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Does Thinning Intensity Affect Wood Quality? An Analysis of Calabrian Pine in Southern Italy Using a Non-Destructive Acoustic Method

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Abstract: In the middle of XIX century, Calabrian pine was planted in southern Italy to increase the forest cover in mountainous areas. Many of these forest stands were never managed, since they were considered non-profitable for wood production. Therefore, in order to promote timber value, it is fundamental to study, more deeply, the characteristics and management options for this species. The acoustic technologies applied to predict the mechanical and physical properties of timber are well-established practices in forest research. In this study, we hypothesized that the tree stand density could influence the dynamic modulus of elasticity (MOEd) and, therefore, the future wood quality. We specifically aimed to verify if different management options, when applied, could influence the timber quality of Calabrian pine growing in similar environmental conditions. The study was conducted in the Aspromonte National Park (Calabria, Southern Italy). We derived the MOEd values from data obtained by the acoustic velocity measured through the TreeSonic™ timer. Calabrian pine trees were selected in stands where different intensities of thinning were applied eleven years before this study began (no thinning, thinning 25%, thinning 50%, and thinning 75%). The percentage refers to the number of trees cut with respect to the total number of occurring trees. The analyses were conducted on a total of 804 trees (201 trees for each intensity of thinning). A strong positive correlation was observed between the acoustic velocity, the thinning treatments and diameter at breast height (DBH). The thinning realized at 25% induced better tree wood quality. We also analyzed the best predictors for MOEd estimation, using variables easily measurable in the field, such as tree diameter, tree height, or their transformations (number of trees per hectare, basal area per hectare). We provide, here, a useful tool for predicting the wood stiffness in relation to stand parameters easily measurable in forest inventories.

Keywords: *Pinus nigra* Arnold subsp. *calabrica*; thinning intensity; Mediterranean mountain forests; acoustic velocity; modulus of elasticity; predictors for wood quality

1. Introduction

In Southern Europe, the Calabrian pine (*Pinus nigra* Arnold subsp. *calabrica*) occurs mainly in Italy (Calabria and Sicilia) and in France (Corsica). In Southern Italy, Calabrian pine forests are strongly related to the complex geological history, lithological and climatic characteristics, and also to the long history of human exploitation of the related forest stands [1]. In the past, Calabrian pine has provided valuable timber useful for building houses and vessels, as well as offering resinous substances (pitch) employed for a variety of purposes [2].

This species is particularly common in Sicily and on the Etna Volcano, but is mainly found in the Sila and Aspromonte National Parks in Calabria Region. Calabrian pine covers an area of approximately 114,000 ha, mostly characterized by pure stands of natural origin and plantations. The latter originated from extensive reforestation projects carried out between 1950 and 1970 on the basis of a specific Italian state law [3]. These plantations were realized with the aim of reducing the hydrological risk in mountainous areas, but also for facilitating the natural succession toward mixed forests with a significant component of deciduous species [4]. Together with soil and watershed protection, Calabrian pine has an important role in the local forest economy. In order to increase the economic value of these forests, the best silvicultural options should be selected and adopted at stand level, to achieve specific objectives. Therefore, different management practices and related intensities can change the tree species composition and richness and, also, the stand density and tree age distribution [5]. Moreover, management practices can increase the quality and quantity of merchantable timber, reducing also the risks derived from diseases and forest fires [6,7]. Forest management is aimed to create a vigorous stand, increasing tree growth and developing structural characteristics useful for timber production. Furthermore, thinning activities can also favor the creation of new habitats for wildlife, favoring the occurrence of healthy and vigorous forests [8].

Thinning activities control the forest stand density, improving the growth of the remaining trees [9] based on sustainable approaches [10], and decreasing, also, the tree mortality rates from a long-term perspective [11]. Thus, selective thinning should be encouraged for proper and sustainable forest management, supporting the forest stability, productivity, and quality.

Furthermore, forest management can determine variation in the physical and mechanical properties of harvested wood, both at stand and tree level [12]. For this reason, the identification of certain wood properties that can increase timber quality is essential, as it is important to select the best forest management options to improve wood quality.

Wood quality can be described as a set of characteristics that make woody materials economically valuable for their end uses [13]. Briggs and Smith [14] defined wood quality as "a measure of the aptness of wood for a given use". These properties can include, for example, the wood density, the uniformity in tree ring size, the percent of knot-free wood, and the proportion between early wood and late wood.

The objective evaluation of the wood quality and quantity is then critical for quantifying the productive value of a forest [15,16]. For this purpose, several non-destructive technologies (NDTs) have been developed in the past years to evaluate the quality of woody materials. For example, at belowground level, (mini) rhizotrons and ground-penetrating radar allows for evaluating tree rooting distribution and growth [17,18]. Moreover, at aboveground level, NDT measures allow for evaluation of the mechanical and technological properties of standing trees [19–22]. More specifically, stress wave-based non-destructive acoustic techniques have been extensively investigated during the past few decades [23], resulting in very useful methods for predicting the mechanical properties of woody materials.

The use of stress wave-based non-destructive tests is relatively common in the forest-to-mill woody supply chain in Australia [24] and in North America [25,26], while it is less common in Europe. Specifically, research developments [27] in acoustic sensing technology can, nowadays, permit the estimation of wood quality and intrinsic woody properties for standing trees, stems, and logs. The information derived from NDT measures could be used to sort and grade trees and logs according to their suitability for different end uses, such as structural products, advanced composites, pulp, and paper, and also for bioenergetics purposes.

Among the parameters measurable by acoustic methods, one of the most important is the modulus of elasticity of wood (MOE). The MOE, also known as wood stiffness, is essentially one of the fundamental wood quality parameters and measures the resistance to deflection [28]. For example, it is important since some woody products, such as laminated veneer and dimension lumber, require stiff and strong woody properties [29].

The recent literature has focused on determining whether stress wave techniques could be used to determine wood quality [30]. Several studies shown a good relationship between the stress wave-based modulus of elasticity (MOE) and the static MOE of lumber cut from logs [31,32]. This methodological approach is also applied to determine the relationships between the environmental conditions, silvicultural practices, and wood fiber properties [33]. The modulus of elasticity and the density of the woody materials strongly affect the acoustic properties of wood [34]. One of the most important mechanical properties, measurable by NDT methods, is Young's modulus, i.e., the modulus of elasticity (MOEd), which describes the material's stiffness.

Many portable instruments have been developed to measure the wood stiffness of standing trees, logs, and sawn timber using acoustic technology [35]. These instruments are able to measure the speed at which an induced sound (stress) wave propagates through a woody sample, which is proportional to its stiffness [36]. When the stress is applied to the wood surface, the generated disturbance propagates through the wood as stress wave. Several studies have hypothesized that the characteristics of the resulting wave are related to the mechanical properties of the wood [37,38].

Stress wave propagation in wood is a dynamic process correlated to several factors, such as the stand developmental stage [39], genetic characteristics [40,41], and also the silvicultural activities and their intensities [42]. More specifically, the quality and properties of wood are generally affected by silvicultural practices, especially the anthropic control of stand density. Silvicultural practices might not only increase the biomass production of trees, but also improve the quality and the related physical and mechanical characteristics of the wood in trees [43,44].

Furthermore, some authors have reported how high thinning intensities adversely influence the patterns of tree ring width and the tree competitive position within a forest stand [45–47].

Wang [48], examining the effect of thinning treatments on the wood quality of radiata pine, found that trees were characterized by higher acoustic velocity and stiffness mostly occurred in uncut stands and in forests characterized by light and medium intensities of thinning, whereas the lowest values occurred in stands that received the most intensive thinning approaches.

In Southern Italy, Todaro and Macchioni [43] and Proto et al. [16] showed a significant improvement of wood properties induced by a medium thinning operation for Douglas fir and Calabrian pine trees, respectively. Moreover, Cown et al. [49] and Barbour et al. [50] reported that heavy thinning approaches caused a slight decrease in wood density for radiata pine and Douglas fir. Finally, Wang et al. [51] indicated that heavy thinning induced the creation of more woody knots and larger-diameter knots than the medium thinning, or where no thinning had been applied.

The general objective of this study was the evaluation of the wood mechanical properties for Calabrian pine trees occurring in a forest stand located in the "Aspromonte" National Park (Calabria, Southern Italy) using innovative non-destructive methods (stress wave techniques). In detail, the evaluation of wood quality was carried out through acoustic measurements useful for assessing the MOE. Specifically, we hypothesized that different intensities of thinning can influence the wood quality of Calabrian pine trees. Three areas characterized by different management options as well as a no-thinning area, as control, were assessed. They were characterized by similar environmental conditions, such that the only discriminating parameter was the applied silviculture.

Furthermore, we also verified if the MOEd values may be predicted by easily recordable variables such as tree diameter (D), height (H), H/D ratio, or their transformations (number of trees per hectare, basal area per hectare).

2. Materials and Methods

2.1. Study Area and Experimental Design

The study area was located in Zervò (Municipality of Santa Cristina d'Aspromonte), in the context of the Aspromonte National Park (Calabria Region—38°14′30″ N; 16°01′09″ E), at an elevation of 1100 m a.s.l. The climate is temperate, with an annual mean temperature of around 10 °C and minimum monthly means of 3 °C (coldest month) and 17 °C (warmest month), respectively. The annual rainfall is 1508 mm, with minimum precipitation occurring in summer, but is, however, unevenly distributed over the year (Meteorological station of Santa Cristina d'Aspromonte—980 m a.s.l.). According to Pavari's phytoclimatic classification [52] the study area belongs to the *Castanetum/Fagetum* zone. The whole area is characterized by gently undulating slopes with northeast exposure and soils developed from high-rank metamorphic rocks, such as schist and biotitic gneisses, and classified according to the IUSS WRB [53].

The investigated forest stands are plantations of Calabrian pine which were established in 1968, with a planting density of 2000 trees per hectare (2.0 m × 2.5 m). In 2007, at the age of 39 years, the whole plantation has been subject to different intensities of thinning, following a randomized block experimental design with three intensities of thinning repeated three times. Moreover, a portion of the stand was not characterized by cutting and considered as control. Then, twelve plots in total were considered in the field measurements. Each block had an extension of 5 hectares (Figure 1).

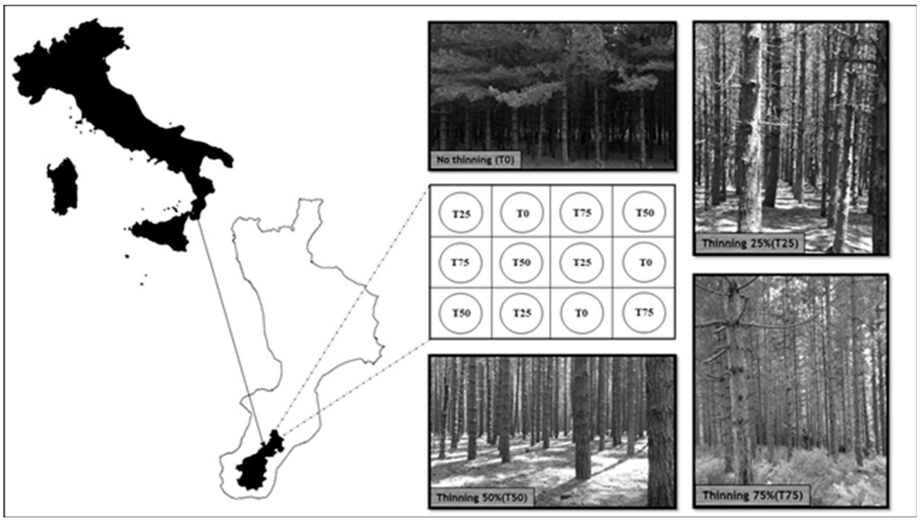

Figure 1. Location of the study area in Southern Italy (Calabrian Region) and the applied experimental design.

The treatments (intensity of thinning) can be described as follows: (1) No thinning (T0—Control); (2) Thinning where the 25% of the occurring trees were cut (T25); (3) Thinning where the 50% of the occurring trees were cut (T50); (4) Thinning where the 75% of the occurring trees were cut (T75).

2.2. Field and Laboratory Activity

In 2018, eleven years after the thinning operation (age of the plantation: 50 years), 804 trees were selected in total. Particular care was taken to select trees in good vegetative conditions, with canopies well separated from each other and referring to the dominant tree layer. The 804 trees were distributed between three blocks containing the four treatments, containing 201 trees for each treatment (67 trees for each replicate).

The diameter at breast height (DBH) and height of trees were measured. Moreover, for each tree, the acoustic wave tests were conducted at breast height. The measurements were conducted from June to July 2018, in order to reduce the effect of air humidity which could affect the obtained results [54]. More specifically, the relative air humidity was measured in the study area during the sampling period 1 m above the ground, using a HOBO1 Pro RH/Temp Data Logger (Onset Computer Corporation, Pocasset, MA, USA).

The system used for measuring acoustic velocity was the TreeSonic™ (Fakopp Enterprise, Agfalva, Hungary), a tool which has already applied in other studies [55]. This tool is characterized by an handheld hammer and two probes, a transmitting accelerometer, and a receiving accelerometer.

The operation consists in the insertion of two sensor probes (a transmit probe and a receiver probe) into the sapwood, introducing, then, the acoustic energy into the tree through a hammer impact. The probes were aligned within a vertical plane on the same face. In our study, a 1.00 m testing span was roughly centered at breast height. The lower probes were placed about 60 – 70 cm above the forest floor. Three measurements were realized for each selected tree and the average of the three recordings was used as the final transit time. In order to measure the acoustic velocity wave, the start and stop sensors were driven at a 45° angle through the bark and into the wood of the standing tree [56]. Indeed, the TreeSonic™ was developed to operate in the longitudinal direction of the tree. The acoustic velocity was then calculated from the span between the two sensor probes and the time-of-flight (TOF) data using the following formula (Equation (1)):

$$CT = S/TOF, \tag{1}$$

where CT = tree acoustic velocity (m/s), S = distance between the two probes (sensors) (m), TOF = time of flight (s).

For determination of the MOEd, it was necessary to determine the wood density. A subsample of trees was selected, considering trees where the TOF was also measured. In detail, woody cores were extracted, bark to bark, at breast height (1.30 m) with a Pressler borer from trees, referring to each of the diameter classes occurring in the different treatments (three cores for each treatment and diameter class). The fresh weight and volume of the tree cores were measured in the laboratory. Samples were then weighed to the nearest 0.01 gram with an electronic scale. Oven drying of all samples was done at 105 °C to constant weight. Density (kg m^{-3}) was calculated by dividing the dry weight with the fresh sample volume.

Afterwards, it was possible to calculate the modulus of elasticity (MOE), according to the following equation (Equation (2)):

$$MOEd = WD_{ij} \cdot CT^2, \tag{2}$$

where WD_{ij} = tree wood density (kg m^{-3}), shared by diameter class (i) and treatment (j); and CT = velocity (m s^{-1}).

The MOE estimated using the above cited formula [57] is called the dynamic modulus of elasticity (MOEd) [58], since the stress wave propagation in wood is a dynamic process and internally related to the physical and mechanical properties of the wood [51].

2.3. Statistical Analysis

The preliminary shape indexes (skewness and kurtosis) were calculated, and the Shapiro–Wilk test was performed to evaluate the distribution of the acquired data. Afterwards, the analysis of variance (ANOVA), based on a scheme of randomized blocks (four treatments repeated three times), was carried out to test the differences in MOEd values obtained among the four treatments and in relation to the occurring diameter classes. The significance level of the differences was tested using Tukey's method. When the significance level (p-value) was ≤ 0.05, the null hypothesis was rejected and significant differences in the means were accepted.

For the estimation of the MOEd, the following parameters (easily measurable in the field) were considered as predictors: diameter at breast height (DBH), height (H), height/diameter ratio (H/DBH), basal area (BA), stand density (number of trees per hectare) and their mutual interactions.

As a preliminary analysis, the correlations between these variables and the MOEd were analyzed using the Spearman correlation coefficient (r). Subsequently, the analysis was carried out by comparing different transformations and combinations of the variables correlated with the MOEd, suitable for expressing the relationship between MOEd and the above cited variables. The process involved regression analysis with a stepwise procedure (in each step, a variable was considered for addition to or subtraction from the set of explanatory variables based on F-tests). We then evaluated the fit of the final model using and analyzing the value of root mean square error (RMSE) and the coefficient of determination (R^2) value. Finally, the Shapiro–Wilk test was used to verify the normality of the error distribution.

Data analysis were carried out using the statistical software R version 3.2.5 [59].

3. Results

The relative air humidity measured in the study area during the sampling period ranged from 39% to 56%. For each treatment, the main measured structural parameters and the derived values of stand density and basal area are reported in Table 1. The skewness and kurtosis values, as well as the Shapiro–Wilk test (*SWT*), revealed that all the attributes were characterized by normal distribution. Tree diameters varied from about 25 to 32 cm, while tree heights showed similar values (19–20 m).

Table 1. The main parameters measured and the related structural characteristics for the four treatments analyzed (DBH: diameter at breast height; H; total tree height; N ha^{-1}: number of trees per hectare; SD: standard deviation; SWTsig: *p*-values of the Shapiro–Wilk Test).

Treatments	Parameters	Mean	SD	Skewness	Kurtosis	SWTsig
T0	DBH (cm)	24.9	6.07	0.228	−0.408	0.106
	H (m)	18.84	2.83	0.447	0.483	0.112
	Stand density (N ha^{-1})	1977	134	0.468	−0.62	0.125
	Basal area (m^2 ha^{-1})	95.9	7.16	−0.873	0.024	0.095
T25	DBH (cm)	26.7	8.19	0.352	0.242	0.053
	H (m)	20.03	2.76	0.298	0.237	0.131
	Stand density (N ha^{-1})	1548	77	0.045	−0.938	0.096
	Basal area (m^2 ha^{-1})	86.88	11	0.049	−0.965	0.364
T50	DBH (cm)	26.4	8.73	0.646	1.001	0.064
	H (m)	20.05	3.65	−0.326	0.042	0.055
	Stand density (N ha^{-1})	939	49	0.676	1.055	0.118
	Basal area (m^2 ha^{-1})	51.45	4.28	−0.451	−0.579	0.247
T75	DBH (cm)	32.5	9.96	0.444	−0.46	0.217
	H (m)	21.1	3.68	−0.503	0.399	0.146
	Stand density (N ha^{-1})	514	29	−0.281	−0.684	0.214
	Basal area (m^2 ha^{-1})	42.67	3.05	0.194	−0.544	0.079

Figure 2 reports the variability and the distribution of the wood density in relation to the type of treatment and the different diameter classes.

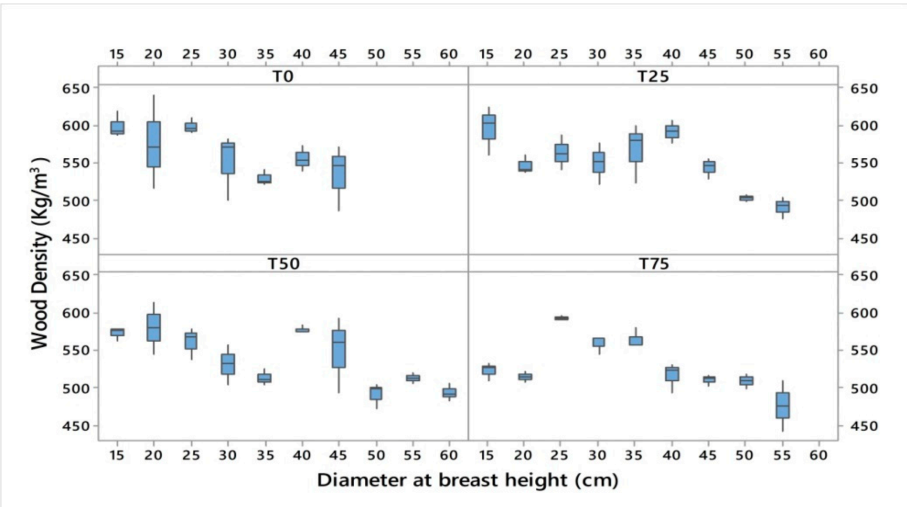

Figure 2. Variability of the tree wood density for each treatment as shared by diameter classes.

Table 2 shows the stress wave times and the related mechanical properties (wave velocity and MOEd) for the sampled trees in relation to the different silvicultural treatments. Moreover, the tree wood density (on average) is also shown.

Table 2. Tree wood density, stress wave time, and mechanical properties for the sampled trees among the different treatments considered (SD: standard deviation; MOEd: dynamic modulus of elasticity). Means in the same column followed by the same letter are not statistically different at $p \leq 0.05$ (Tukey test).

Treatments	Tree Wood Density (kg/m^3)		Stress Wave Time (µs)		Wave Velocity (m s^{-1})		MOEd (MPa)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
T0	563	30.2	282.5 ^{b}	48.0	3637.9 ^{d}	465	7206.2 ^{c}	1699.9
T25	550	35.5	257.0 ^{c}	27.0	3959.7 ^{ab}	397	8487.5 ^{b}	1695.4
T50	538	28.2	245.2 ^{cd}	22.0	4141.6 ^{a}	371	9275.8 ^{a}	1717.5
T75	529	27.4	344.5 ^{a}	90.8	3090.1 ^{c}	681	5371.9 ^{d}	2242.2

With reference to the stress wave time, significant differences were recorded among the different intensities of thinning ($F_{3;794}$ = 134.24; $p \leq 0.001$), while no difference between blocks ($F_{2;794}$ = 2.012; p = 0.134) were observed. The treatment characterized by the higher thinning intensity (T75) revealed a longer stress wave time (344.5 µs), also differing significantly with respect to all other conditions: T75 was about 22% and 40% higher than T0 and T50, respectively. Moreover, each treatment differs significantly in stress wave time from all the others, except T25 and T50, which had similar values.

The wave velocity is positively correlated to the thinning intensities, up to the T50 treatment (Table 2); afterwards, it significantly decreased for the higher thinning intensity (T75) ($F_{3;794}$ = 174.55; $p \leq 0.001$). No differences between blocks ($F_{2;794}$ = 1.579; p = 0.207) were observed.

In Figure 3, the variation of the wave velocity in relation to the tree diameter classes is reported for each treatment.

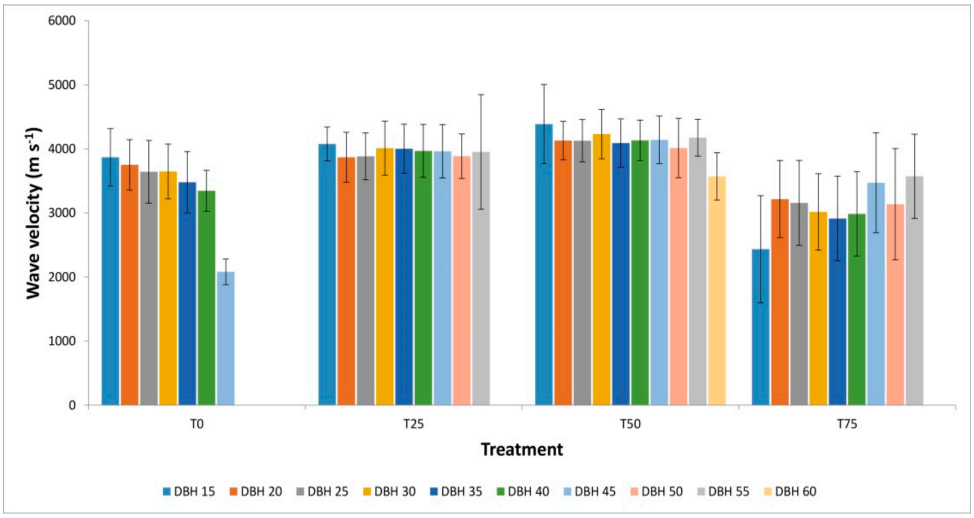

Figure 3. Wave velocity in relation to the diameter classes for each intensity of thinning. DBH: diameter at breast height. For Control, $F_{6;191}$ = 3.371; p = 0.006; for T25, $F_{8;189}$ = 0.658; p = 0.728; for T50, $F_{9;188}$ = 1.600; p = 0.118; for T75, $F_{8;189}$ = 2.330; p = 0.021.

In the control plots, the wave velocity tends to decrease as the tree diameters increase; more specifically, the 45 cm diameter class had significant lower values when compared to all other diameter classes. No significant differences were observed between diameter classes for T25 and T50. On the contrary, the wave velocity values were the lowest for the T75 treatment, revealing significant differences also between diameter classes.

Furthermore, Figure 4 shows the MOEd values obtained for all the sampled trees in each intensity of thinning.

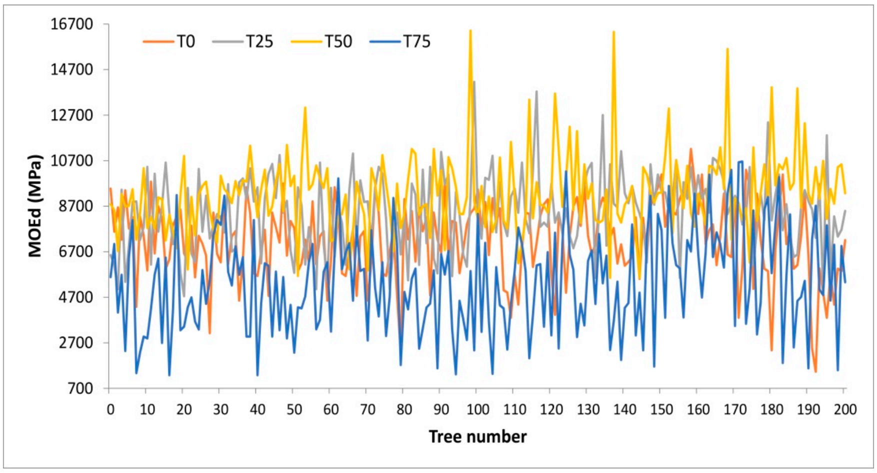

Figure 4. MOEd values obtained for all the sampled trees. Different colors refer to the four intensities of thinning.

Generally, for each tree, lower values always occurred in T75, while higher values occurred in T25 and T50. The analysis of variance (ANOVA) showed a significant effect of the thinning intensity on MOEd values ($F_{3;794}$ = 170.82; $p \leq 0.001$). Table 2 shows that the MOEd was significantly higher in T25 (on average, equal to 8487 MPa) and T50 (on average, 9275 MPa) than in T0 (on average, 7206 MPa) and T75 (on average 5371 MPa). Furthermore, the MOEd values for treatment T75 were always lower than in the T0 (Table 2). No difference between blocks was observed ($F_{2;794}$ = 1.574; p = 0.208). Furthermore, the analysis of variance showed a significant effect of the diameter classes on MOEd values for the thinning intensities T0 and T75, while no significant effects were observed in treatments T25 and T50 (Figure 5).

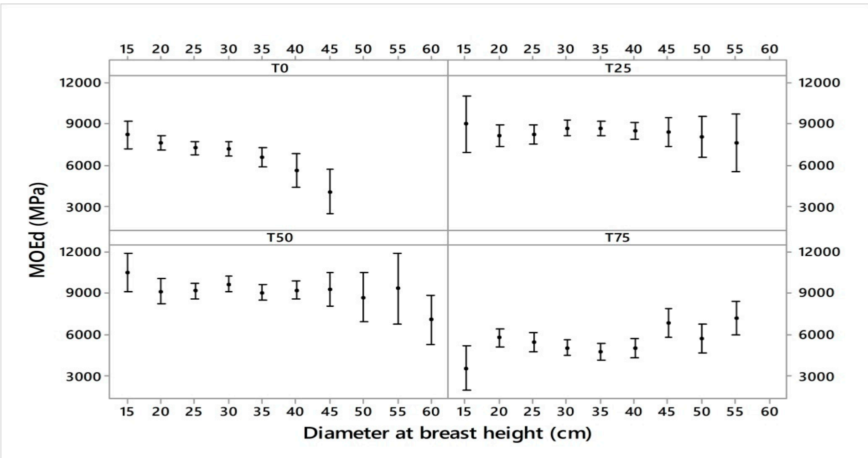

Figure 5. Dynamic modulus of elasticity (MOEd) in relation to the diameter classes for each intensity of thinning. For Control, $F_{6;191}$ = 3.371; p = 0.006; for T25, $F_{8;189}$ = 0.658; p = 0.728; for T50, $F_{9;188}$ = 1.600; p = 0.118; for T75, $F_{8;189}$ = 2.330; p = 0.021.

The MOEd values decrease as the diameters for T0 increase, with significant differences observed between the smallest and largest diameter classes. On the contrary, for the T25 and T50 treatments, the MOEd values were not significantly different when the diameter increased (Figure 5). The thinning, especially in the T25 treatment and, to a lesser extent, in the T50 treatment, had the effect of aligning the MOEd values, making the wood quality uniform in each diameter class. On the contrary, for the T75 treatment, the MOEd values not only were significantly lower than the T0, T25, and T50 treatments, but they also varied significantly with the increase of diameters.

In analyzing the best predictors for the estimation of MOEd, the applied analysis showed correlations between MOEd and DBH (r = 0.011), between MOEd and H (r = 0.040) and between MOEd and H/D (r = 0.033) that were not considered significant. On the contrary, significant correlations emerged between the MOEd and the stand density (r = 0.474) and basal area (r = 0.217).

Therefore, a model that allows for computing the MOEd as a function of the stand density (number of trees per hectare) and basal area (m^2 per hectare) was applied. According to the stepwise regression procedure, the variables were combined in the following model (Equation (3)):

$$MOEd = \beta_0 + \beta_1 \cdot \frac{1}{BA} + \beta_2 \cdot SD + \beta_3 \cdot SD^2 + \beta_4 \cdot SD^3, \quad (3)$$

where *BA* = basal area per hectare; *SD* = number of trees per hectare.

Figure 6 shows the variation of the MOEd in relation to the number of trees per hectare for different basal areas. The analysis covered a basal area lapse ranging from 40 to 70 m^2 ha^{-1}. The MOEd curve is lower for high values of basal area (70 m^2 ha^{-1}) and higher when basal area values decrease (40 m^2 ha^{-1}). The root mean square error (RMSE) was 1850.69 MPa and R^2 was 0.368. Moreover, the Shapiro–Wilk normality test (W = 0.9614; p = 0.096) confirmed the absence of deviation from normality. Furthermore, Table 3 reports the statistical values obtained by the application of the Equation (3).

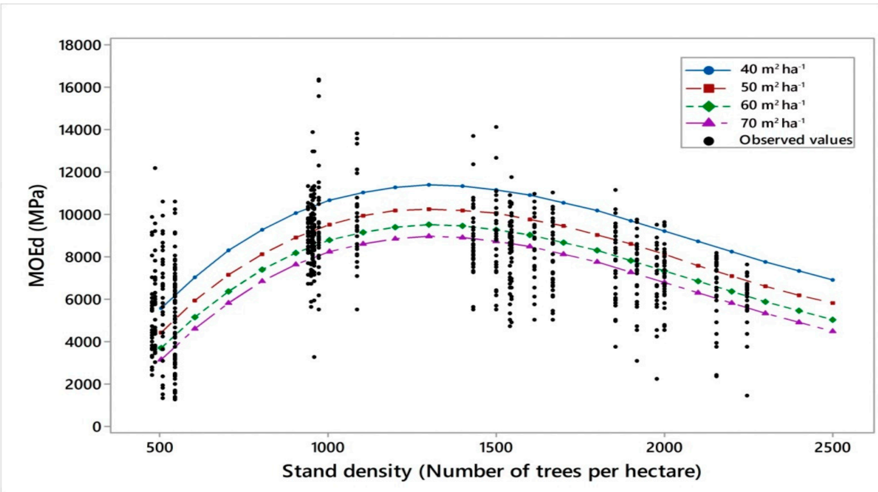

Figure 6. MOEd values in relation to the stand density and to the basal area.

Table 3. Statistical parameters obtained in the model and their significance (BA: basal area; SD: number of trees per hectare; T: results of the Student *t*-test).

Model	Coefficients	Standard Error of Coefficients	T	Significance
(Constant)	−11895.537	1349.925	−8.782	$p < 0.0001$
1/BA	227408.509	44672.651	5.068	$p < 0.0001$
SD	31.669	2.538	12.458	$p < 0.0001$
SD^2	−0.018	0.002	−7.941	$p < 0.0001$
SD^3	0.00000281	0.000	5.371	$p < 0.0001$

4. Discussion

The obtained results demonstrate how the effect of silvicultural practices on wood quality can be successfully identified by measurement of MOEd.

The MOEd values recorded in standing trees were significantly influenced by thinning intensities, since they determined significant variations in MOEd values with respect to the control. Specifically, the T25 and T50 treatments produced significant benefits in terms of wood quality, while a higher thinning intensity (T75) induced a significant decrease of the MOEd, even lower than the control. The strong diametric increment induced by the intensive thinning probably resulted in a less-stiff mature wood, resulting in a significant loss of wood quality.

On other hand, many authors confirmed that wood quality and intrinsic wood properties are generally affected by thinning [16,60,61], especially by stand density [62,63]. In this study, density values were measured on a subsample, rather than all, of the trees. This could lead to slight variations in MOEd values, but should not compromise the obtained results. In Southern Italy, Todaro and Macchioni [43] also found a significant variation of wood properties caused by thinning operations in a Douglas fir forest.

Generally, in the management of forest stands, it is common to apply a strong intensity of thinning in order to obtain a high assortment of diameters [64]. However, our results show that these assortments are of a lower quality compared to those derived from moderate intensities of thinning.

It is also interesting that the increase in the MOEd values from T0 to T25 is more sustained than the increase in MOEd from T25 to T50. This indicates that light thinning has a significant and positive effect on the wood quality, while increasing thinning intensities are always less significant. On the other hand, the T25 treatment had a positive effect on MOEd, both at the stand level and at the diametric class level, making the MOEd values almost equal for each diameter class. On the contrary, in the T0 and T75 treatments, we observed a decrease in wood quality when diameters increased. Other studies conducted on trees of the same age for different conifers (Sitka spruce (*Picea sitchensis* Bongard, Carrière, 1855), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), jack pine (*Pinus banksiana* Lamb.), ponderosa pine (*Pinus ponderosa* Douglas ex C. Lawson), and radiata pine (*Pinus radiata* D. Don) [65,66]) reported that the stress wave velocity was higher for trees with a slower growth rate or narrower rings.

The results obtained here are interesting on the basis of their practical and scientific applications, since they can provide useful silvicultural indications: the application of moderate thinning can favor, at least for the Calabrian pine, the formation of woody materials of good quality, regardless of the tree size from which the assortments are obtained.

More specifically, the MOEd values increase as the number of trees rise, up to 1200–1500 trees per hectare: this tree density seems to be the optimal value for obtaining the best woody materials for Calabrian pine. Briggs [67] showed that the tree acoustic velocity measured in Douglas fir increases as tree age rises, and decreases with increasing DBH; moreover, it is affected by the initial stand density.

Furthermore, higher values of basal area, when the number of trees and tree age are similar, determine lower values of the MOEd. We can then observe that a rapid diameter increment can negatively affect the wood quality.

In Douglas fir forests, Zhang [68] and Todaro and Macchioni [43] also reported that large trees deriving from higher growth rates would generally produce wood of lower stiffness. Furthermore, Chauhan and Walker [69] showed how, in fast-growing trees of radiata pine, the increased diameter with its larger second moment of inertia induced a lower tendency for high material stiffness; moreover, for trees of the same age, slow-growing trees tend to have a high stiffness, helping to sustain the trees under various environmental disturbances. Furthermore, Lasserre et al. [70] have observed that outerwood stiffness increases dramatically with stocking (and so with smaller tree DBH).

The low values of MOEd therefore appeared to be associated to a higher growth rate in trees, which adversely affects the specific gravity as well as the wood's strength and stiffness. Younger wood is lower in specific gravity and stiffness, while fast-growing wood has a larger diameter core of juvenile wood [71].

The moderate thinnings not only increase the biomass production of trees [72–74], but also improve the wood quality in trees, as highlighted in this study. However, Nakamura [75], using ultrasonically induced waves to assess the wood quality in larch trees, had already observed significant differences in the wave velocity and in MOEd values for forest stands characterized by different density some decades ago. In addition, Wang [48], assessing the effect of thinning treatments on the technological properties of Sitka spruce trees in southeast Alaska, showed that trees with higher acoustic velocity and stiffness were mostly found in forest stands that were uncut and/or slightly thinned, while the lowest values were found in stands subjected to high intensity thinning.

These results are encouraging, and indicate that the time of flight in the acoustic technologies may be applied, in the future, to monitor the wood property changes in forest stands. The technology can also be used to determine how silvicultural treatments affect the wood and fiber properties; consequently, the most effective treatment can be selected for maximizing the wood value, improving the timber quality of future plantations [22]. Finally, the precision of the acoustic technology has been strongly improved: nowadays, the tree quality, but also the intrinsic wood properties, can be predicted and correlated with the economic value of the final products [33].

In this study, the model developed can be used as a decision support system useful for the woody supply chain: the determination of the MOEd is fundamental for the final end uses of the woody products.

However, even if many studies have been carried out for estimating the MOEd through various non-destructive tests [76,77], few of them have, in any case, examined the relationships between MOEd and the stand structural features (e.g., stand density, DBH, total tree height, tree taper).

Gorman et al. [78] confirmed that the stress wave velocity is not affected by knots and other defects; nevertheless, it is important to underline that this method only measures the sound velocity within the outermost growth tree rings.

Furthermore, we identified, here, the most useful variables for predicting the MOEd, based on stand and tree characteristics in Calabrian pine.

In accordance with other studies [16,79–81], significant relationships between the dendrometric parameters and MOEd values were found. However, the relationships between MOEd and stand density, which showed a decrease in MOEd at high stand density, have not been previously described. While the MOEd always decreased with higher basal area, MOEd only decreased from a certain number of trees per hectare. However, in addition to the stand density (number of trees per hectare and basal area), the tree diameter classes could be considered for explaining the MOEd values in trees, as also already highlighted by Lei et al. [81]. Finally, as some of these stand structural features are commonly measured in forest inventories we provide, here, a useful tool for predicting the wood stiffness in relation to the tree and stand characteristics measured in the field. This approach allows for determination of the wood quality directly from inventory data.

However, the model used is site- and species-specific since, in other silvicultural systems, the implemented equation can differ. In any case, a pioneer of forest modeling [82] confirmed that no single model can be expected to be the "best" for all the conditions which are common in forest prediction.

5. Conclusions

This study showed that silvicultural practices might not only increase biomass production, but also improve the wood quality in trees. We verified here, through innovative and non-destructive methods, that different intensities of thinning can influence the wood quality of Calabrian pine trees in Southern Italy. Our results demonstrated that the effect of silvicultural practices on the properties of wood can be successfully identified by stress wave MOEd. Furthermore, we proved that MOEd values may be predicted by easily recordable variables in the field.

More specifically, for Calabrian pine, different intensities of thinning can affect the wood quality and, therefore, the final obtainable woody products. We also demonstrated that using a low intensity of thinning could be the best option for obtaining woody materials of good quality, regardless of the tree size from which the assortments derive. The results obtained are encouraging, since they demonstrate the potential of the non-destructive acoustic technique to determine the influence of thinning treatments performed on Calabrian pine. However, it could be interesting to also test the same methodological approach on other tree species and in different ecological contexts.

Finally, we tested a useful tool for predicting the wood stiffness in relation to tree and stand characteristics commonly measured in the field. This approach allows for determination of the wood quality directly from inventory data, even if the model used is site- and species-specific and the implemented equation can differ in other silvicultural systems.

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