Chapter

Influence of Silvicultural Operations on the Growth and Wood Density Properties of Mediterranean Pines

Daniel Moreno-Fernández, Andrea Hevia, Iciar Alberdi and Isabel Cañellas

Abstract

Silvicultural operations are widely used for forest regeneration and promotion of tree growth by reducing competition. The main aim of pruning, on the other hand, is to disrupt vertical fuel continuity and enhance wood quality, although the impact of silviculture on wood properties has scarcely been studied in the case of Mediterranean conifer forests. Our main goal is to synthesize the primary findings regarding the impact of thinning and pruning on tree growth and wood density of Mediterranean conifers. For this purpose, we used data from three thinning and pruning trials in Central Spain, specifically in forests of *Pinus sylvestris* and two subspecies of *Pinus nigra*. Our results indicate that thinning enhanced tree growth for the three species but did not significantly affect wood density. In contrast, no significant effects of pruning were observed, either on tree growth or on wood density. We concluded that thinning in combination with pruning is a suitable way to promote tree growth without compromising wood quality.

Keywords: knot-free timber, microdensitometry, Mediterranean forestry, sustainable forest management, timer quality

1. Introduction

High-quality wood, such as sawn wood and veneer, typically necessitates high-grade logs, large in diameter, containing mostly clear wood, with straight stems and a significant amount of heartwood [1]. For this, it is desirable that any knots are limited to a narrow central core in order to obtain the so-called clear wood [2], free of knots, of more valuable wood [3]. However, clear wood not only increases the quality of the highest-value by-products by removing visual defects but also reduces the influence of knots on the magnitude of pith eccentricity, stem curvature, and bending [1, 4, 5].

Besides the abovementioned wood properties that are desirable for high-quality uses, other characteristics such as wood density are a major physical criterion for wood quality [6] since they are related to many other aspects of quality such as wood strength and shrinkage, fiber properties, and flexibility or stiffness, among others [7, 8]. Furthermore, it has been demonstrated that wood density affects carbon storage [9–11].

The variability of wood density is not only dependent on the functional group or species [12, 13] but has also been observed to vary among provenances [14] and climate [15], a high level of variability being attributable to this factor. Other factors, such as site conditions or genetics, also affect wood density [16]. In addition, wood density does not remain constant across the trunk but varies both in radial (from pith to bark) and axial directions, forming juvenile and adult wood (also known as corewood and outerwood, respectively) [17, 18]. Furthermore, variations in wood density also occur at the intra-ring level because of the differentiation between early and latewood. Earlywood usually presents lower density values than latewood, although its section is normally larger [19]. In contrast to earlywood, the density and section of latewood increase with cambial age [20, 21]. In this regard, the proportion of latewood emerged as a key variable in the characterization of wood density.

Silvicultural treatments, such as thinning, have commonly been employed to reduce stand density and increase the diameter growth rates of the remaining trees [22, 23] having a major influence on wood quality [8]. Pruning operations, meanwhile, involve the removal of branches, which contributes to limiting knots and other branch-related defects to a central "knotty core" [13] resulting in more valuable wood (clear wood) [3]. Additionally, both operations can play a key role in the crown fire hazard [24] since thinning can reduce fuel loading and connectivity and pruning disrupts the vertical continuity of fuel, reducing the severity of forest fires [25]. On the other hand, pruning usually has a negative impact on tree diameter growth [3, 26, 27] although the magnitude of this effect depends on the proportion of crown removed by pruning [4, 28]. As regards the impact of silvicultural operations on wood density, most studies state that thinning has a limited impact on wood density [9, 20, 29, 30]. As for pruning, while [16] and [31] reported an increment in wood density after pruning, other authors such as [32] found no significant influence of pruning on wood density properties.

The way in which silviculture affects wood density is an important issue as higher growth rates coupled with lower wood density as a result of thinning and/or pruning operations could lead to bias in the estimation of forest biomass and therefore carbon accounting [33, 34].

The joint impact of thinning and pruning on tree growth and wood density has been poorly evaluated in Mediterranean conifer forests. In this study, our objective is to synthesize and evaluate the primary findings presented by [2, 35] regarding the impact of these silvicultural practices on tree growth and wood density. For this purpose, we used data from three thinning and pruning trials in Central Spain, specifically in forests of *Pinus sylvestris L.* and two subspecies of *Pinus nigra* Arnold. These species are important not only for the forestry sector in Spain but also from an ecological perspective.

2. Material and methods

2.1 Material

We used data from three thinning and pruning trials located in Central Spain. These experimental trials were established in monospecific reforestations of *P. sylvestris*, *Pinus*

Feature	*P. sylvestris*	*P. nigra*
Coordinates	40°520 N, 3°510 W	41°020 N, 3°040 W
Altitude (m asl)	1650	1050
Aspect	North facing	None
Slope (%)	10–40	0–3
Average annual rainfall (mm)	1062	620
Average annual temperature (°C)	7	10.5

Table 1.
Ecological characteristics of the thinning trials.

nigra subsp. *nigra* Arnold, and *Pinus nigra* subsp. *salzmannii* (Dunal) Franco. The trials were initiated at the beginning of the 1990s when the *P. sylvestris* stand was 37 years old, the *P. nigra nigra* 26 years old, and the *P. nigra salzmannii* 31. While both the *P. nigra* trials are adjacent and share similar ecological characteristics, the *P. sylvestris* stand is located at a higher altitude with colder and wetter conditions (see **Table 1**).

The *P. sylvestris* trial was initiated in 1991 when the first thinning was undertaken. Since then, five inventories have been conducted, in 1991, 1996, 2001, 2006, and 2011, including diameter at breast height measurements. The experiment consisted of nine permanent plots, each covering 0.1 hectares, with a 10 m buffer area to eliminate the edge effect (**Table 2**). Three treatments were applied (i.e., three plots per treatment): control treatment in which only dead trees were felled (C), thinning from below without pruning (T), and thinning from below combined with pruning (TP). Thinning intensity was around 30% in terms of basal area. In the TP treatment, trees were pruned to a height of 6 meters, and 40 dominant and codominant trees per plot were selected for pruning. This resulted in a stand density of 400 trees per hectare, ensuring an adequate number of pruned trees to achieve the desired stand density during the regeneration phase (200–300 trees per hectare).

In 2001, the second thinning operation (ca. 15% in basal area) was carried out in the study plots. However, it is important to note that one plot per treatment had to be excluded from the analysis due to a severe storm in January 1996, which resulted in significant snow-throws.

The *Pinus nigra nigra* experiment with six plots was established in 1993. Dasometric inventories were conducted in 1993, 1998, 2002, 2006, and 2011 (**Table 1**). **Figure 1** illustrates the appearance of a thinned plot in May 2023.

In the case of *Pinus nigra salzmannii*, the establishment, inventories, and thinnings followed the same schedule as the *Pinus nigra nigra* trial. The same three treatments (C, T, and TP), with two replicates in six plots (0.1 ha), were evaluated in the *P. nigra salzmannii* trial and in six plots of *Pinus nigra nigra*. Thinning intensity, however, was greater for *P. nigra nigra* (40% in terms of basal area) than for *Pinus nigra salzmannii* (25–30%) In 2006, the second thinning with an intensity of 16% of the basal area was performed in these two trials.

To investigate the impact of silvicultural operations on wood density, six cores were taken at a height of 1.3 m above ground level (breast height) from six trees per treatment and taxa in January 2013. Therefore, the full dataset included 18 cores for taxa, i.e., a total of 54 cores. These trees were selected from the second and third quartiles of the diametric distribution, representing the codominant trees within the stand. It is worth noting that both dominant and codominant trees were present in the stand

Treatment	First thinning					Second thinning				
	Age	N	Dg	BA	%BA	Age	N	Dg	BA	%BA
Pinus sylvestris										
C	37	2332	14.5	38.5	0.7*	47	1997	17.2	46.4	9.9*
T	37	2037	14.6	34.1	28.2	47	928	20.7	31.2	18.6
TP	37	2082	14.4	33.9	34.8	47	821	21.2	29.0	14.4
Pinus nigra nigra										
C	26	1392	18.2	36.2	0.0	39	1250	21.2	44.1	0.0
T	26	1447	17.8	36.0	41.9	39	725	23.6	31.7	17.6
TP	26	1455	17.7	35.8	40.2	39	756	23.3	32.2	16.5
Pinus nigra salzmannii										
C	31	1597	15.7	30.9	0.0	44	1446	18.1	37.2	0.0
T	31	1574	15.6	30.1	24.8	44	1064	19.6	32.1	16.9
TP	31	1498	16.6	32.4	30.4	44	907	20.9	31.1	16.9

*C = control treatment. T = thinning without pruning. TP = thinning with pruning the best trees. Adapted from [35]. *Natural mortality.*

Table 2.
Mean values of quadratic mean diameter (dg; cm) before thinning, basal area (BA; m^2 ha^{-1}) before thinning and percentage of basal area removed (%BA) per treatment and thinning intensity.

Figure 1.
Photograph of a P. nigra nigra thinned plot in May 2023 (author D. Moreno-Fernández).

until the start of the regeneration period. To obtain the wood cores, a 5 mm diameter increment borer was used. In the TP treatment, increment cores were exclusively taken from the pruned trees, as these were the focus of this particular treatment.

2.2 X-ray microdensitometry measurements

In the laboratory, each increment core obtained was mounted on a wooden holder. The cores were then cut into longitudinal radial strips, approximately 1 mm thick, using a twin-blade saw. To remove resins, the samples were refluxed in 96% ethanol using a Soxhlet apparatus. The refluxing process lasted 24 hours for *P. sylvestris* and 48 hours for *P. nigra*. The resulting thin strips were then stored under constant temperature and humidity conditions before being subjected to X-ray analysis. X-ray imaging was performed using an Itrax Multiscanner (Cox Analytical Systems, Mölndal, Sweden) at the CETEMAS laboratory in Asturias, Spain. The Multiscanner, equipped with a Cu-tube operating at 30 KV, 50 mA, 25 ms with 20 μm steps, produced radiographic images that were later analyzed using WinDendro software (Regent Instruments, Québec, QC, Canada). From the radiographic images, average wood density values for tree rings (*RD*, in g cm^{-3}) and the proportion of latewood density relative to the entire ring width (*LWP*, in %) were extracted. This extraction involved calibrating the greyscale intensities to wood densities using a light calibration curve derived from a calibration wedge [36]. Cross-dating accuracy was assessed using statistical parameters provided by the dendrochronological software COFECHA (University of Arizona, Tucson, AZ, USA) [37].

2.3 Statistical analyses

To evaluate the effect of the silvicultural operations on the stand variables and tree wood density of each taxon, we used linear mixed models. The assumption is made that measurements obtained from the same tree or plot exhibit a stronger correlation than those from different trees or plots. Additionally, measurements taken in closer proximity in time on the same tree or plot are expected to have a higher degree of correlation than those taken further apart in time [38, 39]. Consequently, the traditional assumptions of independent and homogeneous error variance are no longer applicable due to the inherent correlation pattern among observations. To solve this, we entered an autocorrelative structure of errors and random effects in the wood density models [39, 40]. As response variables, we considered the *id*, tree diameter increment (mm $year^{-1}$) calculated as the ratio of the difference between two consecutive forest inventories and the temporal lapse between inventories, *RD*, ring density (g cm^{-3}), and *LWP*, percentage of latewood (%). Thus, the linear mixed model included an intercept, treatment, Time (periods between inventories for *id* and year for *RD* and *LWP*), as well as their interaction, as fixed effects. The model also included random intercept effects for the tree and plot to account for the abovementioned correlations. Both random effects follow a normal distribution with mean zero and variance σ_b^2 and σ_s^2. We included the diameter recorded in the previous inventory and the ratio of the basal area of larger trees to the plot basal area (*BAL/B*) in the *id* model to control the effects attributable to tree size and competition [41, 42]. In the dataset for *P. sylvetris*, there were 1533 *id* observations for C, 696 for T and 630 for TP. Meanwhile, the dataset for *P. nigra* contained 1025 *id* observations for C, 549 for T and 576 for TP, while the dataset for *P. nigra salzmannii* included 1188 *id* observations for C, 818 for T and 693 for TP.

To account for the initial differences in wood density properties, a covariate (*AM5*) was used. This covariate was calculated as the arithmetic mean of the specific wood property within the annual rings formed 5 years prior to the commencement of the trials [29, 43, 44]. Finally, the models included a ε random error term. All the statistical analyses were run in R using the "lme" function of the "nlme" package [45] and the restricted maximum likelihood option. Model structures were compared using Akaike's Information Criterion. We used Tukey's post hoc test to conduct pairwise comparisons between group means to identify which groups differ significantly from each other using the "emmeans" package.

3. Results

3.1 Impact of silvicultural operations on diameter increment

The species displaying the largest tree diameter increment, regardless of the thinning treatment applied, were *P. nigra* and *P. sylvestris* (mean growth for both species was 2.8 mm $year^{-1}$ with standard deviation of 1.6 mm $year^{-1}$), while *P. nigra salzmannii* exhibited slightly lower growth rates (2.1 ± 1.3 mm $year^{-1}$).

We found a significant effect ($p \leq 0.05$) of the Treatment and Time on tree growth for the three taxa, while the interaction between them was found to be significant in the *P. nigra nigra* trial (**Table 3**). Tukey's post hoc test revealed that the trees in C plots exhibited significantly lower growth than those in thinned plots (**Figure 2**). As regards the thinning treatments, we only found significant differences between T and TP for the *P. nigra* trial, with TP presenting larger diameter increment than T.

The diameter at the beginning of the period and the competition index BAL/B were found to have a significant effect on tree growth (**Table 3**) in both the *P. sylvestris* and the *P. nigra* trials. The diameter at the beginning of the period displayed a

Species	Treatment	Time	Treatment*Time	dbeg	BAL/B
P. sylvestris	<0.0001	<0.0001	n.s.	<0.0001 (−)	<0.0001 (−)
Polycelis nigra nigra	<0.0001	<0.05	<0.001	<0.001 (−)	<0.0001 (−)
P. nigra salzmannii	<0.05	<0.0001	n.s.	<0.0001 (−)	<0.0001 (−)

Adapted from [2]. dbeg: diameter at the beginning of each period, respectively, and BAL/B: the ratio between the basal area of the largest trees and the stand basal area. n.s. = non-significant (p > 0.05).

Table 3.
Mixed model results for the diameter increment models for Pinus sylvestris (2859 observations), Pinus nigra nigra (2510 observations), and Pinus nigra salzmannii (2699 observations).

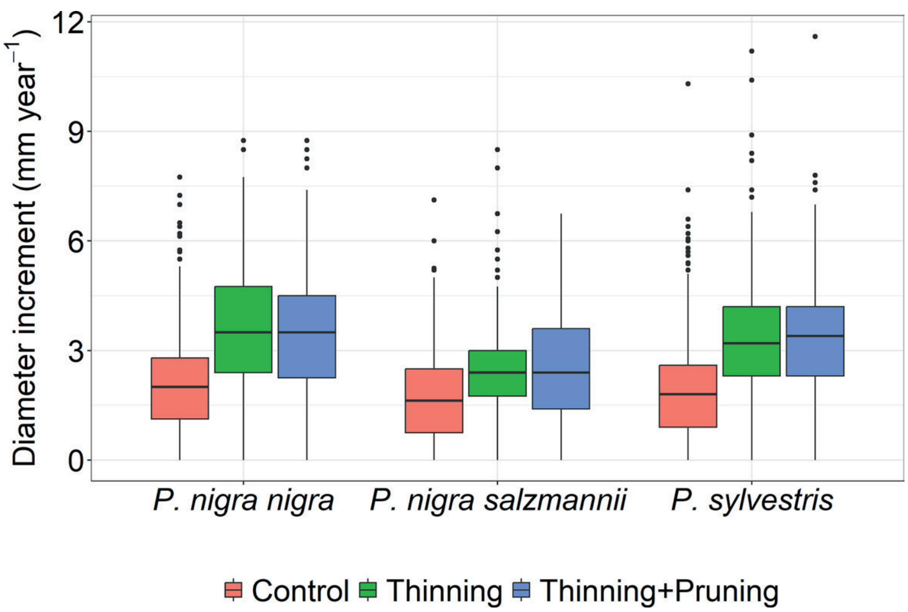

Figure 2.
Boxplot of tree diameter increment for the three studied species and treatments.

negative relationship with diameter increment, indicating that thinner trees exhibited more growth than larger trees. The *BAL/B* was negatively correlated with diameter growth in *P. sylvestris* and both *P. nigra* subspecies. A negative estimation coefficient for BAL/B implies that trees with larger BAL/B (thinner diameters and more competition) exhibited less growth compared to larger trees. This divergence between the effect of the diameter at the beginning of the period and BAL/B can be explained by the strong, negative correlation between the two variables (α = 99.9%).

3.2 Impact of the silvicultural operations on wood properties

The mean value of *P. nigra salzmannii* wood density was 0.66 kg cm^{-3} with a standard deviation of 0.10 kg cm^{-3}. *P. nigra nigra* a had a wood density mean value of 0.62 ± 0.11 kg cm^{-3}, whereas *P. sylvestris* exhibited a mean value of 0.54 ± 0.08 kg cm^{-3}. As regards latewood percentage, this variable reached a value of 37.5 ± 14.4% for *P. nigra salzmannii*, 31.9 ± 10.7% for *P. nigra nigra*, and 28.0 ± 11.2% for *P. sylvestris*. All of these values were calculated using the temporal series starting from experiment initiation (1991 for *P. sylvestris* and 1993 for *P. nigra*) up until the date the cores were extracted.

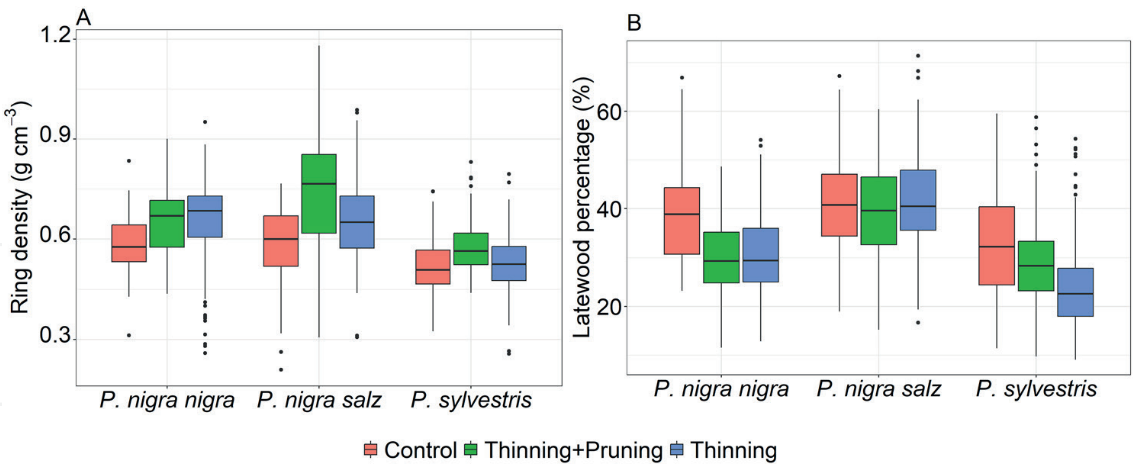

Figure 3.
Boxplot of (A) tree ring density values and (B) latewood percentage for the three studied species and treatments. The data used ranged from experiment initiation to core collection date.

Variable	AM5	Time	Treatment	Treatment x Time
Pinus sylvestris				
RD	<0.0001	n.s.	n.s.	n.s.
LWP	<0.05	n.s.	n.s.	n.s.
Pinus nigra nigra				
RD	<0.0001	n.s.	n.s.	n.s.
LWP	n.s.	n.s.	n.s.	n.s.
Pinus nigra salzmannii				
RD	<0.0001	n.s.	n.s.	n.s.
LWP	n.s.	n.s.	n.s.	n.s.
Adapted from [35]. n.s. = non-significant ($p \geq 0.05$).				

Table 4.
P-value of AM5 (5-year arithmetic mean prior to the initiation of the trials), time, treatment, and interaction of treatment × time in the RD (ring density) and LWP (percentage of latewood) models.

Despite the visual differences observed among treatments as shown in **Figure 3**, there was no statistically significant effect of the treatment factor on the two wood density variables studied (RD and LWP) for any of the three species. Additionally, the covariate *AM5* appeared to be significant in all models except for *LWP* in both *P. nigra nigra* and *P. nigra salzmannii* (**Table 4**), suggesting that the abovementioned differences between treatments may be partially associated with RD and LWP temporal trends prior to initiating the trials.

4. Discussion

In this chapter, we have evaluated the impacts of common silvicultural treatments on tree growth and wood properties (wood density and LWP) of two dominant pine species found in the Spanish mountains.

This positive effect of thinnings on tree diameter growth is in agreement with the findings of most previous studies [46–48]. In addition to promoting secondary growth in trees, thinning may enhance components of tree resilience (*sensu* [49]) during drought periods [50] serving as a climate change adaptation tool. These effects are not accompanied by a significant loss in wood quality in terms of wood density and latewood proportion, which is in line with previous results reported for conifers [9, 20, 29, 30]. In contrast, [22] reviewed the impacts of thinning on the set of properties defining wood quality in *P. sylvestris* and reported a negative impact of this silvicultural operation. However, many of the properties covered by these authors, such as strength, stiffness, knottiness, distortion, wood heterogeneity, and compression wood, have not been considered here. Moreover, the thinning experiments discussed in [22] were conducted with the future crop trees in mind, aiming to foster the growth of the highest-quality trees. This approach may lead to a more substantial release of space compared to our study, potentially exerting a greater influence on wood quality. Our findings indicate that pruning has a negligible effect on the growth, ring density, and latewood percentage in *P. sylvestris* and *P. nigra* subspecies. This suggests that pruning is an appropriate treatment to remove branches and obtain knot-free timber without a reduction in wood density. Previous studies, however, postulated that pruning significantly impacts tree growth and that this effect is directly related to the percentage of green crown removed [3, 26–28]. It is important to note that we have not quantified the percentage of crown removed during the pruning operations, but both intensity and timing of the pruning and thinning operations were within the schedules of regular forest prescriptions, that is, 6 m pruning in low-size trunks, ca. 15–25 cm wide [51]. Therefore, it is possible that the 6-m pruning treatment eliminated dead branches and the lower part of the crown, which is expected to have low photosynthetic activity. In particular, this would be the expectation in the case of *P. sylvestris*, which is a self-pruning species.

Our results open a window for further research regarding the combination of thinning and pruning: (i) the impact on growth and wood density at different trunk heights and (ii) the effect on other wood quality properties (e.g., strength, stiffness, knottiness, distortion, wood heterogeneity, and compression wood). Additionally, although more information has become available in recent years on the influence of climate and other site conditions on wood density [52–54], the effects of interaction between climate and management or land-use legacies on wood properties are still scarcely understood [34].

5. Conclusion

Our findings provide strong evidence supporting the efficacy of implementing combined silvicultural practices, that is, thinning and 6 m pruning, in Mediterranean middle-aged pine forests. The thinning intensity and pruning height assessed in this study align with established practices in Mediterranean pine forests. Consequently, the findings presented in this chapter offer valuable scientific insights for forest managers, aiding them in their decision-making for the typical forest operations they undertake. It has been evidenced that not only do these silvicultural interventions enhance wood-quality characteristics, such as promoting larger diameters and knot-free timber, but also the wood density remains at the same levels as untreated plots.

Acknowledgements

This work was funded by IFN-2021 (Monitorización de la red de parcelas permanentes de Gestión Forestal y Tratamientos Selvícolas del CIFOR-INIA) and 101056907-PathFinder (The contribution of forest management to climate action: pathways, tradeoffs and co-benefits). We also thank Adam Collins for revising the English grammar as well as the reviewers and editor for their critical input.

Funding

A. Hevia was supported by "Action 7: Grants for the temporary incorporation of postdoctoral research staff, from the Operational Plan for Research Support of the University of Jaén (POAI-UJA)", "Project LITHOFOR, RTI2018-095345-B-C21, Spanish Ministry of Science, Innovation and Universities, R&D Program Oriented to the Challenges of Society, 2018 Call" and by "the fellowship II.4 from VII-PPITUS 2022 (Univ. Sevilla)".

Conflict of interest

The authors declare no conflict of interest.

Author details

Daniel Moreno-Fernández[1]*, Andrea Hevia[2,3], Iciar Alberdi[1] and Isabel Cañellas[1]

1 Institute of Forest Sciences (INIA-CSIC), Madrid, Spain

2 Universidad de Jaén, Campus Las Lagunillas s/n, Jaén, Spain

3 Departamento de Biología Vegetal y Ecología, Universidad de Sevilla, Avda. Reina Mercedes s/n, Sevilla, Spain

*Address all correspondence to: daniel.moreno@inia.csic.es

References

[1] Ruano A, Alberdi I, Adame P, Moreno-Fernández D, Amiano AC, Fernández-Golfín J, et al. Improving stem quality assessment based on national forest inventory data: An approach applied to Spanish forests. Annals of Forest Science. 2023;**80**:20. DOI: 10.1186/s13595-023-01187-7

[2] Moreno-Fernández D, Sánchez-GonzálezM,Álvarez-GonzálezJG, Hevia A, Majada JP, Cañellas I, et al. Response to the interaction of thinning and pruning of pine species in Mediterranean mountains. European Journal of Forest Research. 2014;**133**:833-843. DOI: 10.1007/s10342-014-0800-z

[3] Hevia A, Gabriel Álvarez-González J, Majada J. Comparison of pruning effects on tree growth, productivity and dominance of two major timber conifer species. Forest Ecology and Management. 2016;**374**:82-92. DOI: 10.1016/j.foreco.2016.05.001

[4] Neilsen WA, Pinkard EA. Effects of green pruning on growth of *Pinus radiata*. Canadian Journal of Forest Research. 2003;**33**:2067-2073. DOI: 10.1139/x03-131

[5] Víquez E, Pérez D. Effect of pruning on tree growth, yield, and wood properties of *Tectona grandis* plantations in Costa Rica. Silva Fennica. 2005;**39**:381-390

[6] Alves A, Hevia A, Simões R, Majada J, Alia R, Rodrigues J. Improving spatial synchronization between X-ray and near-infrared spectra information to predict wood density profiles. Wood Science and Technology. 2020;**54**:1151-1164. DOI: 10.1007/s00226-020-01207-z

[7] Erdene-Ochir T, Ishiguri F, Nezu I, Tumenjargal B, Baasan B, Chultem G, et al. Modeling of radial variations of wood properties in naturally regenerated trees of *Betula platyphylla* grown in Selenge, Mongolia. Journal of Wood Science. 2021;**67**:1-10. DOI: 10.1186/s10086-021-01993-5

[8] Macdonald E, Huber J. A review of the effects of silviculture on timber quality of Sitka spruce. Forestry. 2002;**75**:107-138. DOI: 10.1093/forestry/75.2.107

[9] Peltola H, Kilpeläinen A, Sauvala K, Räisänen T, Pekka IV. Effects of early thinning regime and tree status on the radial growth and wood density of scots pine. Silva Fennica. 2007;**41**:489-505. DOI: 10.14214/sf.285

[10] Larjavaara M, Muller-Landau HC. Rethinking the value of high wood density. Functional Ecology. 2010;**24**:701-705. DOI: 10.1111/j.1365-2435.2010.01698.x

[11] Zobel BJ, van Buijtenen JP. Wood Variation. Its Causes and Control. New York: Springer-Verlag; 1989. p. 363

[12] Farias HLS, Pequeno PACL, Silva WR, Melo VF, LCS DC, De Perdiz RO, et al. Amazon forest biomass: Intra- and interspecific variability in wood density drive divergences in Brazil's far north. iForest. 2023;**16**:95. DOI: 10.3832/ifor4137-016

[13] Camarero JJ, Hevia A. Links between climate, drought and minimum wood density in conifers. IAWA Journal. 2020;**41**:236-255. DOI: 10.1163/22941932-bja10005

[14] Szaban J, Jelonek T, Okí Nczyc A, Kowalkowski W. Results of a 57-year-long research on variability of wood density of the scots pine (*Pinus sylvestris*

L.) from different provenances in Poland. Forests. 2023;**14**:480. DOI: 10.3390/f14030480

[15] Hevia A, Campelo F, Chambel R, Vieira J, Alía R, Majada J, et al. Which matters more for wood traits in *Pinus halepensis* mill., provenance or climate? Annals of Forest Science. 2020;**77**:55. DOI: 10.1007/s13595-020-00956-y

[16] Burkhart HE, Amateis RL. Effects of early pruning on ring specific gravity in young loblolly pine trees. Wood and Fiber Science. 2020;**24**(52):139-151. DOI: 10.22382/wfs-2020-013

[17] Ruano A, Ruiz-Peinado R, Fernández-Golfín J, Hermoso E. Height growth for assessing core–outerwood transition on *Pinus sylvestris* and *Pinus nigra* Spanish stands. European Journal of Forest Research. 2020;**139**:273-278. DOI: 10.1007/s10342-019-01231-0

[18] Ruano A, Zitek A, Hinterstoisser B, Hermoso E. NIR hyperspectral imaging (NIR-HI) and μxRD for determination of the transition between juvenile and mature wood of *Pinus sylvestris* L. Holzforschung. 2019;**73**:621-627. DOI: 10.1515/hf-2018-0186

[19] Fries A, Ericsson T. Genetic parameters for earlywood and latewood densities and development with increasing age in scots pine. Annals of Forest Science. 2009;**66**:404-404. DOI: 10.1051/forest/2009019

[20] Mäkinen H, Hynynen J. Wood density and tracheid properties of scots pine: Responses to repeated fertilization and timing of the first commercial thinning. Forestry. 2014;**87**:437-447. DOI: 10.1093/forestry/cpu004

[21] Guller B, Isik K, Cetinay S. 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. 2012;**26**:975-986. DOI: 10.1007/s00468-011-0675-2

[22] del Río Gaztelurrutia M, Bravo Oviedo JA, Pretzsch H, Löf M, Ruiz-Peinado R. A review of thinning effects on scots pine stands: From growth and yield to new challenges under global change. Forest Systems. 2017;**26**:9. DOI: 10.5424/fs/2017262-11325

[23] Pretzsch H. Density and growth of forest stands revisited. Effect of the temporal scale of observation, site quality, and thinning. Forest Ecology and Management. 2020;**460**:117879. DOI: 10.1016/j.foreco.2020.117879

[24] Hevia A, Crabiffosse A, Álvarez-González JG, Ruiz-González AD, Majada J. Assessing the effect of pruning and thinning on crown fire hazard in young Atlantic maritime pine forests. Journal of Environmental Management. 2018;**205**:9-17. DOI: 10.1016/j.jenvman.2017.09.051

[25] Donovan VM, Roberts CP, Fogarty DT, Wedin DA, Twidwell D. Targeted grazing and mechanical thinning enhance forest stand resilience under a narrow range of wildfire scenarios. Ecosphere. 2022;**13**:e4061. DOI: 10.1002/ecs2.4061

[26] Reventlow DOJ, Nord-Larsen T, Skovsgaard JP. Pre-commercial thinning in naturally regenerated stands of European beech (*Fagus sylvatica* L.): Effects of thinning pattern, stand density and pruning on tree growth and stem quality. Forestry. 2019;**92**:120-132. DOI: 10.1093/forestry/cpy039

[27] York RA. Long-term taper and growth reductions following pruning intensity treatments in giant sequoia (*Sequoiadendron giganteum*). Canadian Journal of Forest Research.

2019;**49**:1189-1197. DOI: 10.1139/cjfr-2019-0118

[28] Amateis RL, Burkhart HE. Growth of young loblolly pine trees following pruning. Forest Ecology and Management. 2011;**262**:2338-2343. DOI: 10.1016/j.foreco.2011.08.029

[29] Mäkinen H, Hynynen J, Penttilä T. Effect of thinning on wood density and tracheid properties of scots pine on drained peatland stands. Forestry. 2015;**262**:359-367. DOI: 10.1093/forestry/cpv006

[30] Todaro L, Macchioni N. Wood properties of young Douglas-fir in Southern Italy: Results over a 12-year post-thinning period. European Journal of Forest Research. 2010;**130**:251-261. DOI: 10.1007/s10342-010-0425-9

[31] Carson SD, Cown D, McKinley R, Moore J. Effects of site, silviculture and seedlot on wood density and estimated wood stiffness in radiata pine at mid-rotation. New Zealand Journal of Forest Science. 2014;**44**:26. DOI: 10.1186/s40490-014-0026-3

[32] Gartner BL, Robbins JM, Newton M. Effects of pruning on wood density and tracheid length in young Douglas-fir. Wood and Fiber Science. 2005;**37**:304-313

[33] Sæbø JS, Socolar JB, Sánchez EP, Woodcock P, Bousfield CG, Uribe CAM, et al. Ignoring variation in wood density drives substantial bias in biomass estimates across spatial scales. Environmental Research Letters. 2022;**17**:054002. DOI: 10.1088/1748-9326/ac62ae

[34] Alfaro-Sánchez R, Jump AS, Pino J, Díez-Nogales O, Espelta JM. Land use legacies drive higher growth, lower wood density and enhanced climatic sensitivity in recently established forests. Agricultural and Forest Meteorology. 2019;**276-277**:107630. DOI: 10.1016/j.agrformet.2019.107630

[35] Moreno-Fernández D, Hevia A, Majada J, Cañellas I. Do common silvicultural treatments affect wood density of Mediterranean montane pines? Forests. 2018;**9**:80. DOI: 10.3390/f9020080

[36] Schweingruber FH. Tree Rings and Environment Dendroecology. Bern: Paul Haupt; 1996. p. 609

[37] Holmes RL. Computer-assisted quality control in tree ring dating and measurements. Tree-Ring Bulletin. 1983;**43**:69-78

[38] Zuur A, Ieno EN, Walker N, Saveliev AA, Smith GM. Mixed Effects Models and Extensions in Ecology with R. New York: Springer; 2009. p. 574

[39] Littell R, Pendergast J, Natarajan R. Tutorial in biostatistics: Modelling covariance structure in the analysis of repeated measures data. Statistics in Medicine. 2000;**19**:1793-1819

[40] Zuur A, Ieno E, Smith G. Analyzing Ecological Data. New York: Springer; 2007

[41] Wykoff WR. A basal area increment model for individual conifers in the Northern Rocky Mountains. Forest Science. 1990;**36**:1077-1104

[42] Vanclay JK. Mortality functions for North Queensland rain forests. Journal of Tropical Forest Science. 1991;**4**:15-36

[43] Mäkinen H, Isomäki A. Thinning intensity and growth of Norway spruce stands in Finland. Forestry. 2004;**77**:349-364. DOI: 10.1093/forestry/77.4.349

[44] Jaakkola T, Mäkinen H, Saranpää P. Wood density of Norway spruce: Responses to timing and intensity of first commercial thinning and fertilisation. Forest Ecology and Management. 2006;**237**:513-521. DOI: 10.1016/j.foreco.2006.09.083

[45] Pinheiro J, Bates D, Deb Roy S, Sarkar D, R Core Team. Nlme: Linear and Nonlinear Mixed Effects Models. R Package Version 4.31. 2023.

[46] Moreno-Fernández D, Cañellas I, Calama R, Gordo J, Sánchez-González M. Thinning increases cone production of stone pine (*Pinus pinea* L.) stands in the Northern Plateau (Spain). Annals of Forest Science. 2013;**70**:761-768. DOI: 10.1007/s13595-013-0319-3

[47] Mäkinen H, Isomäki A. Thinning intensity and growth of scots pine stands in Finland. Forest Ecology and Management. 2004;**201**:311-325. DOI: 10.1016/j.foreco.2004.07.016

[48] Moreno-Fernández D, Aldea J, Gea-Izquierdo G, Isabel I, Darío-Benito M. Influence of climate and thinning on *Quercus pyrenaica* Willd. Coppices growth dynamics. European Journal of Forest Research. 2021;**140**:187-197. DOI: 10.1007/s10342-020-01322-3

[49] Lloret F, Keeling EG, Sala A. Components of tree resilience: Effects of successive low-growth episodes in old ponderosa pine forests. Oikos. 2011;**120**:1909-1920. DOI: 10.1111/j.1600-0706.2011.19372.x

[50] Aldea J, Bravo F, Bravo-Oviedo A, Ruiz-Peinado R, Rodríguez F, del Río M. Thinning enhances the species-specific radial increment response to drought in Mediterranean pine-oak stands. Agricultural and Forest Meteorology. 2017;**237**:371-383. DOI: 10.1016/j.agrformet.2017.02.009

[51] Serrada R, Montero G, Reque JA. Compendio de Selvicultura Aplicada en España. Vol. 2008. Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria. Ministerio de Educación y Ciencia. Madrid: Fundación Conde del Valle Salazar; 2008

[52] Bouriaud O, Leban JM, Bert D, Deleuze C. Intra-annual variations in climate influence growth and wood density of Norway spruce. Tree Physiology. 2005;**25**:651-660. DOI: 10.1093/treephys/25.6.651

[53] Nabais C, Hansen JK, David-Schwartz R, Klisz M, López R, Rozenberg P. The effect of climate on wood density: What provenance trials tell us? Forest Ecology and Management. 2018;**408**:148-156. DOI: 10.1016/j.foreco.2017.10.040

[54] Pritzkow C, Heinrich I, Grudd H, Helle G. Relationship between wood anatomy, tree-ring widths and wood density of *Pinus sylvestris* L. and climate at high latitudes in northern Sweden. Dendrochronologia. 2014;**32**:295-302. DOI: 10.1016/j.dendro.2014.07.003