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Wood properties of young Douglas-fir in Southern Italy: results over a 12-year post-thinning period

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Abstract This paper describes the study of a 31-year-old Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stand located in Southern Italy, which was thinned 19 years after planting. The aim of the study is to evaluate the influence of three thinning treatments (unthinned, selective, and geometrical) performed twelve years later on wood density (WD), moisture content, shrinkage, ring width (RW), latewood proportion (LW%), modulus of elasticity, compression (CS), and bending strength (BS). The WD was higher in the unthinned stand. LW% and BS were lowest in the selective thinning and in the geometrical thinning, respectively. No significant differences were found in other variables. In addition, the thinning processes mostly affected the medium tree class more than the dominant and suppressed ones. Regression analysis established a correlation between mechanical characteristics and WD, RW and LW%. Mechanical strength is strongly correlated with WD than other variables. The stepwise model showed that WD and RW are most closely related to the behavior of CS, whereas only WD explained variation in BS. Stand density reduction may improve the development of stands without greatly affecting wood quality.

Italian Douglas-fir thinning and properties.

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Introduction

The utilization of wood for building is increasing and suggests good market perspectives even for Italian timber. However, little is known about the characteristics of Italian grown timber utilized for structural purposes and particularly those of softwood from plantations.

In Italy, natural coniferous species dominate the Alpine chain in the Northern part of the country with a less continuous distribution in the Central and Southern Apennines. More than one half of the growing stock consists of *Picea abies* Karst, *Pinus silvestris* L., *Pinus nigra* Arnold, *Pinus laricio* Poiret, *Larix decidua* Mill, and *Abies alba* Mill.

For a long time in Italy, conifers were widely planted for reforestation, and one of the most utilized species was Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), generating a great interest in its management and utilization. More than 10,000 hectares were planted during the 20th century.

Several studies have described the technical and silvicultural aspects of Italian-grown Douglas-fir (e.g., Ciancio and Nocentini 1978; La Marca 1986), but the relationship between management regime and wood quality (*sensu* Macdonald and Hubert 2002) of young trees was insufficiently analyzed.

Wood properties vary with several factors, such as silvicultural activities (Zobel and van Buijtenen 1989), developmental stage of the stand (Vanninen et al. 1996), and genetic source (Vargashernandez and Adams 1994; Rozenberg et al. 2001).

The first variable that can be controlled by silvicultural treatment is the initial spacing distance when planting (Barbour et al. 1997). The same authors reported that wood quality is affected by the timing and intensity of the first thinning, but this relationship is extremely complex because of the additional effects of the environment and genetics on growth and wood density. Nevertheless, especially thinnings may have an effect on some wood properties, depending on type and intensity of thinning, tree ring width patterns, and competitive position of a given tree within the stand (Schweingruber 1988; Wang et al. 2005; Peltola et al. 2007).

Wood density is generally considered the most important characteristic among those defining wood quality (Kennedy 1995), although wood quality strictly depends on the wood's final utilization and also on other factors, such as juvenile wood content (DiLucca 1989), grain angle, microfibril, knots, and ring width characteristics. Their effect on wood quality and value has been discussed in detail by Jozsa and Middleton (1994).

For most conifers, the published results on the relationship between growth rates and wood density are very mixed (Jozsa and Middleton 1994) and sometimes conflicting.

Tree specie like spruce normally exert a negative relationship between ring width and wood density, even if sometimes only a moderate or weak relationship was found between the two variables (Dutilleul et al. 1998).

Different situations occur for some hard pines such as Douglas-fir, where an abrupt earlywood–latewood transition is observed.

Jozsa and Kellogg (1986) examined the density pattern from pith to bark at different sampling heights in Douglas-fir. The authors reported relatively low-density juvenile wood in Douglas-fir in the 15–20 years period of growth, followed by an increasing density to about 30 years. Then, a stable or further slightly increasing wood density trend was observed. Similar results are reported by Kennedy (1995). The same author compared wide and narrow rings at the same age and stated that the influence of ring width on wood density is quite weak.

The increase in growth ring width and the decrease in wood density can be caused by reduction in the level of competition (Polge 1984; Hecker and Becker 1996) but also other silvicultural treatments can accelerate diameter growth, e.g., fertilization (Erickson and Harrison 1974). However, there can be a high wood density in wide growth rings if latewood quantity is large (Schweingruber 1988).

Gartner et al. (2002) reported that wood density is a good predictor of performance and economic value for Douglas-fir, because it is directly correlated with mechanical strength or pulp yield; thus, predicting wood density also has a potential economic value. However, in structural size samples, the presence of other reducing factors (e.g., knots and spiral grain) means that wood density alone is not always a good predictor of mechanical strength (Macdonald and Hubert 2002).

Aim of the study

The aim of the study is to evaluate the effects of three different thinning regimes on initial wood characteristics of young-growth Douglas-fir forests in Southern Italy.

Our hypothesis is that wood density (WD), ring width (RW), and latewood proportion (LW%) could be used as predictors of wood mechanical properties and that these predictors are correlated with different thinning regimes.

In order to validate these assumptions, the physical and mechanical timber properties were measured and analyzed. Taking into account the three different treatments, a statistical study of the mechanical characteristics in relation to WD, RW, and LW% was performed using simple Pearson correlations and stepwise model equations.

Materials and methods

Stand description and experimental design

The experimental area is located at *Serra Salinaro* at 900–1,000 m a.s.l., within the Pellegrina-Cinquemiglia forest (39°26′15″ N; 16°03′45″ E), in Southern Italy, where 1,119 hectares have been planted with Douglas-fir in 1966. The other species planted during the same years were *Pinus strobus* L., *Cedrus atlantica* (Endl.) Carrierre), *Abies alba* Mill., *Pinus pinaster* Ait., and *Larix leptolepsis* (sieb. Et Zucc.) Gard. = *L. kampferi* Sarg.).

Natural vegetation is represented by *Fagus sylvatica* L., *Alnus cordata* L., *Castanea sativa* Mill., and sporadically *Juglans regia* L.

Paleozoic and Mesozoic very low- to low-grade metamorphic rocks with ophiolites represent the Lithological units (Terranova et al. 2009). The prevalent soil is brownish *podzoli* typical of silicate eruptive and metamorphic rocks with some brownish Mediterranean soil in the slopes exposed to South.

Temperature and precipitation patterns indicate an irregular distribution of precipitation throughout the year. Data from a meteorological station close by in Guardia Piemontese (515 m a.s.l., 5 km from the study site) show the mean annual temperature to be 11.5°C. The mean monthly maximum temperature is 20°C, while the minimum is 3°C. Mean annual precipitation is 1,264 mm, distributed as follows: 501 mm in winter, 291 in spring, 384 in autumn, and 88 in summer. Soil water depletion during summer is mitigated by fog and low clouds, carried by western weather systems from the Tyrrhenian Sea that is close by.

The vegetative material appears uniform, although the genetic provenance is unknown. The initial spacing was two meters square. Each tree was pruned up to 2 m in 1984, 18 years after planting. In 1984, twelve randomly plots of 900 m^2 were established to carry out the thinning experiment.

This was an experiment carried out by other researchers (see Menguzzato and Tabacchi 1986). These authors have initially selected 28 plots. In each plot, they measured the dominant height (the mean height of the 100 largest trees × ha^{-1}) that was used to stratified four blocks containing seven plots. At each plot was then assigned a treatment randomly selected. Among the seven original treatments, we choose only the three most significant based on the type of treatment and intensity of logging.

The following thinning treatments were applied:

1. Unthinned (*unth*): no treatment;
2. Selective thinning (*sel th*): the suppressed trees were removed as well as poorly deformed trees, and 53% of living trees were eliminated, corresponding to 39% of the basal area;
3. Geometrical thinning (*geom th*): thinning was carried out by removing every third row, thus eliminating 33% of living and dead trees and 31% of the basal area.

Sample trees were felled in the autumn of 1997 at 31 years of age.

Sampling, measurements

DBH and total height were measured on all trees at each plot. These measurements were utilized to calculate the total volume (m^3 ha^{-1}) through an appropriate volume-diameter equation (without considering the branches). For each treatment, Table 1 shows the number of trees (no. trees ha^{-1}), the basal area (m^2 ha^{-1}), the mean DBH (cm), and the volume (m^3 ha^{-1}) immediately before and after thinning and 12-years after the thinning, while Fig. 2 shows the variation over time of plot-level attributes. In order to evaluate the physical and mechanical characteristics of wood, twelve trees were randomly selected from each treatment. In total, 36 sample trees were felled. In each plot, three trees were felled, one for each DBH tree class. In fact, selected trees were classified based on their DBH, as small (suppressed tree), medium (intermediate tree) and large (dominant tree). Table 2 illustrates the mean characteristics of felled trees.

Felled stems were cut into 2-m-long logs. From the bottom of each log (two for each tree), a 5-cm-thick disk was taken. The wooden surface was cleaned by sand paper, until tracheids were clearly visible under a 40× stereomicroscope. Ring count was recorded for each basal disk, and LW and RW were measured with an accuracy of 0.01 mm on each of 4 radii. All measurements were taken with a semiautomatic measuring device called dendrograph "Lega Smile" (Corona et al. 1989).

Table 1 Attributes of experimental plots immediately before, after thinning, and 12 years after thinning

Plot	Treatment	Before thinning				After thinning				12 years after thinning				
		Plants (no ha^{-1})	BA (m^2 ha^{-1})	DBH (cm)	V (m^3 ha^{-1})	Plants (no ha^{-1})	BA (m^2 ha^{-1})	DBH (cm)	V (m^3 ha^{-1})	Plants (no ha^{-1})	BA (m^2 ha^{-1})	DBH (cm)	MTH (m)	V (m^3 ha^{-1})
3	Unth	1644	39.47	17.7	296.8	1644	39.47	17.7	296.8	1467	56.7	22.2	22.4	466.2
13	Unth	1811	42.41	19.5	316.2	1811	42.41	19.5	316.2	1233	50.5	22.8	22.5	420.7
15	Unth	1467	41.15	21.3	311.6	1467	41.15	21.3	311.6	1044	48.0	24.2	23.6	409.3
22	Unth	1656	41.02	20	308.5	1656	41.02	20	308.5	1244	49.9	22.6	23.7	413.7
Mean value		1645	41	20	308	1645	41	20	308	1247	51.3a	23.0a	23.0	427.5a
8	Sel th	2233	43.76	17.8	322.4	1055	27.07	20.4	203.9	1033	54.6	25.9	24.1	447.4
17	Sel th	2055	44.41	18.7	329.6	1111	28.02	20.2	213.4	900	44.8	25.2	24.8	387.3
26	Sel th	2166	45.69	18.5	338.6	911	27.64	22.2	210.7	833	47.8	27.0	24.9	422.9
6	Sel th	2033	46.94	19.3	351.3	867	27.12	22.5	207.1	844	51.5	27.9	24.8	459.2
Mean value		2122	45	19	335	986	27	21	209	903	49.7ab	26.5b	24.6	436a
10	Geom th	1622	33.51	18.3	247.7	1156	23.58	18.2	174.1	856	33.3	22.2	20.3	273.6
14	Geom th	1678	37.45	19	278.7	1100	24.75	19.1	184.7	856	37.2	23.5	20.7	312.5
29	Geom th	2055	43.68	18.6	324.1	1322	29.59	19	220.6	1011	52.1	25.6	20.6	453.0
7	Geom th	1866	45.7	19.9	343.4	1244	31.22	20.2	235	911	43.5	24.6	21.0	373.1
Mean value		1805	40	19	298	1206	27	19	204	909	41.5 b	24.0a	20.6	353b

The different letters indicate significantly different means at $P < 0.05$ (Duncan's MR test)

BA basal area, *DBH* diameter at breast height, *MTH* mean total height, *V* volume

Table 2 Characteristics of Douglas-fir trees sampled from each treatment 12 years after thinning

Treatment	Tree type	DBH (cm)	SD	Mean RW (mm)	SD	Height (m)	SD
Unthinned	Small	15.4	1.8	3.3	0.5	19.5	0.7
	Medium	23.0	0.7	3.8	0.2	24.0	0.6
	Large	33.0	1.5	5.2	0.9	27.6	0.5
Selective thinning	Small	16.2	1.5	2.7	0.4	21.5	2.5
	Medium	26.6	0.7	4.1	0.3	24.6	2.3
	Large	33.4	0.9	5.1	0.6	28.1	1.1
Geometrical thinning	Small	17.3	1.9	3.0	0.4	20.6	0.9
	Medium	24.0	0.7	3.8	0.3	23.9	2.4
	Large	32.8	1.2	5.3	0.6	26.1	3.3

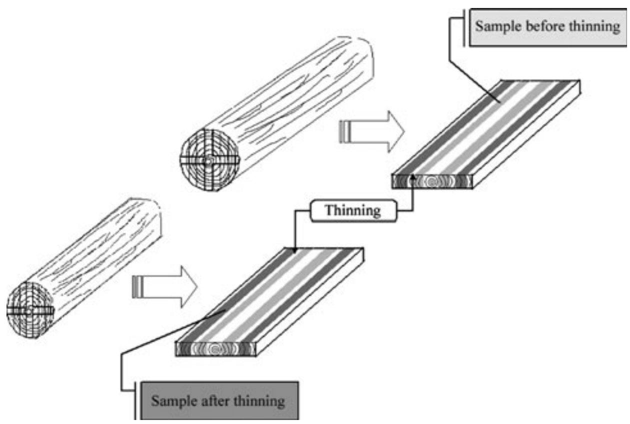

Fig. 1 Preparation of test samples

From each disk, clear wood samples were then extracted from pith to bark along 4 perpendicular radii. A total of 1,146 samples were used for each physical test, 382 for each treatment. The dimension of samples was 20 × 20 × 20 mm (tangential, radial, and longitudinal). The moisture content and the WD were determined and calculated according to UNI-ISO 3130 (1985a) and 3131 (1985b). Tangential, radial, and total shrinkages were calculated according to UNI-ISO 4469 (1985e) and 4858 (1988). The two logs cut from each tree were sawn into 30-mm-thick boards (Fig. 1). After sawing, boards were conditioned to equilibrate at 12% moisture content in a climatic room and then cut into clear samples for mechanical tests. The samples' dimensions were 20 × 20 × 40 mm and 20 × 20 × 300 mm (tangential × radial × longitudinal) for measuring compression and bending strength. The same number of samples was selected among the three tree sizes within each of the three thinning treatments, so that 96 clear wood samples for each treatment, 32 for each tree size, were available. At the end, a total of 288 clear wood samples, 96 × 3 treatments, were analyzed for each mechanical test. For specifying the difference between treatments in terms of mechanical strength, half of the samples (144) were obtained from the wood grown after thinning (mature wood region) and the other half (144) from the wood immediately before thinning (juvenile wood region). None of the samples included the pith section (Fig. 1). The mechanical tests (compression strength parallel to grain and static tangential bending strength) were performed according to UNI-ISO 3787 (UNI-ISO 1985d) and 3133 (1985c). WD, RW, and LW% were also measured on each clear wood sample used in mechanical tests.

The dynamic modulus of elasticity (DMOE) was determined by the transverse free vibration method, using the Bing 2000 v1.0 system software package developed by CIRAD-Forêt (Brancheriau and Bailleres 2002). After these tests, only WD was determined on each sample.

Statistical analysis

For the statistical analyses, mechanical characteristics (compression and bending strength) were considered as a function of WD, RW, and LW%. Pearson product correlation coefficients were computed between mechanical properties and WD, RW, and LW%, and mechanical properties were then related to these same variables by multiple regression using a stepwise procedure with $P < 0.05$. The Pearson correlation (r) appears to be a useful complement to identify the single effect of WD, RW, and LW% on the mechanical resistance for each treatment. Pearson r measures a relationship between two variables only to the extent in which it is linear. The observed variables respect the linearity assumptions.

In order to develop an improved model and considering the dependence of CS and BS on each variable, we investigated the results by expressing the CS and BS as a function of all parameters. A tabulated final model was made after eliminating the variables that were not significant in the stepwise regression using the 0.05 *P*-value.

This is expressed by:

$$(\mathrm{CS};\mathrm{BS}) = \alpha(\mathrm{WD}) + \beta(\mathrm{RW}) + \lambda(\mathrm{LW\%}) + \mathrm{const}$$

where α, β, and λ are the coefficients of the model.

We followed the stepwise regression procedure where the variable choice was made in a successive order after the addition of the independent variable, which had the highest correlation with the dependent one (Hocking 1976). For each cycle, the marginal contribution of the last model variable is tested by the statistics "F". The variables already selected in the previous cycles were also tested, because they could become superfluous due to the associations with the variables added afterward. The nonsignificant terms are deleted by the model itself. The procedure continues until no variable is added or deleted by the model anymore. At the end, the significant variables and the R^2 from the stepwise regression were reported for each treatment.

The analysis of variance (ANOVA) was performed by the general factor model procedure of the SPSS software (version 10.0). Each measured parameter was estimated and compared in relation to the treatments and tree size, using Duncan's multiple range test (Duncan 1955).

Results

Physical and mechanical properties

Unth showed a high level of self-thinning (Fig. 2a), while *sel th* showed an increase in the basal area, average DBH, and volume (Fig. 2b–d). After 12 years, *sel th* reached the level of the basal area and volume measured for the *unth* treatment. *Geom th* does not seem to be affected by the thinning operation.

The amount of LW% (Fig. 3) was always high (around 50% of the total ring width), without being affected by thinning treatments, although for a very short period after

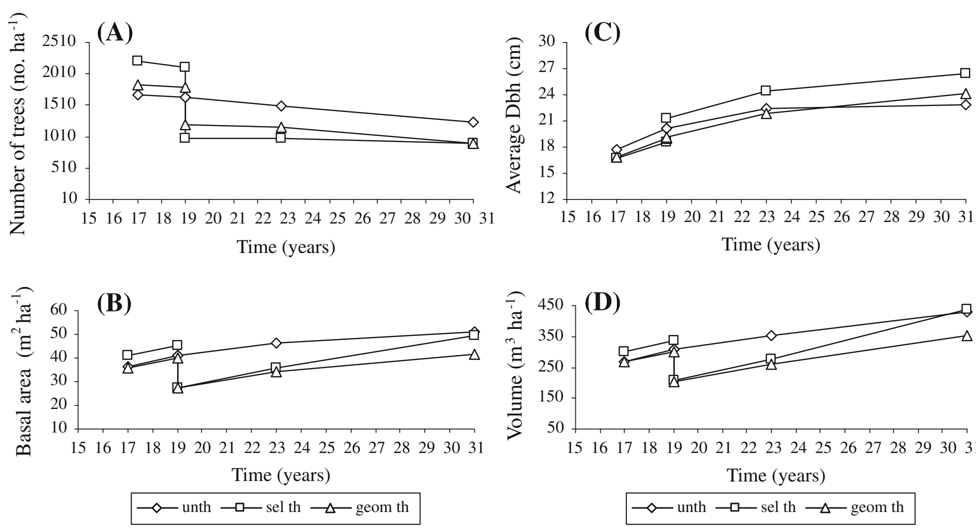

Fig. 2 Trends in stand attributes over time in different thinning treatments. **a** number of trees; **b** basal area; **c** average DBH; **d** volume

Fig. 3 Trend in ring width and latewood proportion for medium trees in different thinning systems as related to age since plantation (at breast high) in Douglas-fir

Table 3 The properties of wood from the different thinning treatments

Variable	Unthinned	Selective thinning	Geometrical thinning
WD (MC 12%) (g cm^{-3})	0.533a	0.502b	0.499b
SD	0.061	0.056	0.067
No. of samples	382	382	382
WD (MC > 30%) (g cm^{-3})	0.695ns	0.672ns	0.674ns
SD	0.140	0.159	0.169
No. of samples	382	382	382
WD (MC 0%) (g cm^{-3})	0.500a	0.469b	0.466b
SD	0.061	0.056	0.065
No. of samples	382	382	382
Total volume shrinkage (%)	11.1a	10.0b	10.3ab
SD	3.2	2.6	2.7
No. of samples	382	382	382
Tangential shrinkage (%)	6.7ns	6.6ns	6.7ns
SD	1.6	1.7	1.9
No. of samples	382	382	382
Radial shrinkage (%)	4.6a	4.2b	4.1b
SD	1.4	1.6	1.3
No. of samples	382	382	382
Ring width (mm)	4.1ns	4.0ns	4.0ns
SD	2.72	2.77	2.76
No. of samples	288	288	288
Latewood proportion (%)	47.7b	45.0a	47.2b
SD	10.08	9.10	9.84
No. of samples	288	288	288
CS (N mm^{-2})	55.1ns	53.3ns	52.9ns
SD	9.4	8.0	8.8
No. of samples	96	96	96
BS (N mm^{-2})	96.9a	93.2a	87.2b
SD	17.6	15.6	19.0
No. of samples	96	96	96
DMOE (N mm^{-2})	12,220ns	12,554ns	12,559ns
SD	3413	2837	3872
No. of samples	48	48	48

Results of WD, shrinkage, RW, and LW% are from sample disks, while those of CS, BS, and DMOE are from clear sample. The different letters indicate significantly different means at $P < 0.05$ (Duncan's MR test)

thinning (principally in the *sel th* one) the LW% decreases compared to *unth*.

The highest wood density value at 12% of moisture content, 0.533 g cm^{-3}, was found in the *unth* (Table 3). No significant difference was found between the treatments for green WD, tangential shrinkage, and RW (Table 3).

The *unth* radial shrinkage (4.6%) was statistically different from both *sel th* (4.2%) and *geom th* (4.1%) (Table 3). Total volume shrinkage was statistically higher in *unth* (11.1%) compared to *sel th* (10.0%) but not in *geom th* (10.3%) (Table 3). LW% was lowest in *sel th* (Table 3).

For the CS, there was no difference among the average values (Table 3). For the BS, the value of the *geom th* samples was significantly lower than in the other treatment samples (Table 3). No significant difference was observed in DMOE (Table 3).

Mechanical properties predicted by WD, RW, and LW%

The linear regression allows a comprehensive understanding of the relationships between variables. Table 4 (CS-variables) and Table 5 (BS-variables) show the Pearson correlation coefficient (r) and p-value for each treatment. High positive correlations occur between mechanical strength and WD. Mechanical strength–RW relationships were negatively correlated but not as much as with the WD. On the contrary, the mechanical strength–LW% relationships were not always clear. CS (Table 4) shows a significant correlation CS–LW% only for *sel th*, while for BS (Table 5) the BS–LW% relationship was significant both in *unth* and in *geom th* but not in *sel th*. WD is always negatively correlated with RW and positively with LW% (Tables 4, 5).

The DMOE–WD correlation coefficient is positive and significant in all treatments: ($r = 0.53$ in *unth*), ($r = 0.49$ in *sel th*), ($r = 0.45$ in *geom th*).

All parameters were included in the CS model just in *unth* (Table 6). RW and especially WD seem to have a major influence on CS values (Table 6).

WD is the most important variable to explain BS (Table 7). Only in *sel th*, the equation included a negative influence of LW%. Contrary to the CS model, the equations never included RW.

The R^2 of CS in *unth* treatment is always higher than in other treatments (Table 6). This means that the WD plays an important role in *unth*, in association with a higher LW%.

In our study, the R^2 obtained in all treatments was better than any of the linear models taken individually. Similar results were found by Leban and Haines (1999).

WD and RW were the main properties related to the behavior of the CS (Table 6), while for BS the only important property seemed to be WD (Table 7). The presence of LW in the models only in selective thinning (Table 7) could be related to the treatment regime. In fact, this parameter significantly decreased when the intensity of treatment increased (Table 3) mainly for large and medium trees (Table 8).

Thinning operation caused a significant variation in terms of RW only in the medium DBH tree class but not in both small and large DBH tree classes (Table 8). Different results were obtained for LW%. In fact, this parameter was

Table 4 Simple Pearson correlation among compression strength (CS), wood density (WD), ring width (RW) and latewood proportion (LW%)

	Unthinned			Selective thinning			Geometrical thinning		
	CS	WD	RW	CS	WD	RW	CS	WD	RW
WD	**0.858**			**0.848**			**0.854**		
	0.000			*0.000*			*0.000*		
RW	**−0.452**	**−0.326**		**−0.425**	**−0.339**		**−0.587**	**−0.475**	
	0.000	*0.001*		*0.000*	*0.001*		*0.000*	*0.000*	
LW%	**0.021**	**0.249**	**0.203**	**0.219**	**0.366**	**0.056**	**0.178**	**0.309**	**0.103**
	0.424	*0.011*	*0.032*	*0.021*	*0.000*	*0.303*	*0.053*	*0.002*	*0.176*

Pearson's correlation coefficients in bold and their *P*-values in italics

Table 5 Simple Pearson correlation among bending strength (BS), wood density (WD), ring width (RW), and latewood proportion (LW%)

	Unthinned			Selective thinning			Geometrical thinning		
	BS	WD	RW	BS	WD	RW	BS	WD	RW
WD	**0.757**			**0.632**			**0.785**		
	0.000			*0.000*			*0.000*		
RW	**−0.380**	**−0.445**		**−0.410**	**−0.410**		**−0.310**	**−0.287**	
	0.000	*0.000*		*0.000*	*0.000*		*0.003*	*0.005*	
LW%	**0.196**	**0.302**	**0.301**	**0.054**	**0.407**	**0.207**	**0.286**	**0.382**	**0.309**
	0.031	*0.002*	*0.002*	*0.308*	*0.000*	*0.026*	*0.005*	*0.000*	*0.003*

Pearson's correlation coefficients in bold and their *P*-values in italics

Table 6 Compression strength (CS): results from stepwise model for each thinning treatment

Variable	Coefficient	SE	*t*	*P*-value	R^2
Unthinned					
WD	122.540	8.235	14.881	0.000	0.79
RW	−0.696	0.279	−2.489	0.015	
LW%	−0.121	0.041	−2.934	0.004	
Constant	−2.644	4.849	−0.545	0.587	
Selective thinning					
WD	110.030	8.221	13.384	0.000	0.74
RW	−0.681	0.260	−2.619	0.011	
Constant	−2.279	4.959	−0.459	0.647	
Geometrical thinning					
WD	100.753	8.177	12.322	0.000	0.77
RW	−0.939	0.242	−3.871	0.000	
Constant	4.012	5.103	0.786	0.434	

Table 7 Bending strength (BS): results from stepwise model for each thinning treatment

Variable	Coefficient	SE	*t*	*P*-value	R^2
Unthinned					
WD	206.589	18.787	10.997	0.000	0.57
Constant	−18.552	10.592	−1.751	0.083	
Selective thinning					
WD	211.981	25.584	8.286	0.000	0.45
LW%	−40.895	14.802	−2.763	0.007	
Constant	−1.400	12.708	−0.110	0.913	
Geometrical thinning					
WD	219.702	19.627	11.194	0.000	0.62
Constant	−30.575	10.694	−2.859	0.005	

the highest in *unth* for both medium and large DBH tree classes. Consequently, CS and BS showed the highest values in the same treatment and DBH class combination (Table 8).

Results for suppressed trees were somehow dubious because the samples used for mechanical tests were not completely made of "after thinning" wood, due to their slow growth. Nevertheless, mean values after thinning showed no difference between treatments in terms of RW and CS, while LW% was the lowest in the *sel th* treatment. BS value was the lowest in *geom th*. No statistical difference was shown between treatments before thinning (data not displayed) for all the measured variables (RW, LW%, CS, and BS).

Discussion

Thinning aims to improve the final wood quality by increasing tree size, tree form, and volume (Todaro et al.

Table 8 Ring width, latewood proportion, compression, and bending strength after thinning as function of tree type

Tree type	Variable	Unthinned	Selective thinning	Geometrical thinning
Large trees	Ring width (mm)	3.5ns	3.0ns	3.2ns
	Latewood proportion (%)	55.2a	47.1b	46.6b
	CS (N mm^{-2})	62.4a	54.3b	54.8b
	BS (N mm^{-2})	111.0a	96.6b	86.8b
Medium trees	Ring width (mm)	1.7b	2.4a	2.0b
	Latewood proportion (%)	50.2a	45.2b	45.3b
	CS (N mm^{-2})	60.5a	56.4b	57.6b
	BS (N mm^{-2})	106.4a	95.3b	100.0ab
Small trees	Ring width (mm)	1.4ns	1.2ns	1.3ns
	Latewood proportion (%)	43.9b	50.7a	41.4b
	CS (N mm^{-2})	52.9ns	56.2ns	56.0ns
	BS (N mm^{-2})	96.7a	104.4a	84.4b
Mean value after thinning	Ring width (mm)	2.3ns	2.2ns	2.2ns
	Latewood proportion (%)	49.7b	44.3a	47.9b
	CS (N mm^{-2})	58.6ns	55.8ns	55.91ns
	BS (N mm^{-2})	104.7a	98.9a	88.6b

Results of ring width (RW) and latewood (LW) are from sample disks, while those of compression (CS) and bending strength (BS) are from clear sample. The different letters indicate significantly different means at $P < 0.05$ (Duncan's MR test)

2002). Our results showed that 12 years after treatment, the trees having a larger growing space grew faster, reaching a larger diameter, and producing a higher volume, probably reducing harvesting and processing costs (Macdonald and Hubert 2002).

The width and regularity of tree rings usually allow predictions of physical and mechanical wood characteristics (Hein et al. 2008). Most of the trees in our study presented mean growth ring width lower than 5 mm independent of the treatment; only a few trees exceeded this value. This is the threshold value that several authors (Nepveu and Blanchon 1989; Riou-Nivert 1989) indicated as the value that Douglas-fir should not exceed to have "superior" mechanical properties.

In our study and for each treatment, the WD values at 12% of MC were clearly higher than those found by other authors for Douglas-fir grown in Italy (Susmel 1952; Moretti and Quartulli 1992). Similarly, Douglas-fir grown in America averages only 0.46–0.50 g cm^{-3} (Green et al. 1999).

These differences were probably caused by the favorable climatic conditions typical of the Calabria Coastal Mountain chain with a high relative humidity, due to summer rainfall and frequent fog, that made the vegetative growth cycle longer with an increase in LW% (Zobel and van Buijtenen 1989).

Schweingruber (1988) indicates that climatic factors influence the transition from EW to LW, stating that the quantity of the latter is greater in areas that are climatically more suitable to the growth for Douglas-fir. Kennedy (1995) confirms that rapidly grown wood can have a very high density, but this requests an increase in the amount of LW.

Our results are also supported by the research carried out by Winistorfer (1995) who pointed out a positive linear correlation between the wood density and the LW%.

Erickson and Harrison (1974) also observed that fertilization and thinning caused immediate production of lower LW% and the effects were mainly in the first 3–4 years after treatment. According to Schweingruber (1988), fast growth produces a higher EW% due to the photosynthetic substances made by the new wide crown, which will generate more EW cells rather than LW cell material.

After thinning, we observed that LW% was higher in *unth* compared to other treatments for both medium and large DBH tree classes.

Furthermore, for medium trees, the general (before and after thinning) LW%–RW relationship showed a decrease in LW% when RW increased (data not displayed). This trend was statistically significant in *unth* ($r = -0.75$) and in *geom th* ($r = -0.64$) but not in *sel th* ($r = -0.36$) where the correlation was not significant. Similar circumstances were observed in dominant trees: ($r = -0.60$ in *unth*), ($r = -0.61$ in *geom th*), ($r = -0.35$ in *sel th*).

This means that the new competition for light, nutrient, water and growing space imposed by treatments tends to modify the growth allocation (Peltola et al. 2007; Weiskittel et al. 2007) particularly in terms of timing of the switch from early to latewood transition and the duration of latewood growth. No relevant evidence occurred for suppressed trees.

Linear regression analysis showed that mechanical strengths are better correlated with WD values than with both RW and LW% values. Therefore, WD has turned out to be the most reliable parameter to estimate Douglas-fir wood strength index. The mechanical characteristics increase with density (Zang 1994; Riyanto and Gupta 1996; Wang and Wang 1999) as indicated by the positive and significant correlation with the strength values. In addition, WD content increases with LW%. Conversely, we observed a negative statistical correlation between strength values and RW.

A stepwise model equation showed the dependence of mechanical characteristics on WD, RW, and LW%, reducing the uncertainty due to the linear model. Mechanical properties of wood have often been correlated with some physical properties but the final results are considered empirical relationships (Leban and Haines 1999). The use of a stepwise equation for modeling both CS and BS leads us to propose an analytical determination of Douglas-fir characteristics. RW and especially WD seem to have a major influence on CS values, while for BS the only important variable seems to be WD.

In general, it was observed that the multivariate linear model could be more physically and biologically interpretable because it takes into account several variables that are easy to determine. Moreover, our results confirmed that the relationship between some physical properties (WD, RW, and LW%) and mechanical strengths changed when silviculture practices differed. Nevertheless, this practical assumption probably needs to be tested by carrying out additional research in terms of wood anatomy characteristics (Schweingruber 1988), such as tracheid dimensions (Kennedy 1995) and juvenile wood (DiLucca 1989) where a microfibril angle (Cave and Walker 1994; Leban and Haines 1999) might play an important role. According to Macdonald and Hubert (2002), all these characteristics are also influenced by the interaction between the effect of site factor and silvicultural regime.

The effects of juvenile wood on product quality have been discussed in detail by DiLucca (1989). The author illustrates how the juvenile wood content of simulated Douglas-fir changes with initial spacing and increasing stand age states. Variation in juvenile wood depends also by the position inside and along the stem and crow. As in our research there is no clear separation in the tree stem between juvenile and mature wood, some doubtful results could be affected by the extraction region (mature or juvenile wood) of the samples (e.g., in the suppressed trees).

The different and uncertain results found in the *geom th* treatment could have been caused by the presence of reaction wood, but not quantified in this study, due to the irregular formed canopy (Zobel and van Buijtenen 1989) typical of this treatment. In fact, Weiskittel et al. (2007) indicate that the profile of Douglas-fir branch diameter within the live crown is sensitive to management practices and the branch diameter growth pattern observed is significantly influenced by the thinning. Thus, the size and distribution of a branch could cause growth stresses (e.g., reaction wood) (Marshall and DeBell 2002). However, these hypotheses need further study.

We also observed that thinning affected RW primarily in the medium DBH class. Significant variation in LW%, CS, and BS was also observed in dominant trees. This evidence suggests that it would be better to use trees from the medium DBH tree class in further studies concerning the technological wood characterization. It seems that both dominant and above suppressed trees maintain their social status after a weak thinning treatment. Contrary to our results, Peltola et al. (2007) found that the largest trees had a higher absolute thinning response, in terms of radial growth, compared to the suppressed ones for Scots pine. In addition to the response of radial growth, the same authors found that both the EW and LW width increased as a response to the thinning.

By using an among-tree approach, other researcher (Dutilleul et al. 1998) working on Norway spruce after and before thinning reported a negative relationship of WD with RW only for the slow-grown tree, while it was totally nonexistent in the fast-grown Norway spruce. The same author suggested that the WD–RW relationships depend on growth rate of the tree, and already before the first thinning, a preconditioning was present between the two variables.

A key role is represented by the genetic characteristics of trees, nevertheless due to uncertainness of their provenance was difficult to determine the influence of this parameter on physical and mechanical characteristics.

We should point out that the *sel th* treatment is useful for the Calabrian Douglas-fir stand because it increases the size of each log without greatly affecting wood quality. The difference in terms of wood properties between trees from *sel th* and *unth* was relatively small. It occurs due to the good climatic conditions of the Coastal Chain of Calabria, but also because the weak thinning from below causes nonsignificant wood quality variations.

Within a few decades, the Calabria Region will be able to put a great amount of Douglas-fir timber on the market, taking into consideration the vast areas of cultivation of this species in this territory. Nowadays, Douglas-fir is sold for poles and cellulose use, but its use will surely change in the future considering the promising technological properties found in this study.

Conflict of interest The authors declare that they have no conflict of interest.

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