European Journal of Forest Research (2026) 145:75
https://doi.org/10.1007/s10342-026-01906-5

RESEARCH

Temporal changes in wood density of Norway spruce in southern Finland: evidence from National Forest Inventory data

Harri Mäkinen[1] · **Pekka Nöjd**[2] · **Minna Räty**[1] · **Henrik Heräjärvi**[3]

Received: 7 October 2025 / Revised: 23 January 2026 / Accepted: 10 April 2026

Abstract

The annual volume increment in Finland has doubled over the past 100 years, primarily due to more efficient stand management practices. However, few studies have examined how wood density, an important parameter of wood quality, responds to changes in forest management and site conditions on a large scale. We compared the wood density of Norway spruce (*Picea abies* (L.) Karst.) in current stands to that 20 years earlier in southern Finland. Our analyses are based on extensive, statistically representative Finnish National Forest Inventory (NFI) data. Wood density profiles were measured from pith to bark on NFI cores sampled in 1999 and from 2018 to 2020. The results illustrated that young trees have grown 2–3 times faster in recent decades than in the past. This increased growth rate has not led to a noteworthy decrease in average wood density over time. However, at the level of individual trees, wood density around the pith decreased as the radial increment rate increased. Therefore, increasing the radial growth of young trees has negative consequences for wood density. An additional millimetre in the width of the innermost annual rings caused a 10–40 kg/m^3 decrease in density, with the change being greater the narrower the rings were. The difference between naturally regenerated and planted trees was not statistically significant; however wood density was lower in relatively fertile sites compared to medium-fertile sites. Our results suggest that, on a large scale, the more recently applied forest management methods have not decreased the average wood density compared to older methods. However, the radial increment of juvenile trees is faster, which results in a reduction of their wood density.

Keywords Forest management · Radial increment · Wood properties

Introduction

Forest management practices in the Nordic countries have undergone significant changes over the past seven decades. The increase in stand productivity per hectare resulting from more efficient management practices, facilitated by climate change, has been remarkable (Henttonen et al. 2017, 2024). The total growing stock and annual volume increment in Finland have increased by 84% and 100%, respectively, over the past 100 years (Korhonen et al. 2024). Since the 1990s, Norway spruce (*Picea abies* (L.) Karst.) has been the preferred species for regeneration in southern and central Finland. This propensity is due to the fact that cultivated Scots pine (*Pinus sylvestris* L.) and broadleaved stands are often damaged by the large moose population (e.g., Matala et al. 2020). Consequently, up to 80% of the clear-cut areas in Finland have been replanted with spruce in some years (Vaahtera et al. 2023).

Selective dimensional cutting was a common practice in Finland and Sweden until the 1950s (Lundqvist 2017; Rautio et al. 2025). Consequently, the current mature stands have largely regenerated naturally and initially developed under the canopy of larger trees. However, a shift towards clear-cutting and thinning from below occurred (Kuuluvainen et al. 2012), and artificial regeneration became prevalent in the early 1960s. Furthermore, thinnings have become more intense since the 1960s, largely due to wider

---

Communicated by Michaela Eder

✉ Harri Mäkinen
harri.makinen@luke.fi

[1] Natural Resources Institute Finland, Latokartanonkaari 9, 00790 Helsinki, Finland

[2] Riihimäki, Finland

[3] University of Eastern Finland, P.O.Box 111, 80101 Joensuu, Finland

strip roads resulting from the mechanisation of harvesting operations.

In the juvenile stage, the development of planted seedlings following a clear-cut differs from that of naturally regenerated trees or from that of trees following dimensional selective harvesting. Planted seedlings grow much faster due to limited competition for light, nutrients and water between trees (Sikström et al. 2020; Huuskonen et al. 2023). Furthermore, tree breeding has increased height and diameter growth by 10%–20% (Haapanen et al. 2016; Jansson et al. 2017). Currently, in Finland, a significant proportion of forests regenerated through a combination of clear-cutting and planting are approaching final felling. The difference in early development between planted and naturally regenerated stands has probably resulted in variations in wood properties, which may affect the value of the raw material in industrial processes.

Norway spruce is the most widely used tree species for load-bearing structural applications in Europe. CE marking of structural products has been mandatory in the EU since 2013; products without user safety information cannot be sold on EU markets. A crucial component of a CE marking is the strength grade, which must be defined for each individual sawn timber board. The mechanical properties of timber depend on factors such as knottiness, wood density, ring width and grain direction (EN 338, 2016; EN 1912, 2024). The wood surrounding the pith in coniferous sawlogs is highly valued at sawmills, as it is used to produce strength-graded timber. In case of a typical structural timber dimension of 50 × 100 mm, the material originates within a radius of around 60 mm from the log pith (e.g., Virtanen 2018). In contrast, sawn goods originating from closer to the log surface are used for non-structural applications, where aesthetic or durability requirements are mostly important. Therefore, the growth and resulting wood properties of trees during their juvenile stage are critical for the profitability of sawmilling operations.

Density is the most important quality parameter of wood. Regardless of the underlying cause, lower wood density is generally detrimental to most wood applications (e.g., Panshin and de Zeeuw 1980; Tyrväinen 1995). Insulation and transportability are among the few exceptions where low density is advantageous. Wood density also provides information about the properties of fibres used in pulp production and the energy content of wood used for incineration. In pine and spruce species, an increase in growth rate results in a decrease in wood density and delays the transition from juvenile to mature wood (e.g., Saranpää 2003; Jaakkola et al. 2006). In Norway spruce, when a tree grows faster, more lower-density earlywood cells are formed, whereas the number of denser latewood remains approximately the same. Consequently, the proportion of latewood is lower in wider rings, resulting in a reduction in mean density (e.g., Wimmer and Downes 2003; Jyske et al. 2008).

Several studies have highlighted concerns regarding wood density in planted spruce stands, suggesting that the increased growth rate may already be affecting wood quality (Pretzsch et al. 2018; Pukkala 2023; Krenn et al. 2024; Torresan et al. 2024). As saw logs are an essential part of the bioeconomy, accounting for over 70% of stumpage income in Finland, it is crucial to understand the impact of forest management and other factors on wood density. However, few studies have examined how wood density responds to changes in forest management and environmental conditions on a large scale, and even less information is available on density changes over time on a decadal scale (Pretzsch et al. 2018; Torresan et al. 2024).

Our study illustrates how forest management and changing environmental conditions have influenced the wood density of Norway spruce over time in southern Finland. In addition to the regional scale analysis, a model was constructed at the individual tree level to assess the effect of annual ring width during the juvenile stage on wood density around the pith. As a part of the Finnish National Forest Inventory (NFI), thousands of trees are cored at breast height (1.3 m) each year using an increment borer. The NFI dataset was used to compare the wood density of Norway spruce in recently cored trees with that of 20 years earlier. The analyses in this study are consequently based on extensive, temporally and geographically representative data (Tomppo et al. 2011).

Materials and methods

The NFI data

The NFI encompasses a systematic grid of sample plots distributed across Finland's land surface and covers all ownership types, with a rotation cycle of five years. The next round begins immediately after the previous one. The NFI comprises permanent plots, which are surveyed in consecutive inventories, and temporary plots, which are not revisited in subsequent inventories. Only the sample trees on temporary plots are cored. On angle-gauged sample plots (relascope sampling), every seventh tallied tree was selected as a sample tree (Tomppo et al. 2011). Following the transition to circular fixed-radius sample plots in 2014, sample trees in southern Finland have been selected based on cumulative basal area at 15 $m^2 ha^{-1}$ intervals (Korhonen et al. 2021).

For this study, the sample plots on mineral soils were selected from the Southern Savo, Pirkanmaa, Häme and Uusimaa regions in southern Finland where spruce is a common tree species (Fig. 1). In 2004, modifications were made

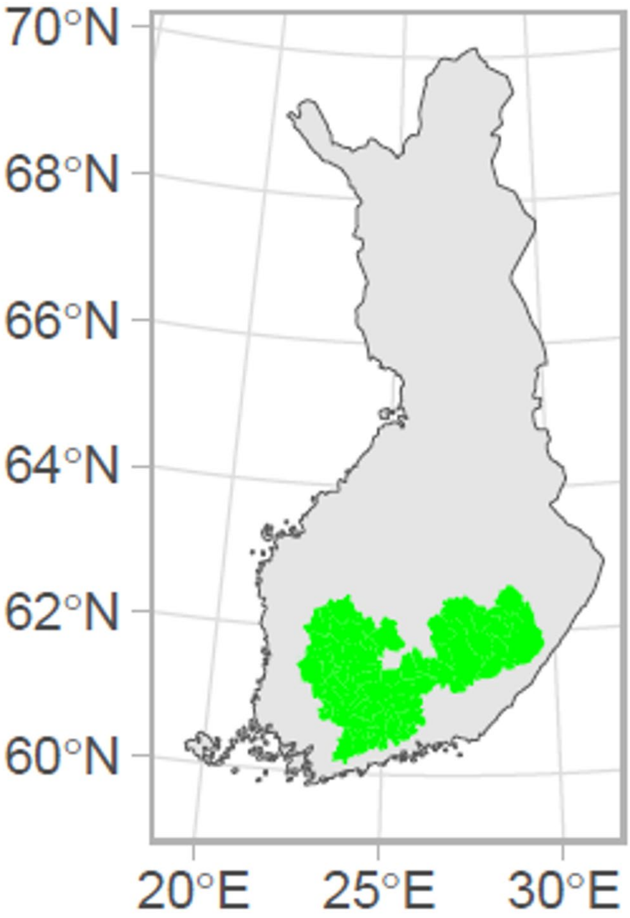

Fig. 1 The study region in southern Finland (green) where the increment cores were sampled in 1999 and 2018–2020

to the NFI fieldwork. Before these changes, field measurements were conducted on a regional basis, with one to three administrative regions being inventoried each year. Since 2004, however, the entire country has been included in the fieldwork each year. In addition, the proportion of permanent plot clusters without coring trees increased from 25% during the 9th inventory rotation (1996–2003) to 80% in the most recent NFI rotation. Wood density profiles were measured from pith to bark on a subset of NFI cores sampled in 1999 and from 2018 to 2020. The latter period included more years to obtain a comparable sample size to that of 1999.

As Norway spruce is a common tree species on herb-rich heath sites (i.e., on relatively fertile sites, OMT) and on mesic heath sites (i.e., on medium-fertile sites, MT) (Cajander 1949), a large majority of the sample trees included in the data originated from these types of sites. The sample comprises only a limited number of trees from relatively infertile sub-xeric sites (VT) (Cajander 1949), where Scots pine is the main tree species present. Accordingly, only a limited number of trees were included from the rare very fertile herb-rich sites.

Wood density measurements

Wood density measurements were taken on increment cores from dominant or codominant Norway spruce sample trees with no visible or only slight signs of damage. Typically, slight damage means that it has not, or only temporarily, affected the tree's growth and technical quality. Slight damage mainly comprises needle damage caused by unidentified insect or fungal species. The sampled trees were classified into 15-year age classes: 16–30, 31–45, 46–60, 61–75, 76–90, 91–105, and > 105 years (Table 1). All NFI cores that met the aforementioned health and age criteria were included in the study from the recent time period spanning from 2018 to 2020. In the 1999 data set, up to 65 trees belonging to the aforementioned age classes were included. If a class had more than 65 trees, only 65 were randomly selected. However, some increment cores were damaged during processing for density measurements, resulting in the final number of trees in all age classes being somewhat lower (Table 1).

The wood density of increment cores was measured using the QTRS-01X microdensitometer (Quintec Measurement Systems, Knoxville, USA). The system consists of an X-ray source and a detector, both connected to a computer for data acquisition. The system determines the absorption of radiation from a collimated beam of X-rays. That absorption at each measurement point is related to actual sample density based on the mass attenuation coefficient determined using calibration samples. To measure wood density, 1.6 mm thick strips were sawn from the air-dried increment cores and scanned at a resolution of 0.02 mm. Mean wood density values for the annual rings of each core were calculated from continuous density profiles. In addition, the mean wood density of the innermost 60 mm segment, from the pith outwards, was calculated to provide an indication of the wood density of a section typically used for strength-graded structural lumber. When calculating the mean wood density

Table 1 The number of measured samples in each age class of trees sampled in 1999 and from 2018 to 2020

	Age class							
	16–30	31–45	46–60	61–75	76–90	91–105	> 105	Total
1999	52	57	46	53	51	20	29	308
2018–2020	36	43	61	42	37	15	18	252
Total	88	100	107	95	88	35	47	560

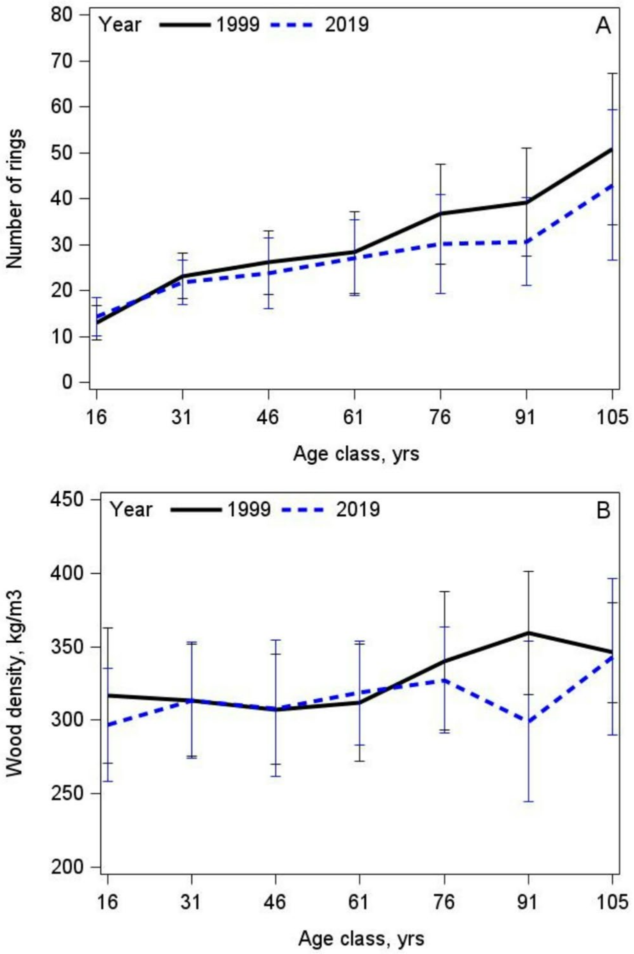

Fig. 2 The number of rings **A** and mean wood density **B** in the innermost 60 mm from the pith outwards, for each age class of trees sampled in 1999 and 2018–2020. The wood density of each ring was weighted according to its cross-sectional area

of each tree and the mean wood density of the innermost rings 60 mm from the pith, the density values of the individual rings were weighted by their basal area, assuming a circular cross-section.

Statistical analyses

The wood density data were analysed statistically using the ANOVA test with the mixed procedure of the SAS system, version 9.4 (SAS Institute Inc. 2023). This test was used to identify differences in wood density between regeneration methods (naturally regenerated and planted stands), site types and sampling dates. A p-value <0.05 was considered to indicate a statistically significant difference. In addition to analysing the mean values and their variance, we also calculated the skewness and kurtosis to provide a more comprehensive picture of the distributions. Skewness quantifies asymmetry, while kurtosis measures the heaviness of the tails, indicating the presence of outliers. Changes in skewness and kurtosis often signal how a tree population is responding to environmental factors and management. This helps identify structural differences or extreme density variations that may lead to mechanical failure, for example.

Table 2 The number of stems, mean wood density and its standard deviation, as well as skewness and kurtosis of the distributions, in naturally regenerated and planted stands, within the innermost 60 mm from the pith outwards, in age classes 16–30 and 31–45, for trees sampled in 1999 and 2018–2020

	N	Mean, kg/m^3	Std	Skewness	Kurtosis
Natural	112	315.1	42.8	0.89	1.80
Planted	76	305.8	38.0	0.26	− 0.15

There were only a few planted stands in the older age classes

We also developed a regression model to predict the mean wood density within a 60 mm radius from the pith outwards using the cores collected in 1999 and from 2018 to 2020. Different combinations of variables describing average growth rate in the innermost 60 mm, age classes, regeneration methods and site types, as well as their transformations, were tested.

Results

The number of rings within a distance of 60 mm from the pith outwards increased with increasing tree age (Fig. 2A), with older trees having grown more slowly when young. The average number of rings in the innermost 60 mm from the pith outwards was 13–14 for the 16–30 year age class, whereas the trees in the oldest age classes had almost three times more rings. On average, the trees sampled between 2018 and 2020 had slightly fewer rings than those sampled in 1999, except for the youngest age class. However, considering the variation, there were no significant differences between the sampling years.

Despite an increasing trend in the number of rings towards older age classes, no age-class-dependent trend in wood density around the pith was identified (Fig. 2B). Accordingly, no systematic differences were evident between the sampling years.

In the age classes of 16–30 and 31–45 years, no significant differences ($p=0.13$) in the average wood density within a distance of 60 mm outwards from the pith were found between the naturally regenerated and planted trees, with an average difference of 10 kg/m^3 (Table 2). The distributions of wood density for both regeneration methods were slightly skewed to the right, the naturally regenerated stands were slightly more so (Fig. 3; Table 2).

The wood density around the pith was approximately 20 kg/m^3 lower in the relatively fertile site type (OMT) than

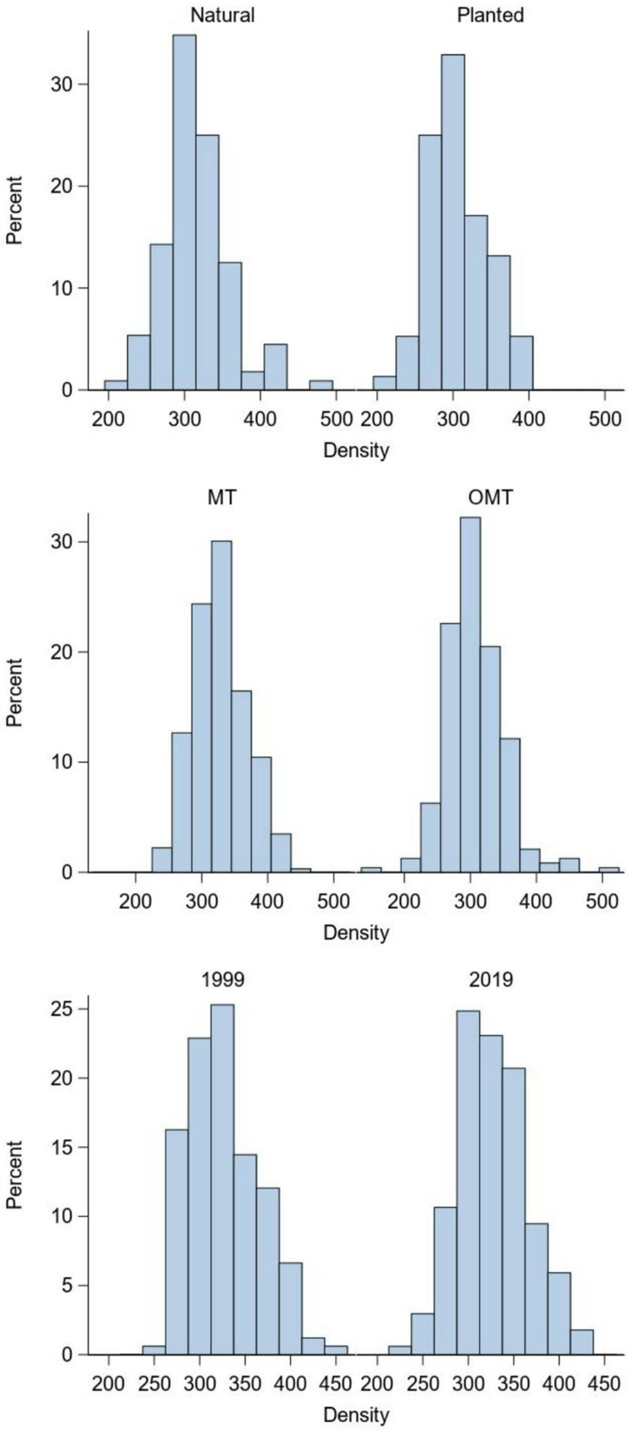

Fig. 3 The distributions of mean wood density (kg/m^3) in the innermost 60 mm from the pith outwards in the naturally regenerated and planted stands (top row), in the different site types (MT=medium fertile, OMT=relatively fertile) (middle row), and mean wood density of the entire increment cores of the stems with a diameter over 20 cm at breast height, sampled in 1999 and 2018–2020 (bottom row)

Table 3 The number of stems, mean wood density and its standard deviation, and skewness and kurtosis of the distributions in different site types, in the innermost 60 mm from the pith outwards, in all age classes of trees sampled in 1999 and 2018–2020

	N	Mean, kg/m^3	Std	Skewness	Kurtosis
Fertile,	3	389.2	89.0	–	–
Relatively fertile, OMT	239	306.4	43.9	0.76	3.10
Medium fertile, MT	316	327.6	40.1	0.25	− 0.28
Relatively infertile, VT	2	412.0	53.8	–	–

Table 4 The number of stems, mean wood density of the entire increment cores and its standard deviation, and the skewness and kurtosis of the distributions of stems with a diameter over 20 cm at breast height, sampled in 1999 and 2018–2020

	N	Mean	Std	Skewness	Kurtosis
1999	166	328.2	38.8	0.55	− 0.05
2018–2020	169	326.3	37.9	0.24	− 0.17

The wood density of each ring was weighted by its area

in the medium fertile type (MT) ($p<0.01$) (Table 3). As with the regeneration methods, the wood density distributions for both site types were slightly skewed to the right; the relatively fertile type exhibited a slightly greater skewness than the medium fertile site type (Fig. 3; Table 3). The number of stems in the fertile and relatively infertile (VT) types was very low ($N=3$ and 2, respectively), so they were excluded from the analysis.

No statistically significant difference ($p=0.65$) was found in the average wood density of log-sized trees (diameter at breast height over 20 cm) between the sampling years (Table 4). The wood density distributions for both sampling years were slightly skewed to the right (Fig. 3; Table 4).

Although the differences in mean wood density between the age classes were not significant, the wood density around the pith decreased with an increasing radial increment rate in all age classes in the trees sampled in both 1999 (Fig. 4) and 2018–2020 (Fig. 5). A model was compiled to predict wood density around the pith (*WD*), using the full data set combining both sampling dates (1999 and 2018–2020).

$$WD = \alpha_0 + \alpha_1 ln(ir) + \in \tag{1}$$

where *ln* is the natural logarithm. Variables describing age classes, regeneration methods and site types were tested, but only the average growth rate in the innermost 60 mm around the pith (*ir*) was statistically significant (Fig. 6; Table 5).

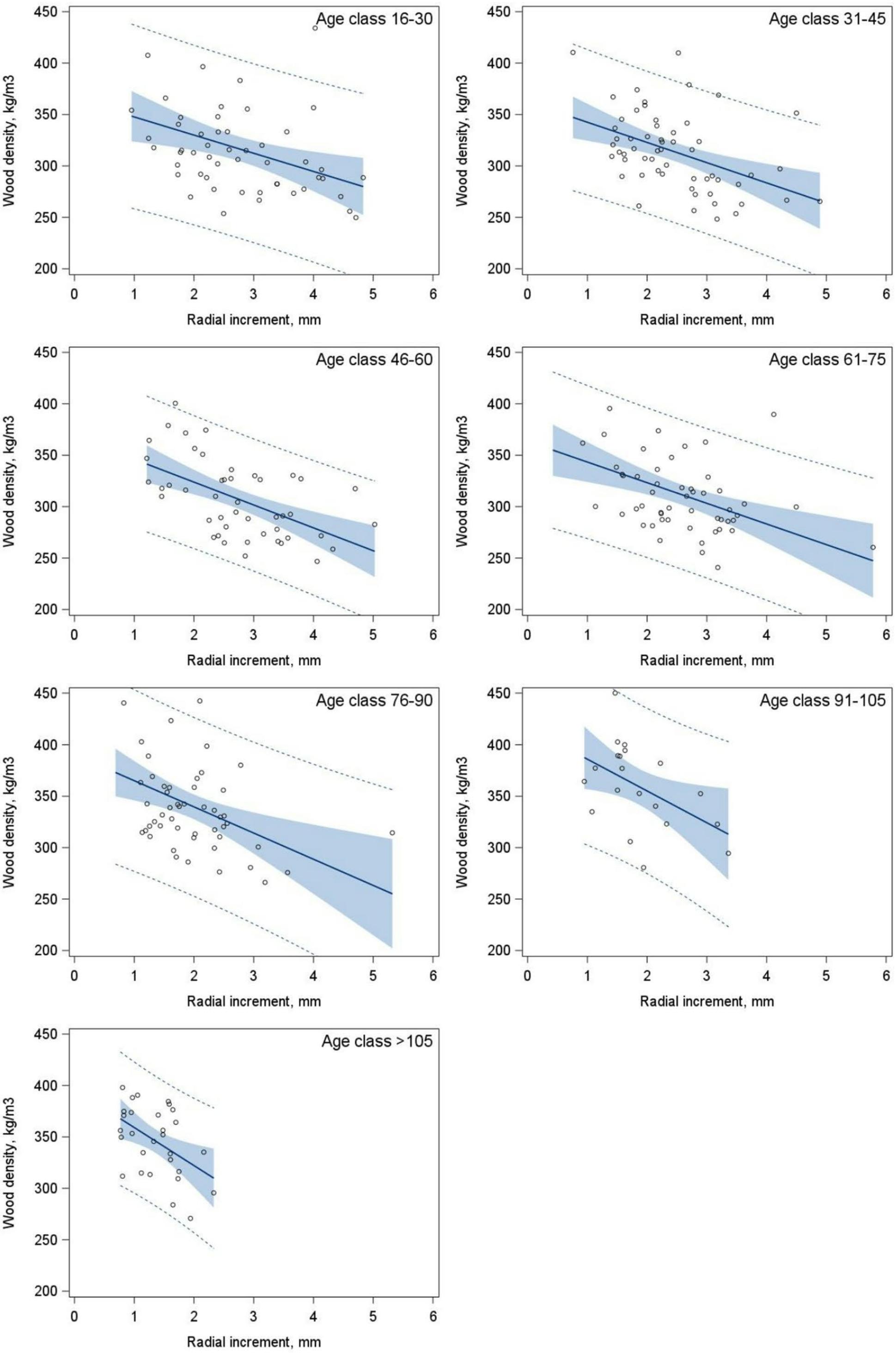

Fig. 4 Mean wood density in the innermost 60 mm from the pith outwards (circles) in relation to the mean ring width in different age classes in trees sampled in 1999, with a fitted linear regression line (solid line). The shaded area shows the 95% confidence limits, and the dashed lines show the 95% prediction limits

Discussion

Intensified forest management initiated during the 1950s and 1960s in Finland (Kuuluvainen et al. 2012), facilitated by climate change and tree breeding, has resulted in a remarkable increase in stand productivity (Haapanen et al. 2016; Henttonen et al. 2017, 2024). Accordingly, the results of this study demonstrate that young Norway spruces have grown more rapidly in recent decades than in the past. This change is primarily due to the efficient regeneration methods that follow clear-cutting. The implementation of efficient soil preparation and planting methods has resulted in the rapid development of young stands (Sikström et al.

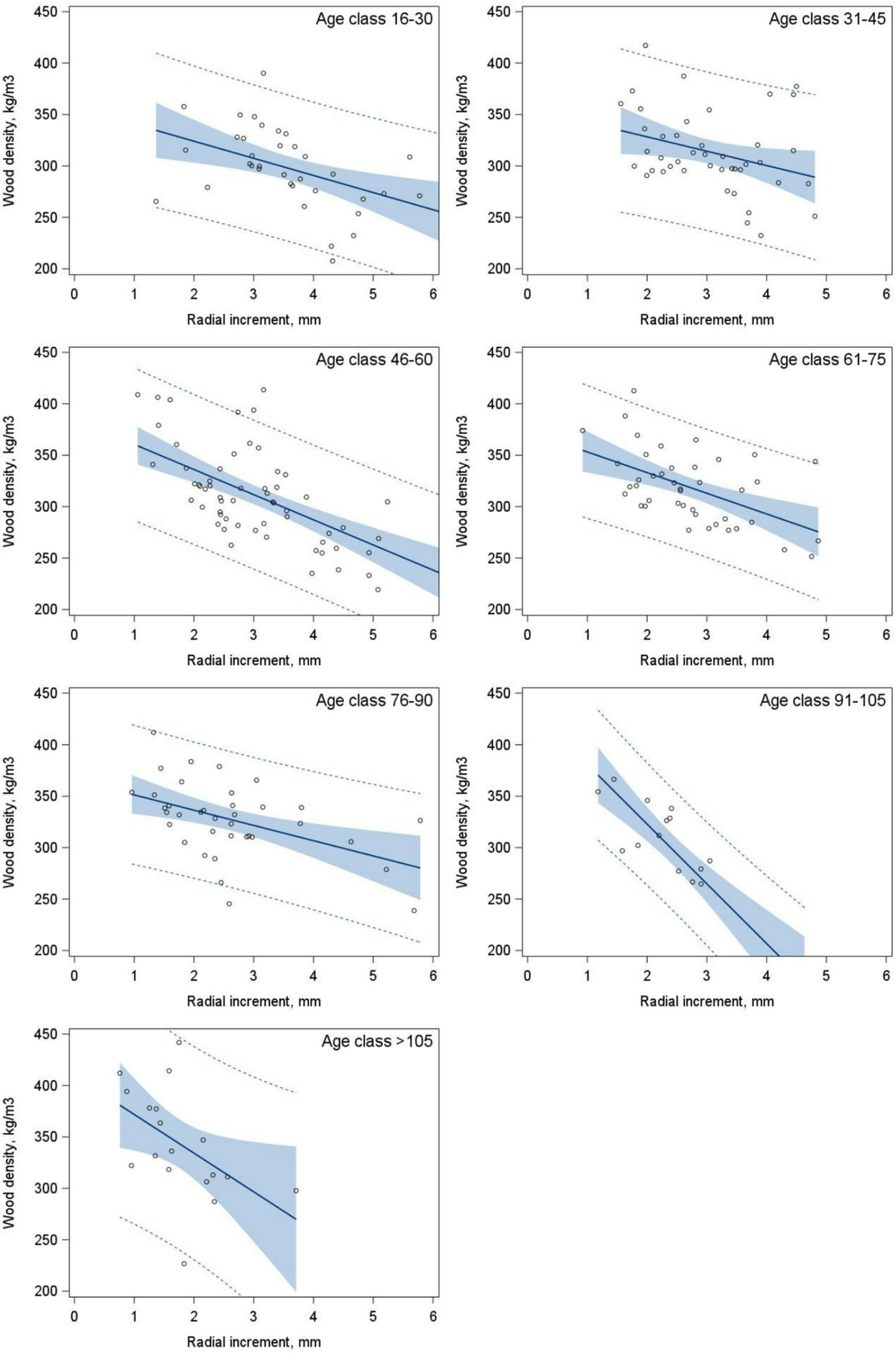

Fig. 5 Mean wood density in the innermost 60 mm from the pith outwards (circles) in relation to the mean ring width in different age classes in trees sampled in 2018–2020, with a fitted linear regression line (solid line). The shaded area shows the 95% confidence limits, and the dashed lines show the 95% prediction limits

2020). Timely early tending of sapling stands further accelerates the growth of the remaining trees.

At the regional scale, no significant differences in the mean wood density within a 60 mm radius of the pith were found between trees grown in past and recent decades, or between tree age classes. However, growth rates and wood densities varied more in the younger age classes than in the older ones. Consequently, the widest annual rings and lowest wood densities were predominantly observed in younger trees. Radial increment during the juvenile phase was 2–3 times faster in younger trees than in older ones. Moreover, a systematic negative correlation was found between wood density and ring width within 60 mm of the pith.

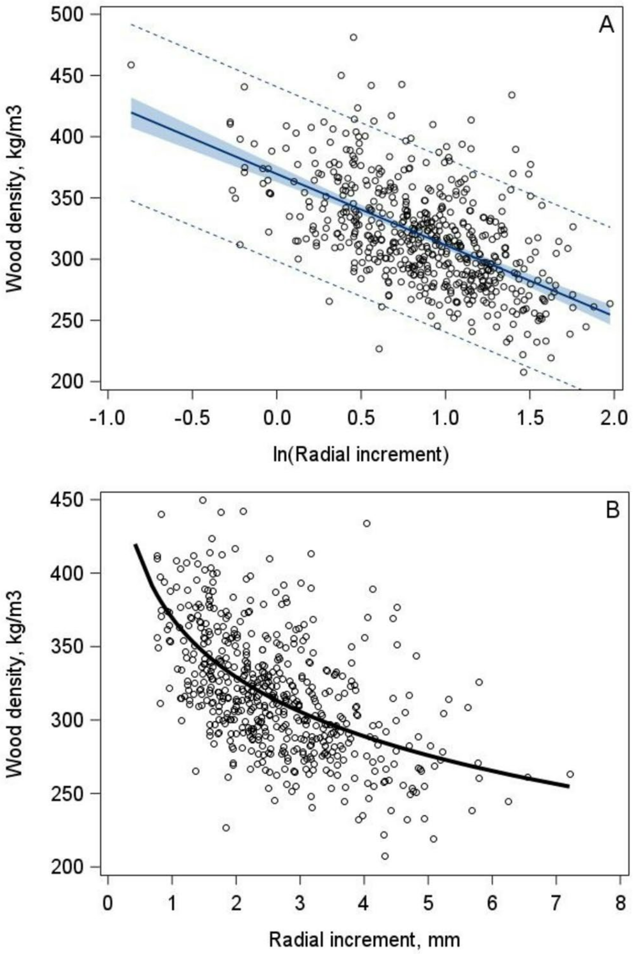

Fig. 6 Measured mean wood density in the innermost 60 mm from the pith outwards (circles) and the predicted wood density (Eq. 1, solid line). The shaded area represents the 95% confidence limits, and the dashed lines denote the 95% prediction limits. The lower figure demonstrates the model behaviour in terms of average increment rate

Table 5 Regression coefficients and their standard errors (SEs) for the model predicting the mean wood density in the innermost 60 mm from the pith outwards

Regression coefficients and statistics	Parameter estimates	SEs	*p* value
Intercept, α_0	369.57	3.43	<0.001
ln(*ir*), α_1	− 58.16	3.54	<0.001
RMSE	36.08		
R^2	0.33		

ir=mean ring width in the innermost 60 mm from the pith outwards

Contrary to the concerns about deteriorating wood quality, the findings of this study suggest that changes in regeneration practices (i.e., a shift from selective dimensional cutting towards clear-cutting, and from natural regeneration in the 1950s to artificial in the 1960s) and thinning intensity (i.e., from low intensity in the 1950s to high intensity in the 1960s) have not affected the mean wood density of Norway spruce in the southern regions of Finland. Moreover, the shapes of the wood density distributions were quite similar. The primary determinants of wood density are growth rate, tree age and heredity (e.g., Lindström 1996; Haapanen et al. 1997; Beets et al. 2007). Thus, it has been demonstrated that stand spacing, regeneration method, and site fertility affect wood density (e.g., Pape 1999; Mäkinen et al. 2002; Drew et al. 2009; Šilinskas et al. 2024). However, previous Finnish studies on Scots pine have shown that intensive thinning increases the growth of remaining trees by around 50%, but results in a relatively small reduction in wood density of 2%–8% compared with a delayed first thinning (Mäkinen and Hynynen 2014). Similarly, previous Finnish studies on Norway spruce (Jaakkola et al. 2005, 2006; Jyske et al. 2008) have shown that an increased growth rate resulting from thinning does not significantly impact wood density. Moreover, Jaakkola et al. (2005) concluded that a more pronounced growth increase in Norway spruce, exceeding that typically achieved through conventional thinning intensity, would be necessary to reduce wood density substantially. Hakkila (1966) demonstrated that differences in mean wood density between fast- and slow-grown Scots pine diminish with tree age, i.e., the most significant reduction in density due to a fast increment rate occurs in juvenile wood. Unlike previous studies (Jaakkola et al. 2006; Mäkinen and Hynynen 2014), which focused on the growth and density of wood formed after commercial thinning operations, our increment core sample mainly consisted of juvenile wood formed in the butt logs before the first commercial thinning, as it represented wood within a 60 mm radius around the pith at a height of 1.3 m. The results indicate that increasing the radial increment rate of young Norway spruce trees would have a negative impact on wood density. According to the model predicting mean wood density in relation to ring width, an additional millimetre in the width of the innermost annual rings results in an average density decrease of 10–40 kg/m^3. This decrease is more pronounced in slowly growing trees (cf., Hakkila 1966; Saikku 1975; Moltesen et al. 1985).

In addition to wood density, faster growth at a young age contributes to faster branch growth and larger knots (e.g., Uusvaara 1981; Nylinder 1990; Björklund and Petersson 1999). Wide annual rings during the first 10–20 years of growth also increase the diameter of the juvenile wood core. Due to the S_2 layer's thickness and high microfibril angle of the secondary cell wall, along with crystallinity, juvenile wood exhibits poor dimensional stability (e.g., Evans et al. 2000; Hakkila et al. 2020; Wang et al. 2024). These features are important quality parameters in wood product applications.

On average, growth increases by around 30% following nitrogen fertilisation in the Nordic countries (Gustavsen and Lipas 1975; Puro 1977; Saarsalmi and Mälkönen 2001), yet wood density typically decreases by 0%–5% (Ericson et al. 1972; Klem 1972; Saikku 1975). However, stands are usually fertilised at an older age, so the changes in wood density may not fully reflect the relationship between growth rate and wood density in young stands. In a nutrient optimisation experiment in a young Norway spruce stand, adding nutrients resulted in radial growth increasing by more than threefold and wood density decreasing by over 20% (Mäkinen et al. 2002). These results illustrate the potential magnitude of change that could be achieved by optimising the nutrient status of a young spruce stand.

Wood density near the pith clearly decreased as the radial increment rate increased. Although tree growth rates have increased over time, especially in young stands, the average differences in wood density between the age classes were not significant due to high density variation between trees. Accordingly, Mäkinen et al. 2002 also indicated that a significant proportion of the observed variation in wood density was due to random variation among individual trees.

In young forests (age group 16–30 years), the innermost 60 mm consists of fewer than 15 annual rings on average. In older stands (76 years and older) the respective number is 30–50 rings. This difference is very large, as the numbers are based on statistically representative data and thus reflect all spruce stands in the studied region. The natural regeneration of Norway spruce has been rare in Finland over the past few decades. Thus, the fast early growth of Norway spruces in recent decades reflects the efficiency of artificial regeneration following the clear cut (i.e., effective soil preparation, planting and tending of sapling stands).

As the NFI is based on systematic cluster sampling, the results are representative of forests in the selected region in southern Finland. However, unlike an organised experimental design, the NFI sample naturally exhibits considerable heterogeneity concerning site properties, management practices and other factors. Consequently, we could only monitor changes in wood density over time, rather than directly linking them to a specific combination of treatments. This lack of direct linking could potentially dilute the observed relationship between growth rate and wood density. Caution should also be exercised when interpreting trends over time, given that they are based on inventory-type data from temporary plots. It is possible that the observed slower initial growth rate in older stands is at least partially due to the felling of fast-growing mature stands and the retention of slower-growing ones. In selective dimensional cuttings, fast-growing trees are also more likely to be cut than slow-growing ones. On the other hand, NFI-based data enable us to evaluate how well the empirical outcomes obtained at the stand level align with changes observed in authentic environmental and management conditions.

Compared to wood sampled in the late 1990s, current forest management practices for young Norway spruce stands have little impact on average wood density on a regional scale. Furthermore, there was no difference in mean wood density near the pith among different age classes. However, on average, younger trees have a much wider range of annual ring widths than older trees. Consequently, the wood with the lowest density was found in young trees. Therefore, we recommend avoiding the intensive promotion of radial growth in young Norway spruce trees to prevent potential issues arising from low wood density. Denser stands are recommended for the first few decades until the innermost core of logs is developed.

Acknowledgements The study was conducted at Natural Resources Institute Finland (Luke). We want to thank Nina Pottonen and Tapio Ylimartimo at Luke for their dedication and expertise in the laboratory work.

Author contributions HM: writing – original draft, visualization, methodology, funding acquisition, formal analysis, data curation, conceptualisation; PN: writing – review & editing, funding acquisition, conceptualisation; MR: writing – review & editing, data curation, funding acquisition, conceptualisation; HH: writing – review & editing, funding acquisition, conceptualisation, project administration.

Funding Open access funding provided by Natural Resources Institute Finland. The study was supported by a grant from Puumiesten Ammattikasvatussäätiö. Conflicts of interest.

Data availability Data will be made available on request.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare that they have no known conflict of financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval Not applicable.

Consent for publication Not applicable.

Consent to participate Not applicable.

References

Beets P, Kimberley M, McKinley R (2007) Predicting wood density of *Pinus radiata* annual growth increments. N Z J Sci 37:241–266

Björklund L, Petersson H (1999) Predicting knot diameter of *Pinus sylvestris* in Sweden. Scand J Res 14:376–384. https://doi.org/10.1080/02827589950152700

Cajander AK (1949) Forest types and their significance. Acta Fenn 56:71. https://doi.org/10.14214/aff.7396

Drew DM, Downes GM, O'Grady AP, Read J, Worledge D (2009) High resolution temporal variation in wood properties in irrigated and non-irrigated *Eucalyptus globulus*. Ann Sci 66:1–10. https://doi.org/10.1051/forest/2009017

Ericson B, Friberg R, Nömmik H (1972) A trial with different amounts of fertilizer in a stand of *Pinus silvestris*. Föreningen Skogsträdsförädling och Institutet för Skogsförbättring, Ärsbok 1971. p. 87–110. (in Swedish with English summary)

Evans JW, Senft JF, Green DW (2000) Juvenile wood effect in red alder: analysis of physical and mechanical data to delineate juvenile and mature wood zones. Prod J 50(7/8):75–87

Gustavsen HG, Lipas E (1975) Effect of nitrogen dosage on fertilizer response. Folia For 246:20 (In Finnish with English summary). https://urn.fi/URN:ISBN: 951-40-0188-5

Haapanen M, Annala M-L, Velling P (1997) Progeny trial estimates of genetic parameters for growth and quality traits in Scots pine. Silva Fenn 31:3–12. https://doi.org/10.14214/sf.a8506

Haapanen M, Hynynen J, Ruotsalainen S, Siipilehto J, Kilpeläinen M-L (2016) Realised and projected gains in growth, quality and simulated yield of genetically improved Scots pine in southern Finland. Eur J Res 135:997–1009. https://doi.org/10.1007/s10342-016-0989-0

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

Hakkila P, Repola J, Lindblad J, Kalaja H, Verkasalo E (2020) Mänty- ja kuusikuitupuun ominaisuudet Etelä-Suomessa. Luonnonvara- ja biotalouden tutkimus 25/2020. Helsinki. 94 p. (In Finnish)

Henttonen HM, Nöjd P, Mäkinen H (2017) Environment-induced growth changes in the Finnish forests during 1971–2010: an analysis based on national forest inventory. Ecol Manage 386:22–36. https://doi.org/10.1016/j.foreco.2016.11.044

Henttonen HM, Nöjd P, Mäkinen H (2024) Environment-induced growth changes in forests of Finland revisited: a follow-up using an extended data set from the 1960s to the 2020s. Ecol Manage 551:121515. https://doi.org/10.1016/j.foreco.2023.121515

Huuskonen S, Lahtinen T, Miina J, Uotila K, Bianchi S, Niemistö P (2023) Growth dynamics of young mixed Norway spruce and birch stands in Finland. Forests 14:56. https://doi.org/10.3390/f14010056

Jaakkola T, Mäkinen H, Saranpää P (2005) Wood density in Norway spruce: changes with thinning intensity and tree age. Can J Res 35:1767–1778. https://doi.org/10.1139/x05-118

Jaakkola T, Mäkinen H, Saranpää P (2006) Wood density of Norway spruce: responses to timing and intensity of first commercial thinning and fertilization. Ecol Manage 237:513–521. https://doi.org/10.1016/j.foreco.2006.09.083

Jansson G, Hansen JK, Haapanen M, Kvaalen H, Steffenrem A (2017) The genetic and economic gains from forest tree breeding programmes in Scandinavia and Finland. Scand J Res 32:273–286. https://doi.org/10.1080/02827581.2016.1242770

Jyske T, Mäkinen H, Saranpää P (2008) Wood density within Norway spruce stems. Silva Fenn 42:439–455. https://doi.org/10.14214/sf.248

Klem G (1972) The influence of fertilization of spruce (*Picea abies* (L.) Karst.) and pine (*Pinus sylvestris* L.) on summerwood-percent, specific gravity and extractive content. Det Norske Skogforsöksvesen Meddelelser 122:283–324 (in Norwegian with English summary)

Korhonen KT, Ahola A, Heikkinen J, Henttonen HM, Hotanen J-P, Ihalainen A, Melin M, Pitkänen J, Räty M, Sirviö M, Strandström M (2021) Forests of Finland 2014–2018 and their development 1921–2018. Silva Fenn 55(5):10662. https://doi.org/10.14214/sf.10662

Korhonen KT, Räty M, Haakana H, Heikkinen J, Hotanen J-P, Kuronen M, Pitkänen J (2024) Forests of Finland 2019–2023 and their development 1921–2023. Silva Fenn 58(5):24045. https://doi.org/10.14214/sf.24045

Krenn T, Berthold D, Ritter N, Bietz B (2024) Effects of growth and treatment conditions on the quality of Norway spruce (*Picea abies* L.) sawn timber. Forests 15:1588. https://doi.org/10.3390/f15091588

Kuuluvainen T, Tahvonen O, Aakala T (2012) Even-aged and uneven-aged forest management in boreal Fennoscandia: a review. Ambio 41:720–737. https://doi.org/10.1007/s13280-012-0289-y

Lindstrom H (1996) Basic density in Norway spruce. Part I. A literature review. Wood Fiber Sci 28:15–27

Lundqvist L (2017) Tamm review: selection system reduces long-term volume growth in Fennoscandic uneven-aged Norway spruce forests. Ecol Manage 391:362–375. https://doi.org/10.1016/j.foreco.2017.02.011

Mäkinen H, Hynynen J (2014) Wood density and tracheid properties of Scots pine: responses to the timing of the first commercial thinning and fertilisation. Forestry 87(3):437–447. https://doi.org/10.1093/forestry/cpu004

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

Matala J, Kilpeläinen H, Heräjärvi H, Wall T, Verkasalo E (2020) Tree dimensions and log quality of Scots pine 34 years after artificial moose browsing damage. Silva Fenn 54(3). https://doi.org/10.14214/sf.10389

Moltesen P, Madsen TL, Olesen PO (1985) The influence of spacing on the production of dry matter and quality of Norway spruce. Forstl Forsøgsv Danm 40(2):53–76

Nylinder M (1990) Automatic grading of pine logs. Rapp Instn virkeslära Sveriges Lantbruksuniv 215:1–63 (In Swedish with English summary)

Panshin AJ, de Zeeuw C (1980) Textbook of wood technology, 4th edn. McGraw-Hill, New York, p 722

Pape R (1999) Influence of thinning and tree diameter class on the development of basic density and annual ring width in *Picea abies*. Scand J Res 14:27–37. https://doi.org/10.1080/02827589908540806

Pretzsch H, Biber P, Schütze G, Kemmerer J, Uhl E (2018) Wood density reduced while wood volume growth accelerated in Central European forests since 1870. Ecol Manage 429:589–616. https://doi.org/10.1016/j.foreco.2018.07.045

Pukkala T (2023) Kasvatetaanko kuusta päin mäntyä. [Are spruces grown wrongly?] Forest Issues. University of Eastern Finland. (in Finnish) https://blogs.uef.fi/forest-issues/2023/01/23/kasvatetaanko-kuusta-pain-mantya/

Puro T (1977) Results of the second fertilisation with nitrogen. Folia For 304:15 (In Finnish with English summary). https://urn.fi/URN:ISBN: 951-40-0268-7

Rautio P, Routa J, Huuskonen S, Holmström E, Cedergren J, Kuehne C (eds) (2025) Continuous cover forestry in boreal Nordic countries. Managing Forest Ecosystems, vol 45. Springer, Cham. https://doi.org/10.1007/978-3-031-70484-0

Saarsalmi A, Mälkönen E (2001) Forest fertilisation research in Finland: a literature review. Scand J Res 16:514–535. https://doi.org/10.1080/02827580152699358

Saikku O (1975) The effect of fertilization on the basic density of Scots pine (Pinus silvestris L). Commun Inst Fenn 85(3):1–49. https://urn.fi/URN:NBN:fi-metla-201207171119

Saranpää P (2003) Wood density and growth. In: Barnett JR, Jeronimidis G (eds) Wood quality and its biological basis. Biological sciences series. Blackwell Publishing Ltd., Oxford, pp 87–117

SAS Institute Inc (2023) SAS/STAT® 15.3 User's guide. Cary, NC

Sikström U, Hjelm K, Holt Hanssen K, Saksa T, Wallertz K (2020) Influence of mechanical site preparation on regeneration success of planted conifers in clearcuts in Fennoscandia: a review. Silva Fenn 54:10172. https://doi.org/10.14214/sf.10172

Šilinskas B, Varnagirytė-Kabašinskienė I, Aleinikovas M, Beniušienė L, Aleinikovienė J, Škėma M (2024) Scots pine and Norway spruce wood properties at sites with different stand densities. Forests 11:587. https://doi.org/10.3390/f11050587

Tomppo E, Heikkinen J, Henttonen HM, Ihalainen A, Katila M, Mäkelä H, Tuomainen T, Vainikainen N (2011) Designing and Conducting a Forest Inventory - case: 9th National Forest Inventory of Finland. Springer Netherlands

Torresan C, Hilmers T, Avdagić A, Di Giuseppe E, Klopčič M, Lévesque M, Motte F, Uhl E, Zlatanov T, Pretzsch H (2024) Changes in tree-ring wood density of European beech (*Fagus sylvatica* L.), silver fir (*Abies alba* Mill.), and Norway spruce (*Picea abies* (L.) H. Karst.) in European mountain forests between 1901 and 2016. Ann Sci 81:49. https://doi.org/10.1186/s13595-024-01264-5

Tyrväinen J (1995) Wood and fiber properties of Norway spruce and its suitability for thermomechanical pulping. Acta Fenn 249:7511. https://doi.org/10.14214/aff.7511

Uusvaara O (1981) The quality and value of sawn goods obtained from plantation-grown Scots pine. Res Notes Finnish For Res Inst 27:1–108 (In Finnish with English summary). https://urn.fi/URN:ISBN: 951-40-0697-6

Vaahtera E, Niinistö T, Peltola A, Räty M, Sauvula-Seppälä T, Torvelainen J, Uotila E (2023) Finnish statistical yearbook of forestry 2022. Natural Resources Institute Finland. 198 p. https://urn.fi/URN:ISBN:978-952-380-584-2

Virtanen S (2018) Sawmill's production planning. In: Varis R (ed) The sawmill industry handbook. Association of Finnish Sawmillmen. Otava Book Printing Ltd, Keuruu, Finland, pp 57–62

Wang X, Zhao W, Zhang Y, Shi J, Shan S, Cai L (2024) Exploring wood micromechanical structure: impact of microfibril angle and crystallinity on cell wall strength. J Build Eng 90:109452. https://doi.org/10.1016/j.jobe.2024.109452

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