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Do Common Silvicultural Treatments Affect Wood Density of Mediterranean Montane Pines?

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Abstract: Wood density is one of the most important and well documented wood quality attributes. However, studies focusing on the effects of thinning combined with pruning on wood density in Mediterranean areas are scarce, even though both are recommended practices in forests managed for the production of high-quality timber. We assess the effects of both silvicultural interventions on wood density traits (tree-ring, earlywood, and latewood) and on the percentage of latewood, on an annual scale, for the main timber species *Pinus sylvestris* L. and *Pinus nigra* Arnold (subsp. *nigra* and subsp. *salzmannii*) in Mediterranean mountains. To this end, three trials (one species per trial) were established in monospecific reforestations in the 1990s. Three silvicultural treatments were applied: thinning, thinning combined with pruning, and a control. At the time of installation, stand ages ranged from 26 to 37 years. Small differences were found among treatments in regard to the wood density attributes, with no significant effects of thinning and pruning on the studied wood traits in either timber species. The two subspecies of *P. nigra* presented comparatively denser wood than *P. sylvestris*. Our results suggest that thinning and pruning treatments can be applied without causing unfavourable changes to wood density.

Keywords: scots pine; black pine; Itrax; microdensitometry; tree-rings; wood quality

1. Introduction

High quality wood products are usually obtained from large-size, knot-free stems [1]. Appropriate forest management is essential to obtaining high-value products from timber species [2]. This will involve thinning operations to reduce competition [3,4], thereby promoting increased growth rates and larger diameters, while knots and branch-related defects can be restricted to a central knotty core through pruning operations [2,5,6]. Silvicultural practices promote changes in tree growth and therefore potential changes in wood properties [7].

Wood density is assumed to be one of the most important wood quality attributes, since it influences mechanical properties such as wood strength, flexibility, and stiffness. It also affects physiological wood construction costs, carbon storage [8–10], and the quality of paper products and by-products [11,12].

However, the influence of wood density on wood quality depends on the integration of other factors such as knots, grain angle, or juvenile wood [1]. In addition, wood density presents intra-ring variations due to the differences in cell structure between earlywood and latewood. It implies differences such as higher density values in latewood than earlywood, proportion of earlywood and latewood (normally more earlywood than latewood) [13], or most wood functions in earlywood (through tracheids) for conifers (mechanical support and water transport) [14]. Furthermore, wood density is influenced by cambial age [15]. Earlywood density remains essentially stable throughout the cambial age, whereas the latewood density increases with cambial age. Additionally, the latewood proportion increases with cambial age [3,16–18]. The combined effect of these factors is that tree-ring density usually increases from the pith of the tree (juvenile wood) to the bark (mature wood) [19,20], although transition from juvenile to mature wood can be affected by factors such as intensive forest management (e.g., by pruning [21]).

In general, wood formation and wood density may vary according to the species, genetics, environmental (i.e., site or climatic influences) and physiological factors, or silvicultural treatments [12,22–24]. As per silviculture practices, thinning of softwoods promotes higher growth rates as a consequence of more resource availability, which in turn may lead to a decline in tree-ring density [25–28]. However, most studies concerning conifer species (however, see [29,30]) report that the application of thinning treatments has only a minor effect or no effect at all on the wood density of the remaining trees in different species such as *Pinus sylvestris* L. [3,8,31,32], *Picea abies* (L.) Karst. [33,34], *Pinus taeda* L. [35], *Pseudotsuga menziesii* (Mirb.) Franco [36], *Picea mariana* (Mill.) B.S.P., and *Pinus banksiana* Lamb. [37]. In relation to pruning, wood density values can also be affected. Knotty wood is not only a visual defect but is also weaker and the timber has a higher density [6] due to both the cross-sectional reduction caused by knots and the effect of the distortion of the fibres [38]. However, the effects of pruning on wood density are less documented. Some studies suggest that pruning has no detectable effect on wood density at breast height (e.g., Gartner et al. [21] in *P. menziesii*), while others maintain that wood density increases after pruning (e.g., Cown [39] and Carson et al. [30] in *Pinus radiata* D. Don) when live branches are removed. Additionally, it is often assumed that pruning can change and accelerate the transition from juvenile to mature wood [21], in accordance with a review by Larson [40]. However, some researchers argue that the shift to mature wood does not simply result from wood density changes after pruning [16,41].

Most studies addressing the relationship between silviculture and wood density have been conducted in boreal areas [32,34,42]. Despite the fact that thinning combined with pruning is recommended in managed forests to produce high-quality timber [4,43], literature concerning the ways in which both of these silvicultural treatments affect wood density in Mediterranean timber species is still scarce.

P. sylvestris and *Pinus nigra* Arnold are important conifer species from an ecological and productive perspective, and two of the main timber species most widely used in reforestations and plantations in the Mediterranean basin. Thinning in conjunction with pruning is commonly carried out in monospecific *P. sylvestris* and *P. nigra* forests to obtain clear wood and hence increase the value of the final products (also reducing the risk of forest fire by breaking the horizontal and vertical fuel continuity) [4]. In addition, wood obtained from these species is employed to obtain high-quality products, such as poles, saw logs, veneer (not *P. nigra*), and construction timber [16,44,45]. However, there are certain differences in the physical and mechanical properties of the wood from each of these species. For instance, wood from *P. nigra* is assumed to possess better mechanical properties (strength, stiffness) for construction and timber for structural applications than that of *P. sylvestris* [44].

In this study, we evaluate the effects of silvicultural treatments on the wood density of *P. sylvestris* and two subspecies of *P. nigra* (subsp. *nigra* and subsp. *salzmannii*) in Mediterranean mountain areas. The specific aim of this research work is to analyse the way in which thinning and pruning affect the wood density traits of tree-ring density, earlywood and latewood density, as well as the latewood proportion. We do not expect the wood density of tree-rings (earlywood and latewood) to be affected by these applied silvicultural treatments.

2. Materials and Methods

2.1. Description of Trials and Data Collection

Three silvicultural trials combining thinning and pruning were established in a Mediterranean mountainous area of Central Spain. The first trial was installed in 1991 in a 37-year-old *P. sylvestris* monospecific reforestation located in La Morcuera Forest (Comunidad de Madrid) (40°52′ N, 3°51′ W) at an altitude of 1650 m a.s.l. on a north-facing 10–40% slope. In this area, the average annual precipitation sum is 1062 mm and the average annual temperature is 7 °C. Nine plots with the following three treatments were established and evaluated (Table 1): control treatment, felling only dead trees (C); thinning from below without pruning (T); and thinning from below combined with pruning (6 m height; 40 best trees per plot) (TPB). This is equivalent to pruning 400 trees ha^{-1}, ensuring a sufficient number of pruned trees to reach the desired stand density at the beginning of the regeneration fellings (200–300 trees ha^{-1}). In 2001, the second thinning was carried out. This trial was affected by a heavy storm that caused large-scale snow-throws in January 1996 [46], thus necessitating the removal of one plot per treatment from the analysis.

Table 1. Average attributes of the stand per treatment and quantification of thinning intensity. See Moreno-Fernández et al. [4] for more details.

Treatment	First Thinning							Second Thinning						
	Year	Age	Ho	G	Dg	N	%G	Year	Age	Ho	G	Dg	N	%G
Pinus sylvestris														
C	1991	37	11.2	38.5	14.5	2340	0.7 *	2001	47	13.3	46.4	17.2	2005	9.9 *
T	1991	37	10.6	34.1	14.6	2040	28.2	2001	47	13.0	31.2	20.7	930	18.6
TPB	1991	37	11.0	33.9	14.4	2080	34.8	2001	47	13.2	29.0	21.2	825	14.4
Pinus nigra nigra														
C	1993	26	13.8	36.2	18.2	1400	0.0	2006	39	17.7	44.1	21.2	1245	0.0
T	1993	26	13.4	36.0	17.8	1450	41.9	2006	39	17.2	31.7	23.6	725	17.6
TPB	1993	26	13.8	35.8	17.7	1460	40.2	2006	39	17.5	32.2	23.3	765	16.5
Pinus nigra salzmannii														
C	1993	31	12.3	30.9	15.7	1600	0.0	2006	44	14.8	37.2	18.1	1445	0.0
T	1993	31	12.2	30.1	15.6	1580	24.8	2006	44	15.0	32.1	19.6	1070	16.9
TPB	1993	31	12.4	32.4	16.6	1500	30.4	2006	44	14.9	31.1	20.9	905	16.9

Ho = dominant height (m) before thinning. G = basal area (m^2 ha^{-1}). Dg = quadratic mean diameter (cm) before thinning. N = density (trees ha^{-1}) before thinning. %G = percentage of trees and basal area removed. C = control treatment. T = thinning without pruning. TPB = thinning with pruning of the best trees. * Natural mortality.

The second and third trials were installed in monospecific stands of *P. nigra* located in La Zarzuela (Guadalajara province) (41°02′ N, 3°04′ W) in 1993. Both trials are located on flat ground at an altitude of around 1050 m a.s.l. The average annual precipitation sum is 620 mm and the average annual temperature is 10.5 °C. However, the subspecies and age of the stands at time of installation differed between the two trials. The subspecies of the second trial, where the trees were 26-years-old at the time of installation, was *Pinus nigra* Arnold subsp. *nigra* (*P. nigra nigra*, hereafter). The third trial was installed in a stand of 31-year-old *Pinus nigra* Arnold subsp. *salzmannii* (Dunal) (*P. nigra salzmannii*, hereafter). Three treatments (C, T, TPB) with two repetitions in six plots (0.1 ha) were evaluated in both *P. nigra* trials. In 2006, the second thinning was performed in these two trials (Table 1).

A 10 m buffer area was established around each plot to eliminate the edge effect. In order to address the influence of silvicultural operations on wood density, we collected six cores per plot from six trees (at breast height) situated in the second and third quartile of the diametric distribution (i.e., in codominant trees) of each plot in January 2013. Both dominant and most codominant trees will be present until the beginning of the regeneration period. However, the competition for resources by codominant trees might be larger than in the case of dominant trees [47], as such, we expected that the effect of the competition reduction of the thinning treatment would be more pronounced in the codominant stratum. All individuals were cored using a 5-mm-diameter increment borer. In the TPB treatment, increment cores were only collected from pruned trees. The effects of pruning and thinning on tree growth in these three trials were reported by Moreno-Fernández et al. [4].

2.2. Measurements with X-ray Microdensitometry

Each sampled increment core was glued onto a wood holder in the laboratory. Each core was then cut using a twin-blade saw to obtain longitudinal radial strips (approximately 1 mm thick). The elimination of resins was carried out by refluxing samples in ethanol (96%) using a Soxhlet apparatus for 24 h in the case of *P. sylvestris* and 48 h for *P. nigra*. The thin strips extracted were kept at constant temperature and humidity conditions before being X-rayed in an Itrax Multiscanner (Cox Analytical Systems, Mölndal, Sweden) at the CETEMAS laboratory (Asturias, Spain). The Multiscanner is equipped with a Cu-tube that operates at 30 KV, 50 mA, 25 ms with 20 μm steps. The resultant radiographic images were analysed using WinDendro (Regent Instruments, Québec, QC, Canada). Average wood density values for tree-rings (RD, in g cm^{-3}), as well as earlywood (ED, in g cm^{-3}) and latewood (LD, in g cm^{-3}) and the proportion of latewood density with respect to the whole ring width (LWP, in %) were extracted from the radiographic images by calibrating the greyscale intensities to wood densities using a light calibration curve derived from a calibration wedge [48]. Cross-dating accuracy was checked using statistical parameters provided by the dendrochronological software COFECHA (University of Arizona, Tucson, AZ, USA) [49].

2.3. Statistical Analysis

For each species, we studied the effects of thinning and pruning on the following wood properties: RD (ring density), ED (earlywood density), LD (latewood density), and LWP (percentage of latewood). We analysed the effect of the treatments on the properties of the wood over the study period by fitting linear mixed models including both fixed and random effects [50]. The fact that the trees are nested within plots indicates a hierarchical design and an expectable correlation. We accounted for this correlation by including a random-trees-nested-within-plots intercept effect, and a random-plot intercept effect in the models. In addition, since it is expected that the measurements of wood properties taken from the same tree will be more strongly correlated than those taken from different trees [51], the temporal correlation was considered using an autoregressive correlation structure of order 1. Therefore, we propose the following linear mixed model:

$$y_{ijlk} = \beta_0 + w_i + \beta_1 h_j + \beta_2 wh_{ij} + \beta_3 AM5_{lk} + b_l + s_k + \varepsilon_{ijlk} \quad (1)$$

where y_{ijlk} indicates the value of the response variable (RD, ED, LD, LWP) taken from the tree k with the treatment i and located in the plot l. β_0 represents the intercept of the model or overall mean; w_i is the fixed effect treatment i; h_j is the Year covariate; wh_{ij} is the fixed interaction effect corresponding to treatment i and Year j. The initial differences between the plots and trees were removed using a covariate (AM5) calculated as an arithmetic mean of the wood property in question in the annual rings formed 5 years prior to the installation of the trials [3,32,33]. β_1, β_2, and β_3 are the coefficients of the Year, the Year × Treatment interaction, and AM5, respectively. b_l and s_k are the random effects of plot l and tree k, respectively. Both random effects follow a normal distribution with mean zero and variance ${\sigma_b}^2$ and ${\sigma_s}^2$. Finally, ε_{ijlk} is a random error term. All statistical analyses were carried out in R 3.3.3. [52] using the "lme" function of the "nlme" package [53] and the restricted maximum likelihood option.

3. Results

Average values for the four variables studied (RD, ED, LD, and LWP) per treatment and species after the establishment of the trials are shown in Table 2. These average values were higher for *P. nigra* (subsp. *nigra* and subsp. *salzmannii*) than for *P. sylvestris*. As expected, the average LD values for the three species were greater than those of ED and the proportion of LWP was lower than 50%. Our results showed large inter-annual variations for all the variables studied in the three trials before and after the treatments (Figures 1–3).

Table 2. Arithmetic mean and standard deviation (between brackets) of RD (ring density, in g cm^{-3}), LD (latewood density, in g cm^{-3}), ED (earlywood density, in g cm^{-3}), and LWP (percentage of latewood, in %) from the time of trial installation to 2012.

Species	RD	ED	LD	LWP
Pinus sylvestris				
C	0.519 (0.088)	0.433 (0.067)	33.04 (12.78)	0.722 (0.165)
T	0.527 (0.090)	0.443 (0.068)	24.62 (10.46)	0.807 (0.163)
TPB	0.578 (0.073)	0.458 (0.056)	29.52 (9.21)	0.890 (0.149)
Pinus nigra nigra				
C	0.589 (0.093)	0.445 (0.068)	37.65 (9.04)	0.784 (0.240)
T	0.656 (0.121)	0.507 (0.112)	30.92 (8.46)	0.965 (0.212)
TPB	0.659 (0.101)	0.494 (0.066)	29.98 (8.25)	1.046 (0.123)
Pinus nigra salzmannii				
C	0.566 (0.129)	0.422 (0.105)	36.44 (15.54)	0.834 (0.200)
T	0.658 (0.130)	0.490 (0.118)	37.87 (14.31)	0.934 (0.176)
TPB	0.734 (0.170)	0.527 (0.125)	37.74 (13.29)	1.066 (0.217)

C = control treatment. T = thinning without pruning. TPB = thinning with pruning the best trees.

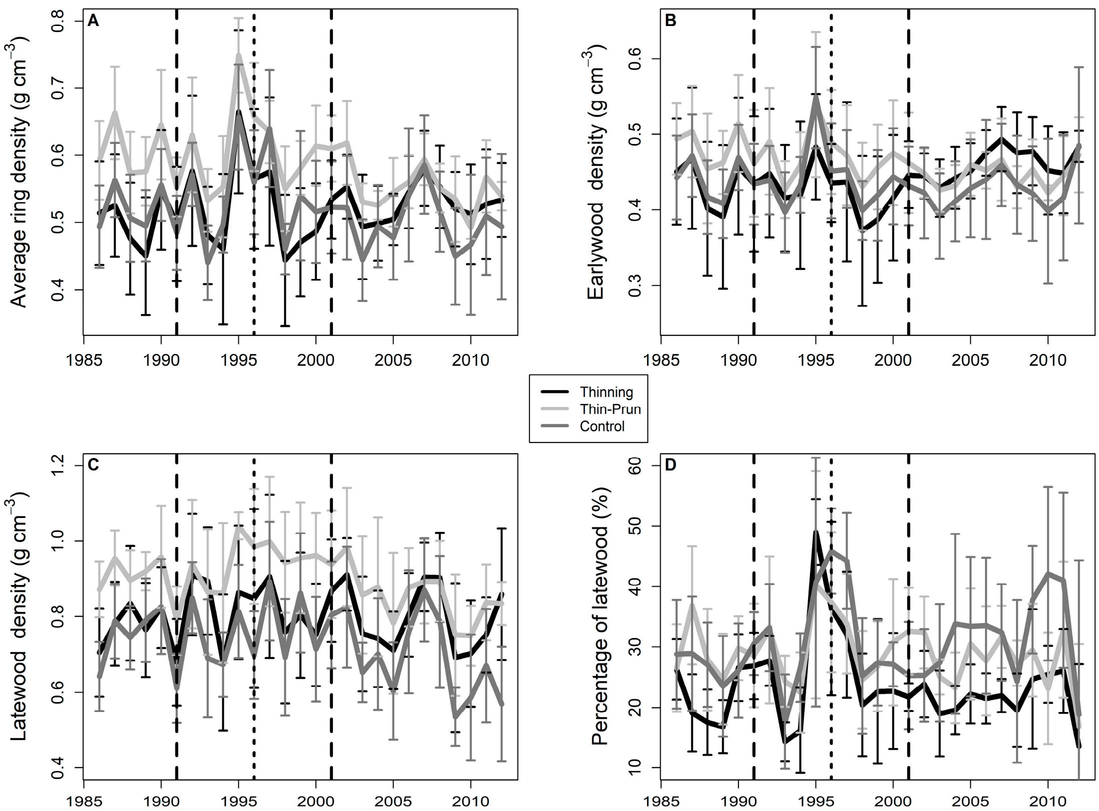

Figure 1. Mean trends ± standard deviation of average ring density (**A**), earlywood density (**B**), latewood density (**C**), and percentage of latewood (**D**) for the treatments in *Pinus sylvestris* trial. Vertical dashed lines indicate thinning treatment dates (1991 and 2001) and dotted line indicates the snow-throws (1996).

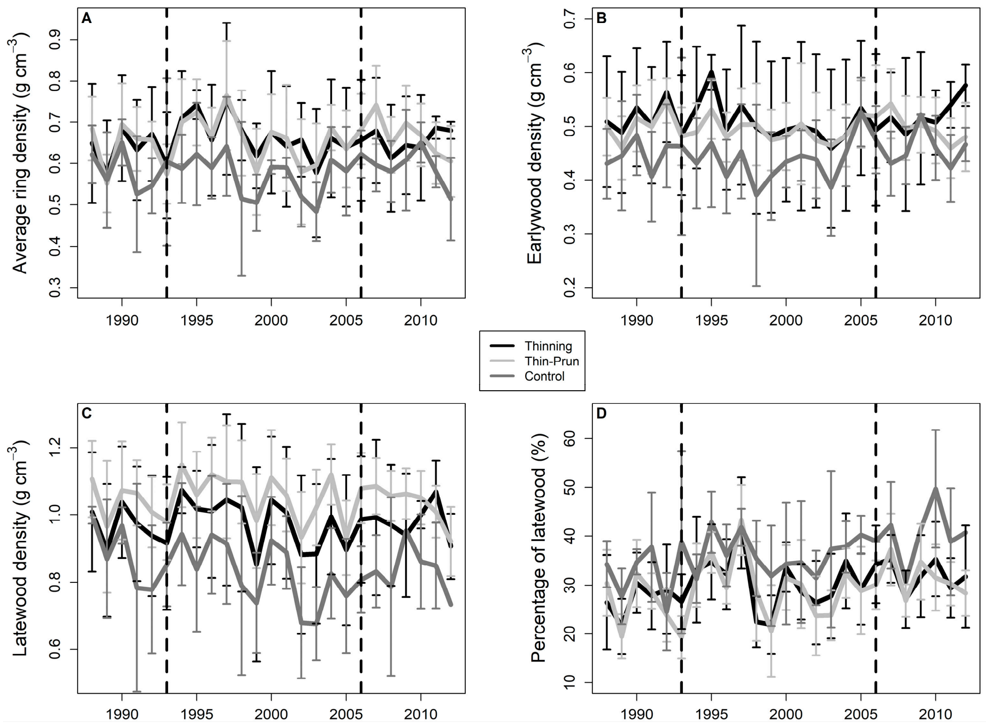

Figure 2. Mean trends ± standard deviation of average ring density (**A**), earlywood density (**B**), latewood density (**C**), and percentage of latewood (**D**) for the treatments in *Pinus nigra nigra* trial. Vertical dashed lines indicate thinning treatment dates (1993 and 2006).

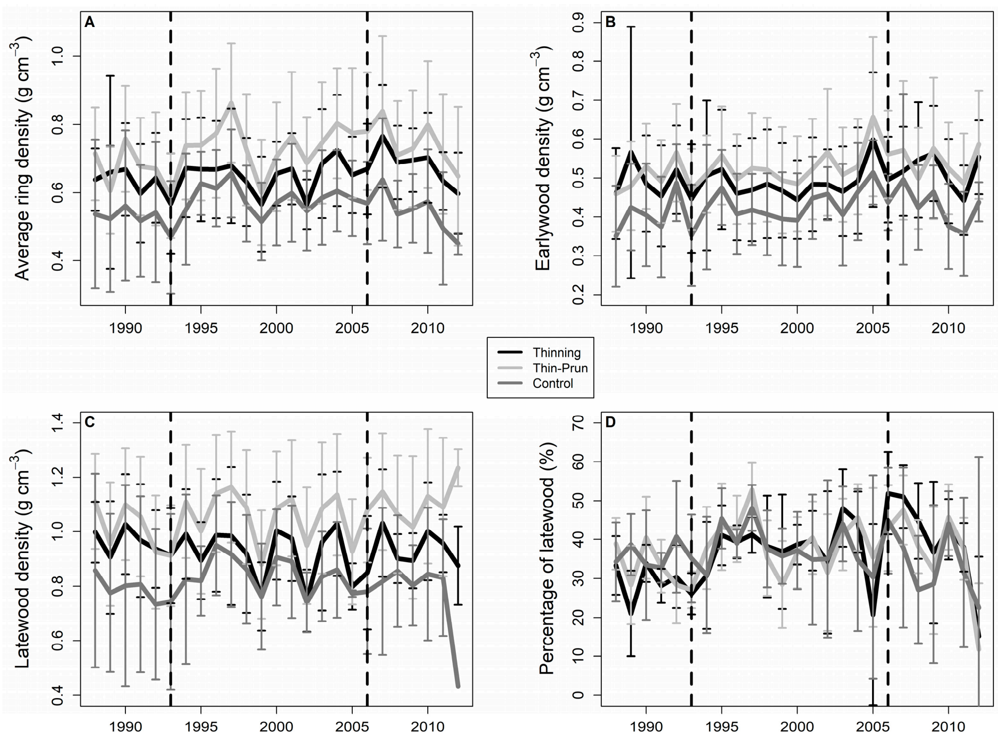

Figure 3. Mean trends ± standard deviation of average ring density (**A**), earlywood density (**B**), latewood density (**C**), and percentage of latewood (**D**) for the treatments in *Pinus nigra salzmannii* trial. Vertical dashed lines indicate thinning treatment dates (1993 and 2006).

We found higher values for RD, ED, and LD in thinned plots (T and TPB treatments) than in C plots in the three trials, with smaller differences between treatments in C and T compared to TPB for all the species (Table 2). The LWP values were lower in trees subjected to silvicultural treatments compared to unthinned plots in the case of *P. sylvestris* and *P. nigra nigra*. In contrast, *P. nigra salzmannii* presented higher values for the treated plots than for untreated plots (C).

However, no statistically significant effect of the treatments was found for the four variables studied in any of the three species. The Year × Treatment interaction only has a significant effect on the ED and LD in the case of *P. nigra salzmannii* (Table 3). This indicates that there were significant differences in the slope of the models according to the treatment. The analysis of the Year × Treatment interaction reveals that the slope in the C treatment was significantly lower than that of T and TPB for the ED and LD models of *P. nigra salzmannii*. This confirms the visual analysis of Figure 3. Additionally, the covariate AM5 appeared to be significant in all the models, except in the case of LWP for both *P. nigra nigra* and *P. nigra salzmannii*, suggesting that the observed differences between treatments presented in Table 2 may be partially associated with trends prior to the installation of the trials (Figures 2 and 3). Additionally, we found a significant relationship between Year and ED (estimation coefficient = 0.0020) and LD (estimation coefficient = −0.0125) in *P. nigra nigra*. This suggests that the ED of *P. nigra nigra* increased with time between 1993 and 2012, whereas the LD of this species decreased with time. In the case of *P. nigra salzmannii*, Year shows a significant relationship with LD (estimation coefficient = −0.0058), i.e., LD decreased between the first thinning and the core collection time.

Table 3. *p*-Values referred to type III sums of squares for the AM5 (5-year arithmetic mean prior to the installation of the trials), Year, Treatment, and Treatment × Year interaction in the RD (ring density), LD (latewood density), ED (earlywood density), and LWP (percentage of latewood) models.

Variable	AM5	Year	Treatment	Treatment × Year
Pinus sylvestris				
RD	<0.0001	0.1553	0.4975	0.4064
ED	<0.0001	0.8673	0.4257	0.3127
LD	<0.0001	0.1272	0.7550	0.7323
LWP	0.0115	0.8462	0.4831	0.3908
Pinus nigra nigra				
RD	<0.0001	0.8225	0.9718	0.9708
ED	<0.0001	0.0465	0.3806	0.1945
LD	0.0019	0.0001	0.2650	0.0627
LWP	0.4618	0.1221	0.5939	0.4983
Pinus nigra salzmannii				
RD	<0.0001	0.1222	0.2480	0.0987
ED	<0.0001	0.7420	0.1584	0.0273
LD	<0.0001	0.0154	0.1332	0.0144
LWP	0.0547	0.1746	0.4859	0.3936

4. Discussion

In this study, we use long-term data from three thinning and pruning trials in order to obtain valuable information concerning the effects of silviculture on wood density in major timber species located in Mediterranean mountain areas and managed to obtain high-quality wood products.

Our results suggest that the positive influence of thinning on tree growth [4] is not accompanied by a significant effect on wood density in *P. sylvestris* or *P. nigra* (subsp. *nigra* and *salzmannii*). This finding agrees with those of previous research concerning conifer species subjected to thinning treatments in other regions. For example, there appeared to be no significant effect of thinning on RD, ED, LD, or LWP in *P. abies* [33,34] or *P. sylvestris* [3,32] in Finland. Similarly, Koga et al. [42] found no significant differences in RD and ED among thinning treatments in Canadian *Abies balsamea* (L.) Mill. stands. Tong et al. [54] reported that thinning operations had no significant influence on RD, ED, LD, or LWP in *P. mariana* in Canada.

The reduction in RD, ED, and LD over time in C plots is unexpected. A decrease in RD could occur due to, on the one hand, a fall in ED and LD and, on the other hand, the increase in production of earlywood relative to latewood as a consequence of rising growth rates caused by thinning [8,25,26,28,33]. This is in accordance with our results for *P. sylvestris* and *P. nigra nigra*, which exhibited decreasing LWP when thinning (T) or thinning combined with pruning (TPB) treatments were applied (Table 2). In contrast, higher wood density values may appear following thinning treatments due to a probable prolongation in the production of latewood [12,55]. This would be consistent with our findings for *P. nigra salzmannii*.

Pruning does not seem to have a significant effect on the wood density of the three species studied when comparing TPB to C and T plots. Gartner et al. [21] found no significant effects of pruning on wood density in *P. menziesii* and neither did Lin et al. [6] in the case of *Taiwania cryptomerioides* Hayata. However, according to the literature, wood density can increase after pruning due to a drop in juvenile wood formation and a rise in LWP [12,25,26] resulting from a decline in pruning-related growth rates [43]. At this experimental site, Moreno-Fernández et al. [4] reported no significant differences in tree growth between T and TPB, suggesting that the portion of crown removed through the pruning intervention was not so excessive as to affect growth rates after the pruning treatment [56]. However, data regarding the percentage of crown removed or the remaining living crown after pruning are not available for this study. In this regard, Gartner et al. [21] suggested that not detecting any effects of pruning on wood density at breast height may be due to the fact that the pruned branches were located in the lower crown and so contribute little to tree growth.

Contrary to previous findings [17,20,57], which suggest that RD increases with age, our results reveal that the average trends of the variables studied remain constant, except in the case of ED and LD in *P. nigra nigra* and LD in *P. nigra salzmannii*. In fact, the increase in RD over time is commonly associated with increments in LD and LWP and stability of ED [16,18]. Nevertheless, statistical analyses were carried out using density data for the period 1991 to 2012 in the case of *P. sylvestris*, and from 1993 to 2012 in the case of both *P. nigra* subspecies. On the one hand, significant trends in wood density over time might be detected when taking into consideration the complete temporal series. Hence, increased RD and LWP can be distinguished from pith to bark (see Figures 1–3). In this regard, *P. nigra* subspecies were expected to exhibit more pronounced radial density trends in juvenile wood than *P. sylvestris* [41], whereas the density of mature wood stabilizes in both species [16,41]. On the other hand, the RD stabilization may also be explained by the fact that most of the rings analysed are located within the mature wood section [41].

Our results confirm that *P. nigra* presents higher RD than *P. sylvestris* [41,57,58]. However, the cambial age of transition from juvenile to mature wood is earlier in *P. sylvestris* than in *P. nigra* [16,41]. Thus, it may be that there is a larger proportion of mature wood (denser than juvenile wood) in *P. sylvestris* than in *P. nigra*. Moreover, in addition to cambial age and growth rates of tree-ring width, the annual variations in wood density can be partially explained by climatic conditions [24]. For instance, Camarero et al. [14] found a significant relationship between the minimum density and spring precipitation in *P. nigra* and *P. sylvestris*.

5. Conclusions

Our findings reveal that the silvicultural practices addressed in this study (thinning and pruning) do not have a negative effect on wood density. Despite the fact that the number of samples is not very large, our results are in concordance with most of the studies carried out in other conifer species. However, it is necessary to consider a larger range of samples, study sites, ages of the trees at treatment application, and wood properties in order to better understand the influence of silviculture on wood quality and value in both *P. sylvestris* and *P. nigra*. Also, we should highlight certain gaps in our current knowledge that need to be addressed in future studies. It is necessary to analyse the influence of silvicultural treatments on the transition age from juvenile to mature wood (and on growth rates within both wood zones) at different stem heights. Additionally, assessing the effect of pruning on wood density, taking into consideration pruning characteristics (e.g., pruning height, crown ratio, branch and knotty core sizes) should also form part of any further research work [21,59]. Finally, under the current context of global change, studying the effects of climate on wood properties in different species would be particularly pertinent [14,24].

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