Beyond planting scheme: tree diameter and micro-drilling resistance as predictors of wood density in a Norway spruce plantation

Gheorghe Ștefan[1,2], Alexandra Ștefan[1], Răzvan V. Câmpu[3]

[1] Câmpulung Moldovenesc Research Station, "Marin Drăcea" National Institute for Research and Development in Forestry, Romania; [2] Interdisciplinary Doctoral School, Transilvania University of Brașov, Romania; [3] Faculty of Silviculture and Forest Engineering, Transilvania University of Brașov, Brașov, Romania.
Corresponding author: A. Ștefan, Ispravnic.alexandra@gmail.com

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Abstract. Initial planting scheme can influence long-term stand development and individual-tree growth, potentially affecting wood properties in Norway spruce (*Picea abies* (L.) H. Karst.) plantation. However, the extent to which wood-density variation reflects initial stand density rather than individual-tree development remains unclear, as does the additional predictive value of micro-drilling resistance beyond conventional tree measurements. This study evaluated wood density and micro-drilling resistance in a 45-year-old Norway spruce plantation established at four initial planting scheme (2,500, 3,300, 5,000, and 7,510 trees ha^{-1}), arranged in four blocks. A total of 313 trees were analysed. Linear mixed-effects models were used to assess the effects of planting scheme and diameter at breast height (DBH) on wood density and micro-drilling resistance while accounting for the experimental structure. Initial planting scheme had no significant effect on wood density ($p = 0.332$) or micro-drilling resistance ($p = 0.383$), and remained non-significant after adjustment for DBH ($p = 0.752$ and $p = 0.231$, respectively). In contrast, DBH was significantly associated with both properties ($p < 0.001$), with wood density decreasing as DBH increased. Predictive models based on DBH and micro-drilling resistance were evaluated using leave-one-plot-out cross-validation across the 16 experimental plots. The model combining micro-drilling resistance and DBH showed the best predictive performance (RMSE = 0.0187 g cm^{-3}, MAE = 0.0147 g cm^{-3}, predictive R^2 = 0.387), reducing RMSE by 8.8% relative to the DBH-only model. The combined model also yielded lower RMSE values in 14 of the 16 plots (paired Wilcoxon signed-rank test, $p = 0.008$). Adding planting-density treatment did not further improve prediction. Overall, the results indicate that individual-tree development is more strongly associated with wood-property variation than initial planting density at the stand age investigated. Combining micro-drilling resistance with DBH provides a useful minimally invasive approach for improving wood-density estimation in standing Norway spruce, although its predictive accuracy at the individual-tree level remains moderate.

Keywords: *Picea abies*, initial planting density, wood density, micro-drilling resistance, predictive modelling.

Introduction. Norway spruce (*Picea abies* (L.) H. Karst.) is one of the most important coniferous species in European forestry because of its broad distribution, high productivity, and economic importance (Skrøppa, 2003; Caudullo et al., 2016). Its wood is widely used for structural applications and pulp and paper production, making wood quality an important consideration in forest management. Among wood-quality traits, wood density is particularly relevant because it is closely related to wood structure and mechanical performance (Lindström, 1996; Lundström et al., 2007; Steffenrem et al., 2007). However, wood density in Norway spruce is highly variable and is influenced by genetic factors, site and growing conditions, cambial age, growth rate, crown development, and silvicultural management (Lindström, 1996; Mäkinen et al., 2002; Jaakkola et al., 2006; Steffenrem et al., 2007).

Initial planting density is a major determinant of stand development because it regulates growing space and competition among trees (Nilsson, 1994; Gizachew et al., 2012). Consequently, initial spacing can affect crown and branch development, radial growth, stem diameter, mortality, and stand structure (Johansson, 1992; Nilsson, 1994; Pfister et al., 2007; Gizachew et al., 2012). Wider spacing generally promotes individual-

tree diameter growth, whereas closer spacing increases competition and may improve some stem-quality attributes through reduced branch dimensions (Johansson, 1992, 1993; Nilsson, 1994; Pfister et al., 2007). Nevertheless, the extent to which these long-term differences in stand development are reflected in wood properties remains less clear.

The relationship between stand density and wood density is complex because competition and growing space influence crown development, radial growth, annual-ring formation, and the relative proportions of earlywood and latewood (Kärkkäinen, 1984; Johansson, 1993; Lindström, 1996, 2000; Pape, 1999a, b; Jaakkola et al., 2005, 2006). Wood density in Norway spruce has consequently been associated with tree diameter, radial growth, annual-ring width, cambial age, crown characteristics, and tree social status (Kärkkäinen, 1984; Lindström, 1996, 2000; Mäkinen et al., 2002, 2007; Jyske et al., 2008). Studies of thinning and spacing further indicate that silviculturally induced changes in radial growth may modify wood density, although the magnitude and direction of these responses depend on treatment intensity and tree development (Pape, 1999a, b; Jaakkola et al., 2005, 2006). Long-term spacing experiments have therefore often revealed pronounced effects on tree dimensions and crown development but comparatively smaller effects on wood density (Johansson, 1993; Pfister et al., 2007).

Individual-tree size may provide an important link between stand density and wood properties. Diameter at breast height (DBH) integrates the cumulative effects of competition, growing space, site conditions, and individual growth history (Nilsson, 1994; Lindström, 1996, 2000; Pape, 1999a, b). Lower stand densities and greater growing space generally promote diameter growth in Norway spruce (Johansson, 1992; Nilsson, 1994; Pfister et al., 2007; Gizachew et al., 2012), whereas relationships between tree size, radial growth, and wood density have been repeatedly documented (Kärkkäinen, 1984; Lindström, 1996, 2000; Pape, 1999a, b; Jaakkola et al., 2006; Jyske et al., 2008). Recent provenance trials in the Romanian Carpathians have likewise reported negative relationships between wood density and growth traits, including DBH and total tree height (Alexandru et al., 2024). These findings suggest that DBH may capture individual-tree variation that is not adequately represented by initial planting density alone.

In addition to conventional increment-core measurements, minimally invasive techniques offer the possibility of assessing wood properties directly in standing trees. Resistance drilling is particularly promising because the resistance encountered by the drilling needle reflects radial variation in wood structure and density. Relationships between resistance-drilling measurements and wood anatomical characteristics have been demonstrated in Norway spruce, providing a biological basis for the use of micro-drilling resistance as an indicator of wood properties (Arnič et al., 2022). Furthermore, studies on standing Norway spruce have reported positive relationships between micro-drilling resistance and wood density and have shown that models combining resistance-drilling measurements with tree dimensions can improve wood-density estimation (Vlad et al., 2022b). Such approaches are particularly relevant when large numbers of standing trees need to be assessed while minimizing destructive sampling.

However, a statistically significant relationship between micro-drilling resistance and wood density does not necessarily imply strong predictive performance for previously unobserved trees or experimental plots. Prediction models may perform well on the data used for model fitting but lose accuracy when applied to independent observations, particularly when measurements are hierarchically structured within experimental plots. Out-of-sample validation is therefore essential for determining whether micro-drilling resistance provides predictive information beyond that already contained in readily available tree-level variables such as DBH. Cross-validation procedures that exclude entire experimental units during model calibration are particularly appropriate for this purpose because they reduce the risk of overestimating predictive performance through information shared among trees from the same plot.

Despite the substantial literature on spacing, tree growth, and wood formation in Norway spruce, comparatively few long-term studies have simultaneously examined initial planting density, individual-tree dimensions, conventional wood density, micro-drilling resistance, and out-of-sample predictive performance while explicitly accounting for the hierarchical structure of planting-density experiments. This distinction is important because

initial planting density may affect wood properties directly, indirectly through its influence on individual-tree development, or may provide little additional information once tree-level predictors are considered. Moreover, determining whether resistance drilling improves predictions beyond those obtainable from DBH alone is necessary to evaluate its practical value as a field-based method for wood-density assessment.

Therefore, the present study investigated a 45-year-old Norway spruce plantation established at four contrasting initial planting densities (2,500, 3,300, 5,000 and 7,510 trees ha^{-1}). The study had three main objectives: (i) to evaluate differences in wood density and micro-drilling resistance among initial planting-density treatments; (ii) to determine whether DBH explains variation in these wood properties after accounting for planting-density treatment and experimental block structure; and (iii) to evaluate the predictive performance of models based on DBH and micro-drilling resistance, separately and in combination, using leave-one-plot-out (LOPO) cross-validation. The contribution of planting-density treatment to predictive performance was also assessed to determine whether information on stand establishment improved predictions beyond tree-level measurements.

We hypothesized that (H1) initial planting scheme would be associated with wood properties through long-term differences in stand and individual-tree development; (H2) DBH would explain significant individual-tree variation in wood density and micro-drilling resistance beyond that attributable to planting-scheme; and (H3) combining micro-drilling resistance with DBH would improve out-of-sample prediction of wood density compared with models based on either predictor alone. We further expected that, if initial planting density exerted an additional persistent influence on wood density, including planting-density treatment in the predictive model would improve its performance when applied to trees from experimental plots excluded during model calibration.

Materials and Methods

Study site and experimental design. The study was carried out at the Tomnatic Experimental Station in the northern Eastern Carpathians, Romania.

The experiment was a Norway spruce (*Picea abies* (L.) H. Karst.) plantation established at four initial planting densities to evaluate the effect of stand density on wood properties: V1, 2,500; V2, 3,300; V3, 5,000; and V4, 7,510 trees ha^{-1}. The experiment was arranged in four blocks (R1–R4), each containing all four planting-density treatments, which resulted in 16 experimental plots (treatment × block combinations). Plot codes combine treatment and block (e.g., V1.R3).

At the time of measurement, the stand was 45 years old. The site lies at a mean elevation of 850 m a.s.l. on an average slope of 16°. The soil is a typical Dystric Cambisol (code 3201), and the site type is "Mountain Norway spruce forest, Bs, deep brown edaphic soil with *Asperula–Dentaria*". The corresponding fundamental forest type is "Mixed conifer–beech forest with mull flora from northern Romania (s)" (code 1312). Relative stocking was 1.0, and productivity was high (yield class I).

Tree measurements and wood properties. For each tree, diameter at breast height (DBH, measured at 1.30 m above ground), total tree height, height to the base of the crown and crown diameter were recorded. Wood density was determined from increment cores, and micro-drilling resistance was measured non-destructively on the same trees.
Wood density (g cm^{-3}) was determined individually for the sampled trees. Only trees without visible defects or damage were selected. Increment cores were extracted at breast height (1.30 m) with a Pressler increment borer. For each core, the total length to the pith and the length of the wood core excluding bark were measured. Cores containing decay, knots, resin pockets or other defects that could affect the measurements were discarded. The cores were oven-dried at 105 °C for 48 h. Wood (basic) density was calculated as the ratio of oven-dry mass to green volume (Chave, 2005).

Micro-drilling resistance was measured on the same trees, with the drilling point located within 5 cm of the core extraction point. This proximity minimized local variation in wood properties between the two measurements while avoiding overlap of the sampling

paths, as in previous resistance-drilling studies in which increment cores and drilling profiles were taken close to each other (Kahl et al., 2009; Arnič et al., 2022; Yao et al., 2024). Measurements were made with a Resistograph IML RESI F500-S (Instrumenta Mechanik Labor System GmbH, Wiesloch, Germany), and micro-drilling resistance was calculated as the weighted mean of the recorded resistance values.

The field measurements resulted in a database of 313 trees. The numbers of trees per planting scheme were V1 = 86, V2 = 82, V3 = 80 and V4 = 65.

Statistical analysis and cross-validation. The effects of planting-density treatment and DBH on wood density and micro-drilling resistance were analysed with linear mixed-effects models, with block (R1–R4) as a fixed effect and plot as a random intercept. Each response was first modelled with treatment and block and then with DBH added as a covariate.

The predictive performance of wood-density models was assessed by leave-one-plot-out cross-validation (LOOCV), which accounts for the experimental structure and prevents trees from the same plot from being used for both calibration and validation. In each of the 16 iterations, one entire plot was excluded, the model was fitted to the trees of the remaining 15 plots, and wood density was predicted for the trees of the excluded plot. Four models were compared: M0, DBH only; M1, micro-drilling resistance only; M2, micro-drilling resistance and DBH; and M3, M2 plus planting-density treatment (PT). Plot-level RMSE values of the models were compared with a paired Wilcoxon signed-rank test, and the uncertainty of the relative RMSE reduction of M2 compared with M0 was estimated by bootstrapping plots with replacement (5,000 resamples).

Predictive performance was quantified by the root mean square error (RMSE), the mean absolute error (MAE) and the predictive coefficient of determination (R^2_{pred}):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2},$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n} | y_i - \hat{y}_i |,$$

$$R^2_{\text{predictiv}} = 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y})^2}.$$

RMSE and MAE were expressed in the same units as wood density (g cm^{-3}). Lower RMSE and MAE values indicate smaller prediction errors, whereas higher (R^2_{pred}) values indicate that a greater proportion of the variation in observations excluded from model calibration is explained by the model; where y_i and $\hat{y}_i$ are the observed and predicted wood density of tree i, $\bar{y}$ is the mean observed wood density, and n is the number of trees.

Results and Discussion. The dendrometric characteristics and wood properties (Table 1) showed considerable variability within and among planting-density treatments. Mean DBH ranged from 22.6 to 25.1 cm, with the highest value in V2 and the lowest in V3, and mean wood density varied within a narrow range among treatments (0.336–0.342 g cm^{-3}). Mean micro-drilling resistance differed only moderately among treatments. The values of wood density and micro-drilling resistance therefore overlapped considerably among the four planting densities.

Table 1
Dendrometric characteristics and wood properties (mean ± SD) of the four initial planting-density treatments

Treatment	*n*	*DBH (cm)*	*Wood density (g cm $^{-3}$)*	*Micro-drilling resistance (%)*
V1	86	24.61 ± 7.77	0.336 ± 0.024	15.31 ± 4.05
V2	82	25.06 ± 7.84	0.336 ± 0.021	15.23 ± 4.67
V3	80	22.61 ± 6.76	0.340 ± 0.024	13.93 ± 5.61
V4	65	23.18 ± 7.02	0.342 ± 0.027	14.53 ± 5.12

n - number of trees included in the analysis; DBH - diameter at breast height; SD - standard deviation.

The distribution of wood density was similar across the four variants (Figure 1A). In the linear mixed-effects model, block was included as a fixed effect and plot as a random effect; initial planting density had no significant effect on wood density ($p = 0.332$), and the effect of block was not significant either ($p = 0.675$). This is consistent with the substantial overlap among the distributions in the boxplot: Tukey's multiple comparisons did not separate the treatments, all four of which belonged to the same homogeneous group.

Micro-drilling resistance likewise did not differ among planting-density treatments ($p = 0.383$; $p = 0.231$ after adjustment for DBH; Figure 1B), whereas DBH was significantly associated with it ($p < 0.001$).

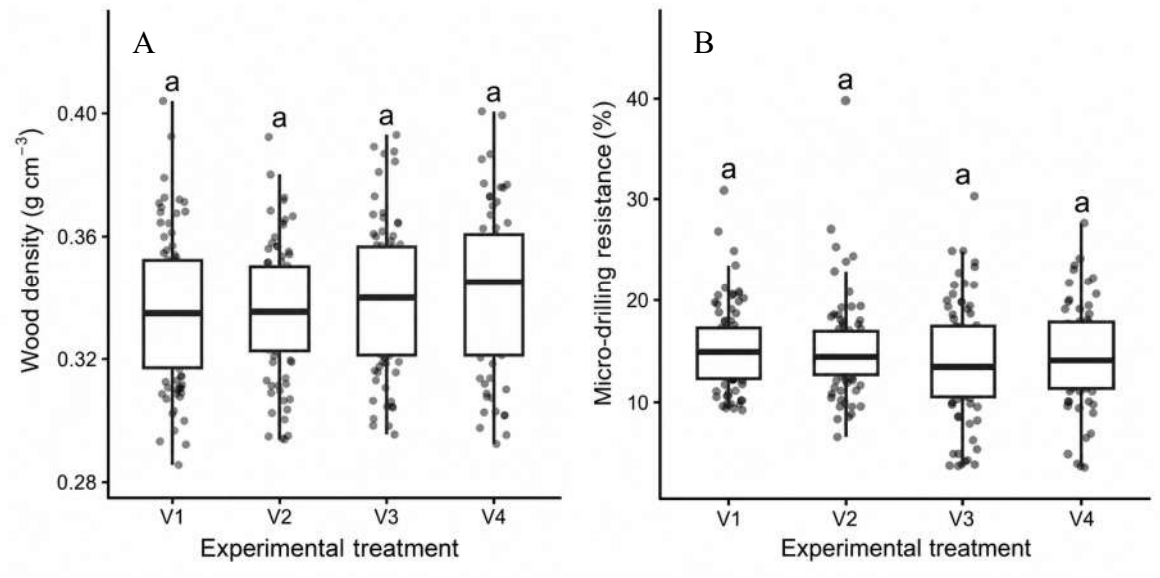


Figure 1. (A) Wood density and (B) micro-drilling resistance across the experimental planting variants (V1–V4).

After DBH was added as a covariate, the effect of planting-scheme remained non-significant ($p = 0.752$), whereas DBH was strongly associated with wood density ($p < 0.001$); the block effect also remained non-significant ($p = 0.400$). Variation in wood density among individual trees was therefore more strongly related to tree size than to initial planting density treated as a categorical factor.

The absence of a significant effect of initial planting density on wood density suggests that, at the present stand age, differences among the four treatments were small relative to the variability among individual trees. This agrees with earlier observations from the same experimental site, where mean wood density differed only slightly among planting densities of 2,500–7,510 trees ha^{-1} (Vlad et al., 2022a), and with Norway spruce thinning experiments in which light thinning had little or no direct effect on basic density, whereas more intensive interventions produced larger changes (Pape, 1999a, b).

The strong effect of DBH after accounting for planting-density treatment indicates that individual-tree size and growth history may predict wood density better than initial

planting density. This interpretation is supported by studies showing that basic density in Norway spruce is related to tree size, growth rate, ring width, crown development and social position in the stand (Kärkkäinen, 1984; Lindström, 1996, 2000; Pape, 1999a). Initial stand density may therefore affect wood density mainly indirectly, through competition, crown development, radial growth and tree dimensions, rather than through a direct treatment effect.

Wood density decreased significantly with increasing DBH in all four planting-density treatments ($p < 0.001$; Figure 2), although the strength of the relationship differed among treatments. The steepest decline was observed in V4 (slope = −0.0025 g cm^{-3} cm^{-1}), followed by V1 (−0.0021), V3 (−0.0017) and V2 (−0.0015). DBH explained a larger proportion of the variation in wood density in V1 ($R^2 = 0.484$) and V4 ($R^2 = 0.448$) than in V2 ($R^2 = 0.295$) and V3 ($R^2 = 0.260$). This consistent decrease in wood density with tree diameter agrees with earlier reports that wood density in Norway spruce is associated with tree diameter, radial growth and annual-ring width (Kärkkäinen, 1984; Lindström, 1996, 2000; Jyske et al., 2008).

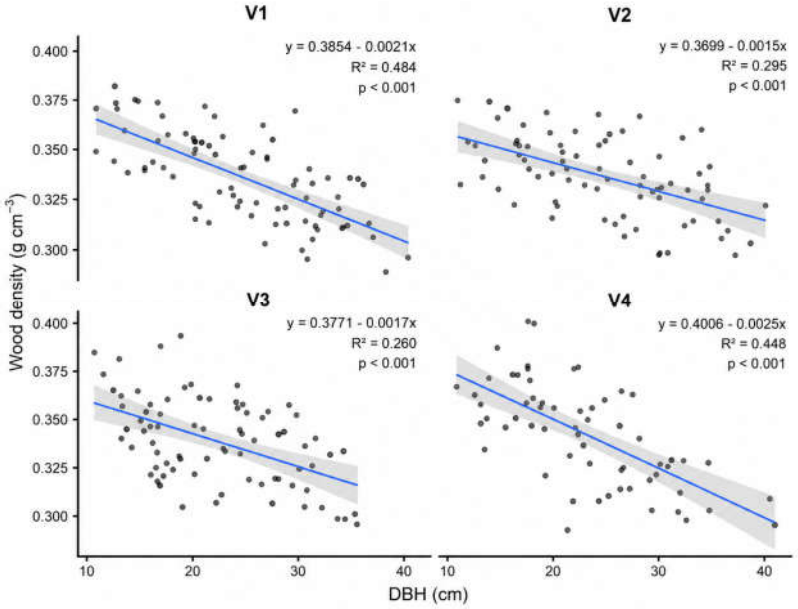


Figure 2. Relationship between diameter at breast height (DBH) and wood density across the four initial planting-scheme.

Wood density was then modelled as a function of micro-drilling resistance and DBH (model M2; Table 2). Wood density increased with micro-drilling resistance (+0.00211 g cm^{-3} per unit; 95% CI: 0.00166–0.00256; $p < 0.001$) and decreased with DBH (−0.00133 g cm^{-3} per cm; 95% CI: −0.00162 to −0.00105; $p < 0.001$). Per standard deviation, the two effects were similar in magnitude (about +0.010 and −0.010 g cm^{-3}, respectively), and the predictors were only weakly correlated ($r = -0.27$). Differences among blocks were small (intercepts between 0.336 and 0.343 g cm^{-3}) and non-significant for all contrasts relative to R1 ($p \geq 0.28$), and between-plot variation was small relative to the residual variation. The positive effect of micro-drilling resistance is consistent with the relationships between resistance-drilling profiles and wood anatomical features, particularly latewood width and tracheid dimensions, reported for Norway spruce (Arnič et al., 2022).
The prediction equations, expressed with uncentered predictors, had the form:

$$WD = b_0 + 0.00211 \times MR - 0.001331 \times DBH$$

where *WD* is the predicted wood density (g cm^{-3}), *MR* is micro-drilling resistance (%), *DBH* is diameter at breast height (cm), and b_0 is the block-specific intercept: 0.3383 (R1), 0.3361 (R2), 0.3390 (R3) and 0.3426 (R4).

Table 2

Fixed-effect estimates for the final model (M2), with standard errors, 95% confidence intervals and p-values

Term	*Estimate*	*Standard error*	*95% CI*	*p-value*
Intercept (R1. mean values)	0.3377	0.0025	0.3319 to 0.3434	<0.001
Micro-drilling resistance	0.00211	0.00023	0.00166 to 0.00256	<0.001
DBH	−0.001331	0.000145	−0.001616 to 0.001047	<0.001
Block R2 vs. R1	−0.0023	0.0036	−0.0104 to 0.0058	0.54
Block R3 vs. R1	0.0007	0.0037	−0.0075 to 0.0088	0.86
Block R4 vs. R1	0.0043	0.0037	−0.0040 to 0.0126	0.28

Wood density is expressed in g cm^{-3}. Predictors were mean-centered, so the intercept corresponds to block R1 at the mean values of micro-drilling resistance and DBH. The model includes a random intercept for plot. CI, confidence interval; DBH, diameter at breast height.

The predictive performance of the models was evaluated by leave-one-plot-out cross-validation (Loocv; 16 plots, N = 313 trees; Table 3). The model combining micro-drilling resistance and DBH (M2) had the best predictive performance (RMSE = 0.0187 g cm^{-3}, MAE = 0.0147 g cm^{-3}, predictive R^2 = 0.387). Relative to the DBH-only model (M0; RMSE = 0.0205 g cm^{-3}, predictive R^2 = 0.263), M2 reduced RMSE by 8.8%. The model based on micro-drilling resistance alone (M1) performed worse than the DBH-only model (RMSE = 0.0214 g cm^{-3}, predictive R^2 = 0.200), and adding planting scheme (M3) did not improve prediction (RMSE = 0.0190 g cm^{-3}, predictive R^2 = 0.371). Mean prediction bias was negligible for all models.

Table 3

Predictive performance of the models in leave-one-plot-out cross-validation (N = 313 trees; 16 plots)

Model	*RMSE*	*MAE*	*Bias*	*Predictive R^2*	*Δ RMSE vs. M0*
M2 (MD+DBH)	0.0187	0.0147	0.00005	0.387	−8.8%
M3 (M2 + PT)	0.0190	0.0149	−0.00001	0.371	−7.6%
M0 (DBH)	0.0205	0.0166	0.00005	0.263	–
M1 (MD)	0.0214	0.0173	0.00021	0.200	+4.2%

RMSE, MAE and bias are expressed in g cm^{-3}; predictive R^2 = 1 − SSE/SST. Number of folds with singular fits: M0 = 16, M3 = 16, M2 = 2, M1 = 0. RMSE, root mean square error; MAE, mean absolute error; ΔRMSE, percentage change in RMSE relative to M0; MD, micro-drilling resistance; DBH, diameter at breast height; PT, planting-density treatment.

The M2 predictions were well calibrated against the observations (slope of observed on predicted wood density = 0.93), but with considerable scatter around the 1:1 line (Figure 3). Predicted values were less variable than observed values (standard deviation 0.016 vs. 0.024 g cm^{-3}), which led to overprediction at the lower end and underprediction at the upper end of the observed range. The RMSE represented about 5.5% of the mean wood density (0.338 g cm^{-3}), corresponding to an approximate 95% prediction interval of ±0.037 g cm^{-3} for an individual tree.

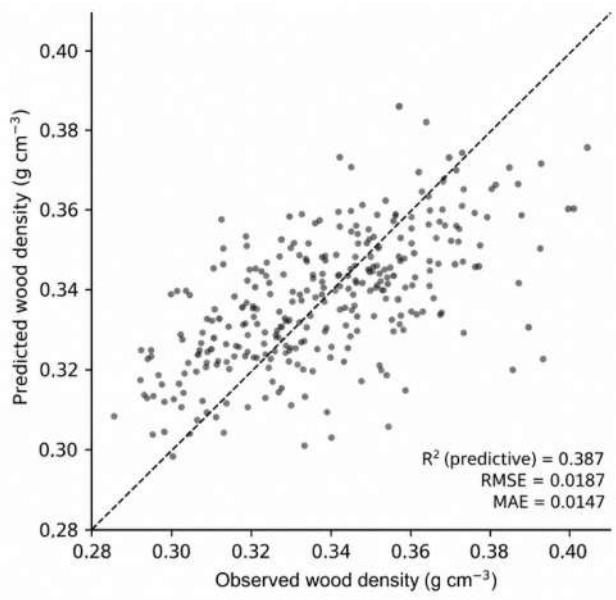


Figure 3. Observed versus predicted wood density in leave-one-plot-out cross-validation (model M2: micro-drilling resistance + DBH; N = 313 trees; 16 iterations). The dashed line is the 1:1 line.

Prediction error varied among plots, with RMSE ranging from 0.0142 g cm⁻³ (V1.R3) to 0.0269 g cm⁻³ (V3.R4; Figure 4). M2 yielded a lower RMSE than M0 in 14 of the 16 plots (paired Wilcoxon test, p = 0.008); the exceptions were V1.R4 and V3.R4. The median relative reduction in RMSE compared with M0 was 9.3% (plot-level bootstrap; 95% CI: 0.1–14.5%), so the improvement is probably real, although its magnitude is uncertain. Mean wood density per plot was not predicted (r = −0.14 between observed and predicted plot means), because observed plot means varied little (0.331–0.347 g cm⁻³); the predictive capability therefore derives from differences among trees within plots. Accordingly, H1 was not supported by the data, whereas H2 and H3 were supported.

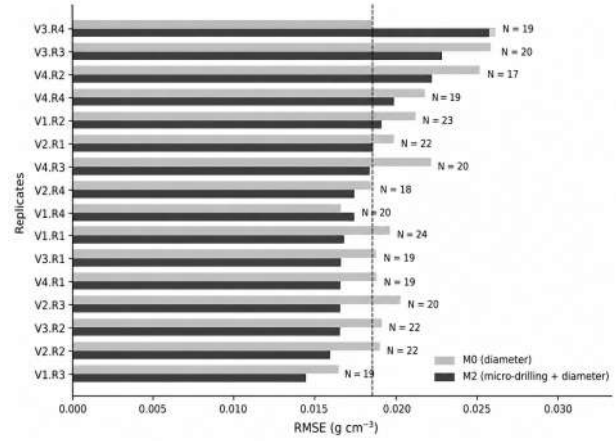


Figure 4. RMSE from leave-one-plot-out cross-validation for each plot. The dashed line is the overall RMSE of model M2 (0.0187 g cm⁻³); N is the number of trees per plot. Plot codes combine planting-density treatment (V1–V4) and block (R1–R4).

Limitations. Several limitations should be considered. The results derive from a single site and a single stand age and cannot be extrapolated to other stands without further validation. Predictive R^2 was moderate, and the models produced singular fits in several folds (M0 and M3 in all 16 folds, M2 in two), which indicates that between-plot variance was estimated close to zero and that the models behaved largely as fixed-effect regressions. Finally, predictions regressed toward the mean, so the approach is better suited to characterising general variation among trees than to estimating the density of an individual tree precisely.

Conclusions. Initial planting scheme had no significant direct effect on wood density or micro-drilling resistance in the 45-year-old Norway spruce stand investigated, despite initial densities ranging from 2,500 to 7,510 trees ha^{-1}. DBH, by contrast, was significantly associated with both properties, indicating that individual-tree development was more strongly related to wood-property variation than initial planting density treated as a categorical factor.

Wood density decreased with increasing DBH in all four treatments, and micro-drilling resistance provided additional information on wood-density variation. The model combining micro-drilling resistance and DBH (M2) had the best predictive performance in leave-one-plot-out cross-validation (RMSE = 0.0187 g cm^{-3}, MAE = 0.0147 g cm^{-3}, predictive R^2 = 0.387). Relative to the DBH-only model, it reduced RMSE by 8.8% overall and gave lower errors in 14 of the 16 plots; the median plot-level improvement was 9.3%, although its magnitude is uncertain.

Nevertheless, the model explained only a moderate proportion of the out-of-sample variation in wood density, prediction errors differed among plots, and predictions were less variable than observations (overprediction of low and underprediction of high densities). The model is therefore better suited to characterising general variation among trees than to obtaining precise density estimates for individual trees or predicting differences in mean density among plots.

Overall, the long-term influence of initial planting density on wood properties appears to operate mainly through its effects on individual-tree growth and stand development rather than through a persistent direct effect on wood density. In practice, combining micro-drilling resistance with DBH is a useful minimally invasive approach for improving wood-density assessment in standing Norway spruce, although further validation across stands, ages and sites is required before broader application.

Author Contributions. GȘ wrote the manuscript; AȘ and RVC read and revised it.

Conflicts of Interest. The authors declare that there is no conflict of interest.

Data Availability. The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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References

Alexandru, A. M., Mihai, G., Stoica, E., & Curtu, A. L. (2024). Variation in wood density among Picea abies provenances in the Romanian Carpathians. *Bulletin of the Transilvania University of Brasov. Series II: Forestry, Wood Industry, Agricultural Food Engineering, 17*(66)(1), 1–10. https://doi.org/10.31926/but.fwiafe.2024.17.66.1.1

Arnič, D., Krajnc, L., Gričar, J., & Prislan, P. (2022). Relationships between wood-anatomical features and resistance drilling density in Norway spruce and European beech. Frontiers in Plant Science, 13, 872950. https://doi.org/10.3389/fpls.2022.872950

Caudullo, G., Tinner, W., & de Rigo, D. (2016). Picea abies in Europe: Distribution, habitat, usage and threats. In J. San-Miguel-Ayanz, D. de Rigo, G. Caudullo, T. Houston https://doi.org/10.7892/boris.80794

Chave, J. (2005). Measuring Wood Density for Tropical Forest Trees. A Field Manual for the CTFS.

Gizachew, B., Brunner, A., & Øyen, B.-H. (2012). Stand responses to initial spacing in Norway spruce plantations in Norway. *Scandinavian Journal of Forest Research, 27*(7), 637–648. https://doi.org/10.1080/02827581.2012.693191

Jaakkola, T., Mäkinen, H., & Saranpää, P. (2005). Wood density in Norway spruce: Changes

with thinning intensity and tree age. *Canadian Journal of Forest Research, 35*(7), 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 fertilisation. *Forest Ecology and Management, 237*(1–3), 513–521. 10.1016/j.foreco.2006.09.083
Johansson, K. (1992). Effects of initial spacing on the stem and branch properties and graded quality of *Picea abies* (L.) Karst. *Scandinavian Journal of Forest Research, 7*(1–4), 503–514. https://doi.org/10.1080/02827589209382743
Johansson, K. (1993). Influence of initial spacing and tree class on the basic density of Picea abies. *Scandinavian Journal of Forest Research, 8*, 18–27. https://doi.org/10.1080/02827589309382752
Jyske, T., Mäkinen, H., & Saranpää, P. (2008). Wood density within Norway spruce stems. *Silva Fennica, 42*(3), 439–455.
Kahl, T., Wirth, C., Mund, M., Böhnisch, G., & Schulze, E.-D. (2009). Using drill resistance to quantify the density in coarse woody debris of Norway spruce. *European Journal of Forest Research, 128*(5), 467–473. DOI 10.1007/s10342-009-0294-2
Kärkkäinen, M. (1984). Effect of tree social status on basic density of Norway spruce. *Silva Fennica, 18*(2), 115-120.
Lindström, H. (1996). Basic density in Norway spruce. Part I. A literature review. *Wood and Fiber Science, 28*(1), 15–27.
Lindström, H. (2000). Intra-tree models of basic density in Norway spruce as an input to simulation software. *Silva Fennica, 34*(4).
Lundström, T., Heiz, U., Stoffel, M., & Stöckli, V. (2007). Fresh-wood bending: Linking the mechanical and growth properties of a Norway spruce stem. *Tree Physiology, 27*(9), 1229–1241. https://doi.org/10.1093/treephys/27.9.1229
Mäkinen, H., Jaakkola, T., Piispanen, R., & Saranpää, P. (2007). Predicting wood and tracheid properties of Norway spruce. Forest Ecology and Management, 241(1–3), 175–188. https://doi.org/10.1016/j.foreco.2007.01.017
Mäkinen, H., Saranpää, P., & Linder, S. (2002). Wood-density variation of Norway spruce in relation to nutrient optimization and fibre dimensions. *Canadian Journal of Forest Research, 32*, 185–194. https://doi.org/10.1139/x01-186
Nilsson, U. (1994). Development of growth and stand structure in *Picea abies* stands planted at different initial densities. *Scandinavian Journal of Forest Research, 9*, 135–142. https://doi.org/10.1080/02827589409382823
Pape, R. (1999a). Influence of thinning and tree diameter class on the development of basic density and annual ring width in *Picea abies*. *Scandinavian Journal of Forest Research, 14*(1), 27–37. https://doi.org/10.1080/02827589908540806
Pape, R. (1999b). Effects of thinning regime on the wood properties and stem quality of *Picea abies*. *Scandinavian Journal of Forest Research, 14*(1), 38–50. https://doi.org/10.1080/02827589908540807
Pfister, O., Wallentin, C., Nilsson, U., & Ekö, P.-M. (2007). Effects of wide spacing and thinning strategies on wood quality in Norway spruce (*Picea abies*) stands in southern Sweden. *Scandinavian Journal of Forest Research, 22*(4), 333–343. https://doi.org/10.1080/02827580701504951
Skrøppa, T. (2003). *EUFORGEN Technical Guidelines for Genetic Conservation and Use for Norway Spruce (Picea abies)*. International Plant Genetic Resources Institute, Rome, Italy. 6 pp.
Steffenrem, A., Saranpää, P., Lundqvist, S.-O., & Skrøppa, T. (2007). Variation in wood properties among five full-sib families of Norway spruce (*Picea abies*). *Annals of Forest Science, 64*, 799–806. https://doi.org/10.1051/forest:2007062
Vlad, R., Ispravnic, A., Dinca, L., Sidor, C., Cuciurean, C., & Stefan, G. (2022a). Influence of planting scheme on some physical properties of Norway spruce (*Picea abies* (L.) H. Karst) wood. *Forests, 13*(4), 540. https://doi.org/10.3390/f13040540
Vlad, R., Pei, G., Sidor, C. G., Cuciurean, C., Ispravnic, A., & Stefan, G. (2022b). Assessing standing-tree wood density by microdrilling in tending forestry work carried out on Norway spruce (*Picea abies* (L.) H. Karst) stands. *Forests, 13*(9), 1450.

https://doi.org/10.3390/f13091450
Yao, (2024). Research on the wood density measurement in standing trees through the micro drilling resistance method. *Forests, 15*(1), 175. https://doi.org/10.3390/f15010175

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Authors:
Gheorghe Ștefan (GȘ), Câmpulung Moldovenesc Research Station, "Marin Drăcea" National Institute for Research and Development in Forestry, Romania, e-mail: stefan_gigi2008@yahoo.com
Alexandra Ștefan (AȘ), Câmpulung Moldovenesc Research Station, "Marin Drăcea" National Institute for Research and Development in Forestry, Romania, e-mail: Ispravnic.alexandra@gmail.com
Răzvan Vasile Câmpu (RVC), Brașov, Faculty of Silviculture and Forest Engineering, Transilvania University of Brașov, Romania, e-mail: vasile.campu@unitbv.ro
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