genetic entry and spacing on growth and wood properties in Scots pine. Dissertation Univ East Finland. https://doi.org/10.14214/df.110

Grekin M, Verkasalo E (2010) Variations in basic density, shrinkage, and shrinkage anisotropy of Scots pine wood from mature mineral soil stands in Finland and Sweden. Balt for 16(1):113–125

Gryc V, Vavrčík H, Horáček P (2007) Variability in swelling of spruce (*Picea abies* [L.] Karst.) wood with the presence of compression wood. J Sci 53(6):243–252. https://doi.org/10.17221/2019-JFS

Guller B, Isik K, Cetinay S (2012) Variations in the radial growth and wood density components in relation to cambial age in 30-year-old *Pinus brutia* Ten. at two test sites. Trees 26:975–986. https://doi.org/10.1007/s00468-011-0675-2

Hakkila P (1966) Investigations on the basic density of Finnish pine, Spruce and Birch wood. Commun Inst Fenn 61(5):1–98

Hakkila P (1979) Wood density survey and dry weight tables for pine, Spruce and Birch stems in Finland. Commun Inst Fenn 96(3):1–59

Hakkila P, Kalaja H, Saranpää P (1995) Etelä-Suomen ensiharvennusmänniköt kuitu- ja energialähteenä [Pine stands as a source of the pulpwood and energy in the first thinning in Southern Finland]. Finnish Forest Research Institute. Research Papers 582. Finnish

Hakkila P, Repola J, Lindblad J, Kalaja H, Verkasalo E (2020) Mänty- ja kuusikuitupuun ominaisuudet Etelä-Suomessa – laadun vaihtelu ja hallinta [Properties of pine and spruce pulpwood in Southern Finland – quality variation and control. Luonnonvara- ja biotalouden tutkimus 25/2020. Luonnonvarakeskus, Helsinki. Finnish

Hannrup B, Ekberg I (1998) Age-age correlations for tracheid length and wood density in *Pinus sylvestris*. Can J for Res 28(9):1373–1379. https://doi.org/10.1139/x98-124

Hara E, Missanjo E, Kadzuwa H (2023) Variation of wood density and shrinkage characters of *Pinus Oocarpa* in Malawi. J Global Ecol Environ 18(2):19–31. https://doi.org/10.56557/jogee/2023/v18i28297

Hernandez R, Green DW, Kretschmann DE, Verrill SP (2005) Improved utilization of small-diameter Ponderosa pine in glulam timber. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, Wisconsin. https://doi.org/10.2737/FPL-RP-625

Huuskonen S, Hakala S, Mäkinen H, Hynynen J, Varmola M (2014) Factors influencing the branchiness of young Scots pine trees. Forestry 87:257–265. https://doi.org/10.1093/forestry/cpt057

International Organization for Standardization (1982) ISO 4858:1982 Wood – Determination of volumetric shrinkage

International Organization for Standardization (1975) ISO 3131:1975 Wood –. Determination of density for physical and mechanical tests

International Organization for Standardization (1981) ISO 4469:1981 Wood –. Determination of radial and tangential shrinkage

Ivković M, Gapare WJ, Abarquez A, Ilic J, Powell MB, Wu HX (2009) Prediction of wood stiffness, strength, and shrinkage in juvenile wood of radiata pine. Wood Sci Technol 43(3–4):237–257. https://doi.org/10.1007/s00226-008-0232-3

Jalava M (1945) Suomalaisen männyn, kuusen, koivun ja haavan lujuusominaisuuksista [Strength properties of Finnish pine, spruce, birch and aspen]. Metsätieteellisen tutkimuslaitoksen julkaisuja. Comm Inst For Fenn 33(3). Finnish

Kankare V, Saarinen N, Pyörälä J, Yrttimaa T, Hynynen J, Huuskonen S, Hyyppä J, Vastaranta M (2022) Assessing the dependencies of Scots pine (*Pinus sylvestris* L.) structural characteristics and internal wood property variation. Forests 13(3):397. https://doi.org/10.3390/f13030397

Kantieva EV, Snegireva SN, Platonov AD (2023) Izmenčivost' usuški drevesiny sosny v stvole dereva [Variability of shrinkage of pine wood in a tree trunk]. Izvestiâ Sankt-Peterburgskoj Lesotehnicheskoj Akademii 246:364–378. Russian. https://doi.org/10.21266/2079-4304.2023.246.364-378

Kärenlampi PP, Riekkinen M (2004) Maturity and growth rate effects on Scots pine basic density. Wood Sci Technol 38:465–473. https://doi.org/10.1007/s00226-004-0243-7

Kärkkäinen M (2007) Puun rakenne ja ominaisuudet [Wood structure and properties]. Metsäkustannus Oy, Hämeenlinna. Finnish

Kask R, Pikk J (2009) Second thinning Scots pine wood properties in different forest site types in Estonia. Baltic For 15(1):97–104

Kask R, Pikk J, Kangur A (2021) Effect of growth conditions on wood properties of Scots pine (*Pinus sylvestris* L). Forestry Stud 75(1):176–187. https://doi.org/10.2478/fsmu-2021-0019

Kellomäki S (1981) Effect of the within-stand light conditions on the share of stem, branch and needle growth in a twenty-year-old Scots pine stand. Silva Fenn 15(2):130–139. https://doi.org/10.14214/sf.a15052

Kimberley MO, Cown DJ, McKinley RB, Moore JR, Dowling LJ (2015) Modelling variation in wood density within and among trees in stands of New Zealand-grown radiata pine. N Z J For Sci 45:22. https://doi.org/10.1186/s40490-015-0053-8

Knapic S, Pereira H (2005) Within-tree variation of heartwood and ring width in maritime pine (*Pinus pinaster* Ait). For Ecol Manage 210:81–89. https://doi.org/10.1016/j.foreco.2005.02.017

Kollmann FFP, Côté WA Jr (1984) Principles of wood science and technology. Vol. 1. Solid wood. Springer–Verlag, Berlin Heidelberg

Lämsä P, Kellomäki S, Väisänen H (1990) Nuorten mäntyjen oksikkuuden riippuvuus puuston rakenteesta ja kasvupaikan viljavuudesta [Branchiness of young Scots Pines as related to stand structure and site fertility]. Folia For 746. Finnish

Larson PR (1969) Wood formation and the concept of wood quality. Yale University, school of Forestry. Bulletin No. 74. New Haven, Connecticut

Mäkinen H, Saranpää P, Linder S (2002) Wood-density variation of Norway spruce in relation to nutrient optimization and fibre dimensions. Can J for Res 32:185–194. https://doi.org/10.1139/x01-186

Mauno T (2021) Pieniläpimittaisen puun tulevaisuudet [The futures of small-diameter wood]. Master's Thesis, University of Eastern Finland. Finnish

Mutz R, Guilley E, Sauter UH, Nepveu G (2004) Modelling juvenile-mature wood transition in Scots pine (*Pinus sylvestris* L.) using nonlinear mixed-effects models. Ann For Sci 61:831–841. https://doi.org/10.1051/forest:2004084

Pang S (2002) Predicting anisotropic shrinkage of softwood. Part 1: theories. Wood Sci Technol 36:75–91. https://doi.org/10.1007/s00226-001-0122-4

Pereira H, Graça J, Rodrigues JC (2003) Wood chemistry in relation to quality. In: Barnett JR, Jeronimidis G (eds) Wood quality and its biological basis. Blackwell Publishing Ltd, Hoboken, pp 53–86

Repola J (2006) Models for vertical wood density of Scots pine, Norway spruce and birch stems, and their application to determine average wood density. Silva Fenn 40(4):673–685. https://doi.org/10.14214/sf.322

Richter C (2015) Wood characteristics: description, causes, prevention, impact on use and technological adaptation. Springer Int Publishing Switz. https://doi.org/10.1007/978-3-319-07422-1_1

Riesco Muñoz G, Díaz González J (2007) Características físicas de la madera de pino procedente de raleos en el noroeste de España [Physical properties of wood from thinned pines in northwest Spain]. Maderas Cienc Tecnol 9(3):233–244. Spanish https://doi.org/10.4067/S0718-221X2007000300004

Riesco Muñoz G, Soilán Cañas MA, Rodríguez Soalleiro R (2008) Physical properties of wood in thinned Scots pines (*Pinus sylvestris* L.) from plantations in northern Spain. Ann Sci. https://doi.org/10.1051/forest:2008026

Rikala J (2003) Spruce and pine on drained peatlands – wood quality and suitability for the sawmill industry. University of Helsinki, Department of Forest Resource Management, Publications 35. 147 p

Ruano A, García de Ceca JL, Cabrero JC, Hermoso E (2022) Shrinkage pattern assessment for black pine juvenile wood delimitation. Eur J Wood Prod 80:131–138. https://doi.org/10.1007/s00107-021-01736-9

Saranpää P (1997) Puun rakenne, ominaisuudet ja kasvu. (Tree structure, characteristics, and growth). Metsätiet Aikakausk. https://doi.org/10.14214/ma.6360

Sarkhad M, Ishiguri F, Nezu I, Aiso H, Ngadianto A, Tumenjargal B, Baasan B, Chultem G, Ohshima J, Yokota S (2022) Preliminary evaluation of anatomical characteristics of four common Mongolian softwoods. For Sci Technol 18:87–97. https://doi.org/10.1080/21580103.2022.2090452

Sauter UH, Mutz R, Munro BD (1999) Determining juvenile-mature wood transition in Scots pine using latewood density. Wood Fiber Sci 31:416–425

Schönfelder O, Zeidler A, Borůvka V, Bílek L, Lexa M (2018) Shrinkage of Scots pine wood as an effect of different tree growth rates, a comparison of regeneration methods. J For Sci 64:271–278. https://doi.org/10.17221/23/2018-JFS

Thörnqvist T (1990) Ungdomsved i barrträd [Juvenile wood in coniferous trees]. Sveriges Lantbruksuniversitet SIMS. Institutionen för Skog-Industri-Marknad studier. Rapport nr 10. Swedish

Toikka M (2024) Wood in energy generation 2023 (provisional). Natural Resources Institute Finland. https://www.luke.fi/en/statistics/wood-consumption/wood-in-energy-generation-2023-provisional. Accessed 28 May 2024

Torvelainen J, Forsman L, Outa-Pulkkinen P, Salo-Kauppinen R, Söderkultalahti P (2021) E-yearbook of food and natural resource statistics for 2020: Statistical facts on agriculture, forestry, fisheries and hunting in Finland. https://jukuri.luke.fi/handle/10024/551182. Accessed 17 January 2025

Uusitalo J (2004) Heartwood and extractive content of Scots pine in southern Finland: models to apply at harvest. Wood Fiber Sci 36(1):3–8

Uusvaara O (1974) Wood quality in plantation-grown Scots pine. Commun Inst Fenn 80(2):1–105

Uusvaara O (1981) Viljelymänniköistä saadun sahatavaran laatu ja arvo [The quality and value of sawn goods obtained from plantation-grown Scots pine]. The Finnish Forest Research Institute Research Papers 27, Finnish

Uusvaara O (1991) Havaintoja nuorten istutusmänniköiden oksikkuudesta ja puuaineen laadusta [Observations about the branchiness and wood quality of young plantation-grown Scots pine]. The Finnish Forest Research Institute Research Papers 377. Finnish

Vargas-Hernandez J, Adams WT (1991) Genetic variation of wood density components in young coastal Douglas-fir: implications for tree breeding. Can J Res 21(12):1801–1807. https://doi.org/10.1139/x91-248

Vargas-Hernandez J, Adams WT, Krahmer RL (1994) Family variation in age trends of wood density traits in young coastal Douglas-fir. Wood Fiber Sci 26:229–236

Varhimo A, Kojola S, Penttilä T, Laiho R (2003) Quality and yield of pulpwood in drained peatland forests: pulpwood properties of Scots pine in stands of first commercial thinnings. Silva Fenn 37(3):343–357. https://doi.org/10.14214/sf.494

Varmola M (1996) Nuorten viljelymänniköiden tuotos ja laatu [Yield and quality of young Scots pine cultivations]. The Finnish Forest Research Institute Research Papers 585. Finnish

Wall T, Fröblom J, Kilpeläinen H, Lindblad J, Heikkilä A, Song T, Stöd R, Verkasalo E (2005) Harvennusmännyn Hankinnan Ja Sahauksen kehittäminen. WOOD WISDOM -tutkimusohjelman Hankekonsortion Julkinen Loppuraportti. The Finnish Forest Research Institute Research Papers 943. Finnish

Watanabe U, Norimoto M, Fujita M, Gril J (1998) Transverse shrinkage anisotropy of coniferous wood investigated by the power spectrum analysis. J Wood Sci 44:9–14. https://doi.org/10.1007/BF00521868

Wilhelmsson L, Arlinger A, Spångberg K, Lundqvist SO, Grahn T, Hedenberg Ö, Olsson L (2002) Models for predicting wood properties in stems of *Picea abies* and *Pinus sylvestris* in Sweden. Scand J Res 17(4):330–350. https://doi.org/10.1080/02827580260138080

Wimmer R, Downes G (2003) Temporal variation of the ring width-wood density relationship in Norway spruce grown under two levels of anthropogenic disturbance. IAWA J 24:53–61. https://doi.org/10.1163/22941932-90000320

Yao J (1969) Shrinkage properties of second-growth Southern yellow pine. Wood Sci Technol 3:25–39. https://doi.org/10.1007/BF00349982

Ying L, Kretschmann DE, Bendtsen BA (1994) Longitudinal shrinkage in fast-grown loblolly pine plantation wood. Prod J 44(1):58–62

Yrjölä T (2002) Forest management guidelines and practices in Finland, Sweden and Norway. European Forest Institute. Internal Report No. 11

Zobel BJ, Sprague JR (1998) Juvenile wood in forest trees. Springer-Verlag, Berlin. https://doi.10.1007/978-3-642-74069-5

Zobel BJ, van Buijtenen JP (1989) Wood variation: its causes and control. Springer-, Berlin

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