ISSN impresa 0717-3644
ISSN online 0718-221X

Maderas. Ciencia y tecnología 2024 (26): 7, 1-16

DOI: 10.22320/s0718221x/2024.07

THINNING WOOD PROPERTIES OF *Nothofagus alpina* UNDER THREE DIFFERENT SILVICULTURAL CONDITIONS

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ABSTRACT

The main objective of this study was to assess the properties of *Nothofagus alpina* (raulí) wood from thinning that originates from two sites with intensive silviculture and one similar to a secondary growth forest, with different soil, climatic conditions and age. To achieve this, some mechanical, physical and chemical-crystalline properties were characterized; studying the differences from pith to bark and between the selected trees that were taken from the thinning of the three plantations. Among the studied plantation sites, there were statistical differences in equilibrium moisture content, density and modulus of elasticity. Furthermore, FT-IR was able to differentiate the chemical-crystalline compositions from pith to bark and between plantations, while the X-Ray diffraction showed differences in the crystallinity index. It was possible to differentiate between the sites with a more intense silvicultural intervention and the one with more variable growth conditions.

Keywords: FT-IR, intensive silviculture, raulí, thinning wood, X-Ray diffraction, wood crystallinity.

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Received: 19.05.2023 Accepted: 24.08.2023

INTRODUCTION

Historically, the most used species from the *Nothofagus* genus in Chile are raulí (*Nothofagus alpina*), roble (*Nothofagus obliqua.*) and coigue (*Nothofagus dombeyi*), with rauli (*Nothofagus alpina*) in particular, being characterized by having a higher productive potential among the *Nothofagus* genus (Donoso and Soto 2010). They naturally grow from the south of the Curicó (35° S) to the south of the province of Valdivia (40°30' S) along the Andes mountain range (Loewe *et al.* 1998), and in the Coastal mountain range from Cauquenes (35°58' S) to the north of the Llanquihue province (41°S) (Sepúlveda and Stoll 2003).

Nowadays, the native forest sawmill industry corresponds only to 2,2 % of the total sawn wood in Chile (INFOR 2022), showing that there is a necessity to stimulate the use of native species. Thus, there is a renewed interest in establishing and managing plantations with native species in Chile, to expand the current national market in addition to the introduced species, such as *Pinus radiata*, *Eucalyptus nitens* and *Eucalyptus globulus*, and to create awareness of the use of native material in the national wood industry.

Intensive silviculture (felling, pruning, thinning, fertilization, weed control, among others) is usually applied to shorten the rotation age, improve the quality of the obtained wood and to increase the commercial value of the used species. There have been experimental plantations for this species in different zones and regions from Chile (Meneses *et al.* 1991, Donoso *et al.* 1993, Reyes *et al.* 2007). The harvest age of the native plantations could be an issue, as the current most used plantation species in Chile, *Pinus radiata*, *Eucalyptus nitens* and *Eucalyptus globulus* (INFOR 2022) have short rotation times.

The use of the wood obtained from thinning could be viewed as an alternative to encourage the use of native species, as it would generate material during the lifetime of the plantation until it reaches its maturity to be harvested. Although wood from thinning is usually juvenile wood, which has issues with drying processes and it has lower quality than mature wood, limiting its use, it would be worth to analyze its properties, to see if it is competitive in the current market. Currently, there is little information available on the properties of raulí (*Nothofagus alpina*) at young ages, as most of the research available is based on wood properties of regrowth (second growth) forest wood (Carabias and Karsulovic 1978, Campos *et al.* 1990).

There are preliminary studies on the variation of density and modulus of elasticity from plantation wood from raulí (*Nothofagus alpina*) (González 2018), but there is no information on the chemical-crystalline structure of the material. Therefore, it is necessary to study and to understand the variations of the chemical, crystalline, mechanical and physical properties of this species under intensive plantation, particularly the wood that comes from the thinning process.

The climate and geographic variables have also an effect on dynamic modulus of elasticity and density in *Eucalyptus nitens* plantations in Australia (Balasso *et al.* 2021). They were even able to predict those properties with a satisfactory level of accuracy both at the tree and site level. Sette Junior *et al.* (2016) with *Eucalyptus grandis* and Balasso *et al.* (2021) showed that wood from lower precipitation and higher temperature areas were denser. Rocha *et al.* (2020) demonstrated that, generally, basic wood density is higher in drier locations; but this behavior becomes unpredictable in humid locations in a selection of *Eucalyptus spp*. plantations in Brazil and Uruguay. Vieira *et al.* (2021), studying 33 year old *Corymbia citriodora*, inferred that more clayey and better-structured soils have higher porosity, which were correlated to wood with lower density, although Gava and Gonçalves (2008), studying *Eucalyptus grandis* clones in Brazil, did not find a relation of the wood density with different soil types.

Thinning has shown no adverse effect on wood density, and it did not have a negative effect on the modulus of elasticity (MOE) of plantation wood of *Eucalyptus nitens* (Díaz Bravo *et al.* 2012). As for the chemical properties, thinning and specially pruning did not have an effect on the lignin, cellulose and hemicellulose contents of plantation-grown loblolly pine (Shupe *et al.* 1996).

Rigatto *et al.* (2004), which analyzed the effects of soil attributes on *Pinus taeda* on the properties of its wood, showed that wood from sites where the clay soil was more predominant provided lower cellulose yields, which were related to lower values of basic density and higher levels of extractives and lignin. On the other hand, utilizing wood from plantations of *Eucalyptus grandis*, Gava and Gonçalves (2008) found out that the total lignin content decreased while the holocellulose content exponentially increased as the soil clay content increased, while Sette Junior *et al.* (2016) showed that wood from lower precipitation and higher temperature had higher lignin content.

A quick method to measure the chemical and structural properties of wood is the Fourier-Transform Infrared Spectroscopy (FT-IR). The spectral data obtained from this method provides details on the functional groups (C-H-O) and their respective molecular bonds that are present in celluloses, hemicelluloses, extractives, lignin and water in lignocellulosic materials (Evans 1991, Rodrigues *et al.* 1998, Pandey 1999).

It has been successfully used as a replacement for the traditional methodologies (wet chemistry) to measure the chemical properties in different wood species (Chen *et al.* 2010, Poletto *et al.* 2012, Funda *et al.* 2020) and in studies were only small variations in the chemical composition between the wood samples were expected (Funda *et al.* 2020). Additionally, it has been used to evaluate changes in the chemical-crystalline structure of wood (Colom *et al.* 2003, Lionetto *et al.* 2012, Wentzel *et al.* 2019).

Further uses of FT-IR analysis show that it was possible to differentiate between *Pinus sylvestris* and *Pinus nigra* and growing locations in a study from different sites in Spain by the differences shown in lignin, polysaccharides and the wood crystallinity (Traoré *et al.* 2018). Similarly, Rana *et al.* (2008) were also able differentiate *Fagus sylvatica*. originated in different sites in Germany utilizing FT-IR. X-Ray diffraction (XRD) has also been used to characterize the chemical-crystalline properties in wood (Segal *et al.* 1959, Thygesen *et al.* 2005). It has been used in combination with FT-IR Spectrocopy to have a deeper look on the crystallinity of wood (Wentzel *et al.* 2019) and to compare *Pinus radiata* D. Don corewood and outerwood in terms of relative crystallinity, crystallite size and lignin content (Li *et al.* 2021).

There have been no almost no studies about wood properties of young raulí (*Nothofagus alpina*), especially when using wood from thinning of plantations. Thus, the aim of this work is to assess some mechanical, physical and chemical-crystalline properties of wood that comes from the thinning process of three selected sites with different ages, site conditions, climate and silvicultural interventions. The differences between the sites and within the trees in the same sites will be studied to analyze the quality of the wood obtained.

This new information will allow us to see if there are noticeable effects of intensively managed plantations on the wood quality, update the information available of young raulí (*Nothofagus alpina*) wood, and to see the potential to use wood from thinning of a native species plantation as an alternative material for the Chilean wood industry.

METHODOLOGY

Description of sampling areas

Wood that originated from thinning of raulí (*Nothofagus alpina* Poepp. & Endl.) plantations was used in this research. Due to the limited availability of plantations of age to be thinned that coincide with the study, sites of 14, 21 and 25 years respectively had to be selected. From each site, eight trees were selected, which were cylindrical, free of defects (bifurcations, abiotic or biotic damage), pruned and straight. All trees used for this study were felled in summer of 2022. Two plantation sites with intensive silviculture and one from a plantation that was not as intensively managed, similar to a secondary growth forest, were used:

Catanlí

An intensive silviculture plantation planted in 2001, with uniform spacing, weed control, fertilization, pruning and thinning, located 14 km south of the city of Panguipulli and 90 km from Valdivia, 250 meters above sea level (39°38’ S and 72°21’ E). It has an average temperature of 10 °C and an average annual rainfall of 2555 mm. It has soils in the form of volcanic ash deposits on sandstones. They are deep to moderately deep soils with medium to moderate textures; well structured, the rooting is good up to 90 cm and in depth the roots are scarce. It has good aeration and a high water retention capacity, which decreases considerably below 30 cm. They are strongly acidic soils on the surface and they become slightly acidic in depth. The establishment density was 1666 trees per hectare, and were thinned to 800 trees and then to 500 trees per hectare.

Las Vertientes

An intensive silviculture plantation planted in 2008, with uniform spacing, weed control, fertilization, pruning and thinning, located 19 km south of Lanco and 82 km from Valdivia, 60 meters above sea level (39°31’ S and 72°44’ W). It has an average temperature of 11 °C and an average annual rainfall of 2065 mm. The soil is formed by volcanic ash deposited on glacio-fluvial materials. It has medium and moderately fine textures that are slightly deep, flat and with moderate drainage, meaning that the water is slowly removed, keeping it moist for a short time. The establishment density was 1300 trees per hectare, and it was thinned once to 850 trees per hectare.

Pelchuquín

A plantation located planted in 1997 in Pelchuquín, 27 kilometers from Valdivia, at 25 meters above sea level (39°36' S and 73°4' E), in a former abandoned nursery, therefore, its growth dynamics simulate the conditions of a regrowth (secondary growth) forest of raulí (*Nothofagus alpina* Poepp. & Endl.). It has an average temperature of 10 °C and an average annual rainfall of 1600 mm. It has soils with a silty loam texture and granular structure, where it is common to find gravels, pebbles and rocks on the surface and in the soil profile. These characteristics allow inferring that they are soils with high usable water capacity (200 mm - 250 mm), good drainage and aeration, which ensures easy rooting.

Selection of trees and sample preparation

The tree selection criteria were that the trees that were going to be thinned had to be at least 22 cm at breast height diameter, so that they could be sawn without issues. The breast height diameters were between 24 cm and 34 cm in Catanlí, 24 cm and 30 cm in Las Vertientes and between 22 cm and 32 cm in Pelchuquín. From the selected trees, wood logs from the base of the tree of 320 cm were obtained. Samples for the characterization of the wood properties were taken from pith to bark and were proportionally separated in boards at three percentiles, 25 %, 50 % and 75 % of the distance from pith to bark (Figure 1a and Figure 1b), to be able to compare them between plantations and within trees from the same sites. The logs from each selected tree were cut to 160 cm boards and dried until they reached 14 % relative humidity (RH). Afterwards they were conditioned at 20 °C and 65 % RH until they reached a constant weight.

Overall, 72 samples per plantation, 216 in total, were obtained for their respective measurements. From the center of each 320 cm board, a 160 cm table was obtained from the (Figure 1b), then they were separated in 4 pieces along the same wood rings, if possible (Figure 1c). Those pieces were then cut in parallel specimens of 20 mm × 20 mm × 340 mm and 20 mm × 40 mm × 340 mm (radial × tangential × longitudinal) respectively (Figure 1d). The parallel samples were used to maximize the comparability of the results within each tree. At the 25 % distance from the pith, the samples had roughly between 3 and 5 yearly rings in all sites, so they were used to compare between the sites, taking into consideration the number of rings in the samples taken for each measurement to be done in the study.

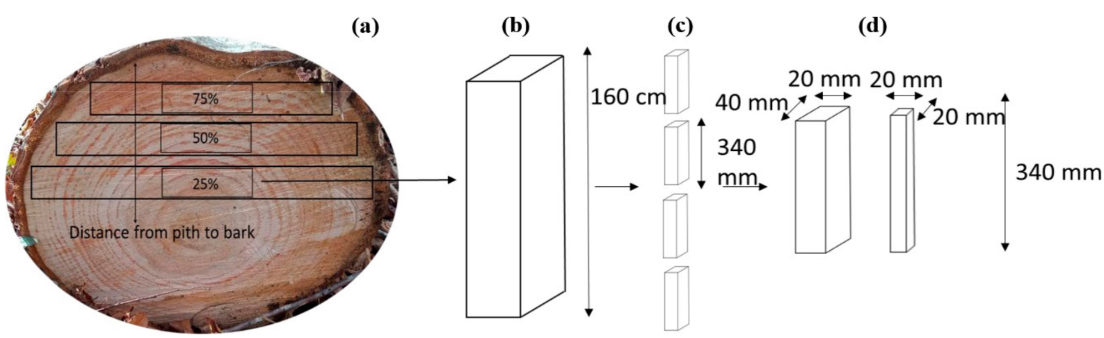

Figure 1: Preparation of the specimens for the measurements. (a) Selection of boards at 25 %, 50 % and 75 % of the distance from pith to bark. (b) Tables from the center part of the board were cut into 160 cm pieces. (c) From this table, 4 pieces along their respective wood rings and length were obtained. (d) Two parallel samples, with the separation of the samples coming in the center of the piece, were obtained from each of the 4 previously cut pieces, witch sizes of 20 mm × 20 mm × 340 mm and 20 mm × 40 mm × 340 mm (radial × tangential × longitudinal) respectively.

Mechanical and physical analysis

A three-point bending test, according to DIN 52186 (1978) was used to determine the modulus of elasticity (MOE) of the dried samples. It was conducted using a universal testing machine to measure on wood specimens of 20 mm × 20 mm × 340 mm (radial × tangential × longitudinal) that were conditioned at 20 °C an 65 % RH before the test. The load was applied in the transversal direction with the testing speed being adjusted individually for each sample to allow failure of the samples within 90 s ± 30 s. The specimens for this test were taken from each of the 72 samples per site, totaling 216 measurements.

The density was measured by dividing the weight by the volume after conditioning at 20 °C and 65 % RH, from each tree at their respective plantation site. The specimen size was 20 mm × 20 mm × 40 mm (radial × tangential × longitudinal) samples, obtained after the mechanical test from the original specimens.

Chemical and crystalline analysis

FT-IR chemical imaging system (PerkinElmer) was used to obtain chemical images from the dry samples, then; an average spectrum is extracted from those, which is processed to obtain the spectra to get the chemical information. The system consists of a spectrophotometer Frontier that has two detectors, type DTGS NIR and MIR, both covering a range between (14700 cm^{-1} and 350 cm^{-1}) with a spectral resolution of 4 cm^{-1}. The imager Spotlight 400, with a detector type MCT MIR (7800 cm^{-1} - 720 cm^{-1}) that has a resolution > 2 cm^{-1}, was used. The system can generate chemical spectra directly on the surface of the wood through chemical images. In this work, diffuse reflectance was used to obtain the spectra with a resolution of 4 cm^{-1} and 16 scans, with a pixel resolution of 50 µm. The spectra were baseline corrected using an interactive baseline correction and then normalized considering maximum ordinate value in the spectrum. The size of the samples was 20 mm × 40 mm × 340 mm (radial × tangential × longitudinal) and conditioned at 20 °C and 65 % RH for a month prior to the FT-IR analysis. The radial surface was chosen for each analysis. After processing, the chemical structure was interpreted from the spectra and the following relative crystallinity index utilizing the ration between spectra bands 1317 cm^{-1} and 1336 cm^{-1}, which represent the ratio between crystalline cellulose and amorphous cellulose (Colom and Carrillo 2002, Colom *et al.* 2003). For each sample, five repetitions were performed.

The X-Ray Diffraction (XRD) analysis for solid wood samples of 20 mm x 40 mm x 20 mm was positioned on the sample holder of a multifunctional Smartlab diffractometer (Rigaku Corporation, Japan) with Theta-Theta Bragg-Brentano geometry goniometer. The coherent X-Ray beam of Cu-K-alpha radiation was generated to 40 kV and 30 mA, and Ni-filtered to be captured by a detector solid-state D/tex Ultra 250. Optical configurations were adjusted by divergent and receiving slits for both sides, with parallel Soller slits of 5 ° and slits of 5 mm, respectively. Patterns were collected between 8 ° - 45 ° 2 Theta range, counting 2 ° per min per step of 0,01 °. The instrumental alignment is regularly checked against the NIST SRM660c LaB_6 powder standard (NIST 2015). The crystallinity index (CI) was calculated according to the method presented by Segal *et al.* (1959) to estimate the order of paracrystalline cellulose, based on a single phase of the peak of the plane 200 and the maximum contribution of the amorphous halo of the disordered cellulose. This proceeding was performed on a third of the selected trees.

Statistical analysis

The statistical analysis consisted in a Shapiro-Wilks test to define if the data set were parametric or non-parametric to either use an ANOVA or a Kruskal-Wallis test to analyze possible differences in the wood properties between the sites and within the trees of the same site. The significance level was tested at p = 0,05. Pearson's correlation analysis was used to estimate the degree of linear correlation among density, and the chemical and mechanical properties. Microsoft Excel 2016 was used to perform the statistical analysis.

RESULTS AND DISCUSSION

Physical and mechanical variation within the trees

The equilibrium moisture content (EMC) tended to decrease from pith to bark in Catanlí and Pelchuquín, but it was very similar on all positions in Las Vertientes (Table 1). The only plantation that showed a significant difference from pith to bark was Catanlí (Table 1), the site that has being the longer under an intensive silviculture plantation regime

The densities increase from pith to bark (Table 1), but they were not significantly different in any of the sites. MOE also presented a tendency of increasing from pith to bark in all sites. This was particularly evident in the measurements taken in Catanlí and Las Vertientes, both sites with intense silviculture, which were statistically significantly different from pith to bark (Table 1). Pelchuquín, which is the site similar to a secondary growth of the species, did not show significant differences. Las Vertientes had the trees with lower MOE among the selected sites (Table 1), but it has to be noted that the samples taken for the MOE tests were not perfect, as they were taken from the center of the wood pieces, thus sometimes they did not have perfectly straight yearly rings. Nevertheless, it was expected that they would present lower mechanical properties as the other sites, since Las Vertientes is a 14-year-old plantation.

Table 1: Average EMC, density and MOE of each position from pith to bark in their respective plantation.

Age of the site and distance from pith (%)	EMC (%)	Density (kg/m^3)	MOE (MPa)
14 years	Las Vertientes		
25 %	12,62 ± 0,12 (a)	550 ± 54 (a)	8719 ± 1701 (a)
50 %	12,69 ± 0,11 (a)	576 ± 65 (a)	10059 ± 2401 (b)
75 %	12,66 ± 0,23 (a)	587 ± 48 (a)	12175 ± 1675 (c)
21 years	Catanlí		
25 %	11,12 ± 0,40 (a)	508 ± 45 (a)	13909 ± 2729 (a)
50 %	10,80 ± 0,14 (b)	515 ± 47 (a)	15239 ± 3083 (b)
75 %	10,66 ± 0,12 (b)	524 ± 39 (a)	18050 ± 3128 (c)
25 years	Pelchuquín		
25 %	12,41 ± 0,10 (a)	537 ± 41 (a)	15257 ± 4385 (a)
50 %	12,30 ± 0,46 (a)	560 ± 21 (a)	15146 ± 2866 (a)
75 %	12,03 ± 0,34 (a)	561 ± 33 (a)	17065 ± 2987 (a)

The average values followed by a different letter are statistically significant different from pith to bark at $p < 0,05$.

The density values in all sites were above 500 kg/m^3, which makes raulí (*Nothofagus alpina*) thinning wood attractive to the market, as long as it is free of defects such as knots. The densities and modulus of elasticity in all sites compare favorably with historical data from pine (*Pinus radiata* D. Don) obtained from a report by Pérez (1983), where the density at 12 % EMC ranged from 440 kg/m^3 to 490 kg/m^3 and the MOE from 6300 MPa to 12600 MPa. In addition, it has similar MOE values at 75 % of the distance from the pith in Catanlí and Pelchuquín (Table 1) with 17-year-old mature wood from *Pinus radiata*, which ranged between 15100 MPa and 17600 MPa (Barrios *et al.* 2017). The Chilean norm INN NCh1198:2014 (2014) about wooden constructions, states that, only considering the values for MOE, it would have a structural class between F11 and F27 and similar values to the allowable stresses for *Pinus radiata* (class G1 and G2).

Chemical and crystalline variation within the trees

The bands that showed significant differences from pith to bark and between trees from different plantations are described in Table 2 and shown in Figure 2.

The peak intensities of the FT-IR spectra from pith to bark of each site showed significant differences in some of the bands. This could be seen in the cellulose bands, which are assigned to the 3490 cm^{-1} band, -OH of cellulose and hemicellulose (Olsson and Salmén 2004), the 1317 cm^{-1} band, Ch_2 waging in crystalline cellulose, (Colom and Carrillo 2005, Popescu *et al.* 2007), and the 898 cm^{-1} band, C-H deformation in cellulose (Faix and Böttcher 1992). They only showed significant differences from pith to bark in Pelchuquín. This also occurred with bands that represented lignin, 836 cm^{-1}, which represents the aromatic C-H out of plane deformations related to the syringyl nuclei (Evans 1991), and hemicelluloses, 1158 cm^{-1}, which shows the asymmetric vibration of C-O-C stretching in cellulose and hemicellulose (Faix and Böttcher 1992, Popescu *et al.* 2007)).

Table 2: Band assignments of FT-IR spectra obtained from raulí (*Nothofagus alpina*) that showed statistically significant differences from pith to bark and between trees from different plantations.

Band (cm^{-1})	Band assignment	References
3490	OH stretching of water and hydroxyl groups and -OH of cellulose and hemicellulose	(Olsson and Salmén 2004)
2892	Stretching of C-H in methyl and methylene in cellulose	(Esteves *et al.* 2013)
2100	Vibrations from the scission and rocking of water	(Olsson and Salmén 2004)
1742	C=O stretch in unconjugated ketones, carbonyls and in ester groups	(Faix 1991, Pandey 1999, Esteves *et al.* 2013)
1635	Adsorbed water	(Marchessault 1962)
1594	Aromatic skeletal vibration plus C=O stretch	(Faix 1991, Casas *et al.* 2012)
1336	CH vibration in cellulose	(Colom and Carrillo 2005, Popescu *et al.* 2007)
1317	Ch_2 waging in crystalline cellulose	(Colom and Carrillo 2005, Popescu *et al.* 2007)
1158	Asymmetric vibration of C-O-C stretching in cellulose and hemicellulose	(Faix and Böttcher 1992, Popescu *et al.* 2007)
1040	Aromatic C-H in plane deformation, guaiacyl type and C-O formation	(Faix 1991)
898	C-H deformation in cellulose	(Faix and Böttcher 1992)
836	Aromatic C-H out of plane deformations related to the syringyl nuclei	(Evans 1991)

Las Vertientes and Catanlí, the sites with intensive silviculture, did not show any significant difference from pith to bark in any of those bands. The band at 1336 cm^{-1}, which indicates CH vibration in cellulose (Colom and Carrillo 2005, Popescu *et al.* 2007), was the only one that showed significant differences in Las Vertientes and Catanlí, showing that there were differences between the sites with intensive silviculture and the one without when analysing the chemical changes from pith to bark. It has to be noted that the band representing the aromatic C-H in plane deformation, guaiacyl type and C-O formation (Faix 1991), was significantly different for all sites. As for the adsorbed water that can be identified in band 1635 cm^{-1} (Marchessault 1962), there was significant change in Las Vertientes and Catanlí, while Pelchuquín was similar from pith to bark.

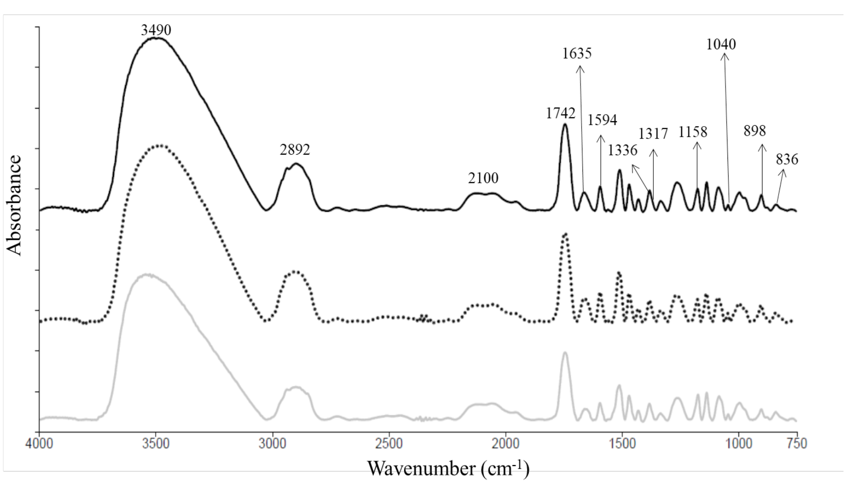

Figure 2: Infrared spectra of FT-IR spectra at 25 % distance from the pith for raulí (*Nothofagus alpina*) showing the bands with statistically significant differences. From top to bottom: Pelchuquín (black line), Catanlí (doted black line) and Las Vertientes (grey line) respectively.

Table 3 shows that Pelchuquín had a higher relative crystalline ratio and crystalline index than the other sites, while all sites tend to increase their crystallinity towards the bark, which was similar to what Li *et al.* (2021) showed using FT-IR analysis in pine (*Pinus radiata*), where the crystallinity was higher in the outerwood than in the corewood. Although Pelchuquín showed a significant difference in the crystalline part of cellulose in the FT-IR analysis, only Las Vertientes showed a significant difference from pith to bark in the relative crystalline ratio (Table 1). Nonetheless, the results obtained for the relative crystallinity can be related to the FT-IR values obtained, as both data sets show a tendency of higher relative crystallinity in Pelchuquín and more amorphous cellulose in Las Vertientes and Catanlí. These differences, in addition to the differences in the variation from pith to bark in the chemical composition between Pelchuquín and the sites with a more intense silviculture, could mean that perhaps the silvicultural regime had an effect on the formation of celluloses and their crystallinity. The external wood of Las Vertientes presents a significant difference between the distance closer to the pith and the ones closer to the bark (Table 3). This difference could be related to the young age of the plantation.

Table 3: Average relative crystalline ratio and crystallinity index of each position from pith to bark in their respective plantation.

Age of the site and distance from pith (%)	Relative crystalline ratio (FT-IR)	Crystallinity index (X-ray diffraction)
14 years	Las Vertientes	
25 %	0,583 ± 0,12 (a)	49,570 ± 3,26 (a)
50 %	0,646 ± 0,20 (b)	52,966 ± 1,26 (a)
75%	0,782 ± 0,19 (b)	53,403 ± 2,23 (a)
21 years	Catanlí	
25 %	0,468 ± 0,26 (a)	54,079 ± 3,57 (a)
50 %	0,543 ± 0,15 (a)	54,382 ± 3,12 (a)
75 %	0,598 ± 0,44 (a)	54,510 ± 3,43 (a)
25 years	Pelchuquín	
25 %	0,816 ± 0,23 (a)	63,041 ± 1,37 (a)
50 %	0,823 ± 0,23 (a)	64,456 ± 2,47 (a)
75 %	0,846 ± 0,17 (a)	64,297 ± 1,12 (a)

The average values followed by a different letter are statistically significant different from pith to bark at $p < 0,05$.

Statistical analysis of the variation within the trees

A Pearson correlation test was run to determine any relationship between density, EMC, MOE, the relative crystalline ratio and the crystallinity index (Table 4). EMC had a strong negative correlation with MOE in all sites. The EMC has an influence on the mechanical properties of wood, as they tend to increase with decreasing moisture content (Skaar 1988), which occurred in all studied sites. The density also presents this tendency, but it was only strongly correlated in the Catanlí site. MOE had a strong positive correlation with the relative crystalline ratio in all sites, and a positive correlation with the density in Catanlí and Las Vertientes, thus, MOE had a strong correlation with all properties in the plantations that had a stronger silvicultural intervention. The relative crystalline ratio had a strong negative correlation with EMC on all sites and a strong positive correlation with density in Las Vertientes and Catanlí.

Table 4: Pearson correlation coefficients of the relations between nominal density, EMC, MOE and relative crystalline ratio from pith to bark for each site.

	Las Vertientes		
	Density	EMC	MOE
EMC	-0,747		
MOE	0,935*	-0,934*	
Relative crystalline ratio	0,904*	-0,960*	0,997*

	Catanlí		
	Density	EMC	MOE
EMC	-0,968*		
MOE	0,984*	-0,908*	
Relative crystalline ratio	0,994*	-0,990*	0,959*

	Pelchuquín		
	Density	EMC	MOE
EMC	-0,758		
MOE	0,503	-0,945*	
Relative crystalline ratio	0,703	-0,997*	0,968*

Each site has their edaphoclimatic particularities and silvicultural intervention, which can be seen in the correlations from pith to bark shown in Table 4. It shows that the crystallinity presents strong relations with EMC and MOE independently of the site. In contrast, the relationship between density and the other studied variables was strong only in two of the three sites. Overall, the only site that presented strong correlations between all the properties was Catanlí, which is the site with a longer intensive plantation regime, while Pelchuquín, the only site without an intensive silviculture regime, showed the weakest correlations.

Comparison of physical, mechanical and chemical properties between sites

The measurements of the samples at 25 % distance from the pith were used to compare results between the sites. All the samples used had between 3 and 5 yearly rings across all sites to mitigate the age difference between them. Table 5 shows the average values of EMC, density, MOE, relative crystalline ratio and crystallinity index for each site, and if there were significant differences between the sites. As seen in Table 1, we would have expected that the higher MOE of Pelchuquin would have been related to a higher density; however, we see that the average density of Pelchuquin wood was not the highest among the studied sites. On the other hand, the lowest MOE was associated with the highest density (Las Vertientes) and the lowest density in Catanlí with an intermediate MOE between the three sites. These MOE variations between sites can be explained by both the EMC and their respective degree of crystallinity. It is expected that lower EMC and/or higher crystallinity are associated with an increase in wood stiffness (MOE). This was corroborated by the crystallinity index (measured with the x-ray diffraction), however, the FT-IR relative crystallinity ratio indicates that Catanlí has the most amorphous material, even so, it has the second best MOE, and this could be explained because it has the lowest EMC. In the case of Las Vertientes, their intermediate relative crystallinity ratio should have been associated with an intermediate MOE, but it was the lowest, possibly because the wood at 25 % distance from the pith was associated with a central cylinder with a larger number of defects, and a higher EMC, which does not favor its rigidity.

Table 5: Average EMC, density, MOE, crystalline ratio and crystallinity index at 25 % distance from the pith in their respective plantation.

Site (Sample position 25 % distance from the pith)	EMC (%)	Density (kg/m^3)	MOE (MPa)	Relative crystalline ratio (FT-IR)	Crystallinity index (X-ray diffraction)
Las Vertientes	12,62 ± 0,12 (a)	550 ± 54 (a)	8719 ± 1701 (a)	0,583 ± 0,12 (b)	49,570 ± 3,26 (a)
Catanlí	11,12 ± 0,40 (b)	508 ± 45 (a)	13909 ± 2729 (b)	0,468 ± 0,26 (a)	54,079 ± 3,57 (a)
Pelchuquín	12,41 ± 0,10 (a)	537 ± 41 (a)	15257 ± 4385 (c)	0,816 ± 0,23 (c)	63,041 ± 1,37 (b)

The average values followed by a different letter are statistically significant different between sites at $p < 0,05$.

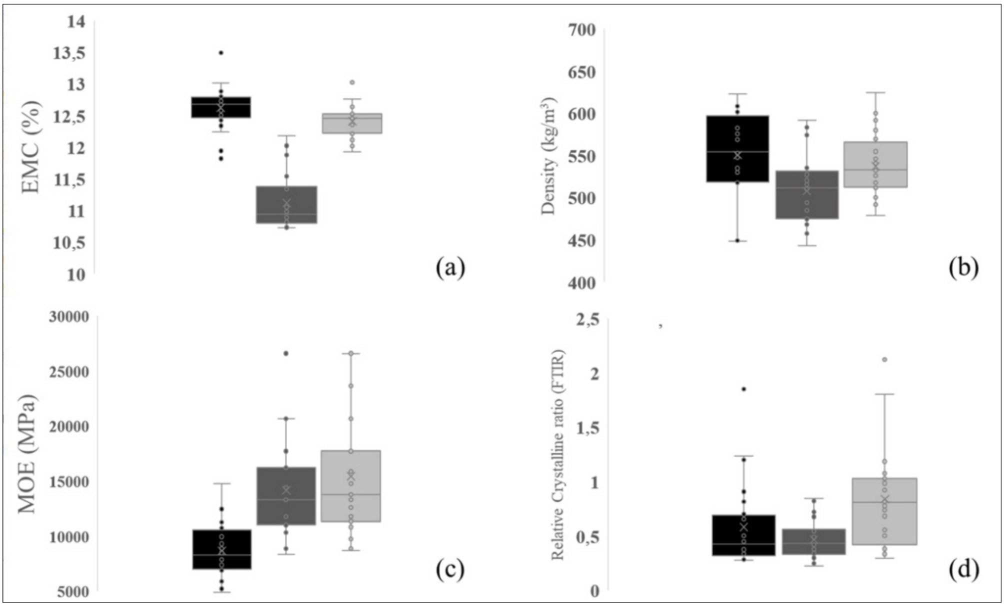

Figure 3: (a) Box plots of EMC, (b) density, (c) MOE and (d) relative crystalline ratio at 25 % of the distance from the pith in Las Vertientes (black), Catanlí (grey) and Pelchuquín (light grey).

Figure 3 shows the spread of the data obtained in form of boxplots. The EMC (Figure 3a) indicates that the Catanlí plantation had the lower values and the bigger spread, while both Pelchuquín and Las Vertientes have very concentrated values around their average EMC. Las Vertientes had the higher spread and differences in the density (Figure 3b) and relative crystalline ratio (Figure 3d); this could be related to the age of the plantation. Pelchuquín showed those characteristics in the MOE (Figure 3c). The higher MOE variation could be related to the more variable growth conditions as a result of less uniform competition due to the lack of intensive silvicultural intervention.

In a previous report by González (2018) on the Catanlí and Pelchuquín sites, at 12 and 18 years respectively, there was no difference between both sites in density and MOE. The measured density in our study kept this tendency, but the MOE presented a significant difference this time. The average diameter of the selected logs was larger in Catanlí and Las Vertientes than in Pelchuquín, which shows, at least, that thinning and pruning are having an effect in the volume of wood that can be obtained from a plantation with intensive silviculture. Nonetheless, there were no effects on the density, similar to what Díaz-Bravo *et al.* (2012) found in a 15 year old *Eucalyptus nitens* plantation, as there was no significant difference between the tree sites (Table 5). Some reports suggest that the density changes due to the composition of the soil (Sette Junior *et al.* 2016, Vieira *et al.* 2021), but there are also other studies that indicated that there was no influence of the soil on the density of the species planted (Gava and Gonçalves 2008). This suggests that the soil characteristics, which were different in each of the studied sites, possibly did not have an effect on the density of the material.

Balasso *et al.* (2021) developed a model that predicted density and dynamic modulus of elasticity on *Eucalyptus nitens* plantations in Tasmania, where there was a tendency of trees with higher density in areas with lower rainfall and warmer zones, while the modulus of elasticity increased when the sites were in higher latitudes. All our sites presented similar average temperatures (10 °C in Catanlí and Pelchuquín, 11 °C in Las Vertientes). In relation to the rainfall in the studied sites, there was a tendency of decrease in density as the rainfall increases (2555 mm, 2065 mm and 1600 mm Catanlí, Las Vertientes and Pelchuquín respectively), but there was no significant difference between the densities of the studied sites. There could also be some influence of the sample preparation, as the quantity of the yearly rings or the thickness of the annual growth in the samples may have an effect in the measurement of density. In the case of the MOE, all sites come from relative similar latitudes, so it is not possible to see if there was similar effect to what Balasso *et al.* (2021) predicted. There were statistical differences between all sites with the MOE, which could be related more to the age of the plantations than the site conditions. Only Catanlí was statistically different when comparing the EMC values, which could be related to the edaphoclimatic condition of that particular site, or the site being the oldest one in a silvicultural intense regime.

The relative crystalline ratio and the crystallinity index showed differences between all sites, while the crystallinity index was statistically different between Pelchuquín and the plantations with intense silviculture (Table 5). Catanlí and Las Vertientes had similar values and did not show a significant difference. Traoré *et al.* (2018) showed that crystallinity was affected by the site, location and environmental conditions of the plantations. In this study we also have differences between the sites, but it seems that apparently the impact of the intensity of silvicultural intervention was relevant.

The band 3490 cm^{-1} shows the OH stretching of water and hydroxyl groups and –OH of cellulose (Olsson and Salmén 2004). The stretching of C-H in methyl and methylene in cellulose is present around the 2892 cm^{-1} band (Esteves *et al.* 2013) and the C-H deformation in cellulose (Faix and Böttcher 1992) can be seen in the 898 cm^{-1} band. Both the amorphous cellulose, represented by the CH of methyl groups in methoxyl groups in the 1332 cm^{-1} band (Colom and Carrillo 2005, Popescu *et al.* 2007) and the crystalline cellulose, characterized by the waging of CH_2 in crystalline cellulose in the 1317 cm^{-1} band (Colom and Carrillo 2005, Popescu *et al.* 2007), show significant differences between the sites. Rigatto *et al.* (2004) found out that the type of soil influences the cellulose yields of *Pinus taeda*, which may be one of the reasons of the difference between the studied sites. As can be seen in Figure 2, Pelchuquín shows the highest absorption in the bands that represent the celluloses. This confirms that there is a structural chemical difference between this site and Catanlí and Las Vertientes, which can be related to the fact that those sites have a similar silvicultural regimen, more intense than in Pelchuquín.

Hemicelluloses (polysaccharides) are also represented at the 3490 cm^{-1} band (Olsson and Salmén 2004) and at the 1742 cm^{-1} band, which shows the ketones present in free aldehyde (Faix 1991, Pandey 1999, Esteves *et al.* 2013). Lignin is represented by the aromatic skeletal vibration plus a C = O stretch around the 1594 cm^{-1} band (Faix, 1991, Casas *et al.* 2012) and the aromatic C-H out of plane deformations related to the syringyl nuclei around the band 836 cm^{-1} (Evans 1991). Pelchuquín showed lower absorption in the bands that characterize lignin. All of those bands were significantly different between the sites. Gava and Gonçalves (2008) and Sette Junior *et al.* (2016) affirm that the soil had an influence on the lignin and holocellulose content of the wood. In the sites, there were similar tendencies to what was reported by those authors.

All the principal chemical components of the wood presented significant differences between sites, something that Traoré *et al.* (2018) and Rana *et al.* (2008) showed in their studies utilizing FT-IR. Additionally, in our study, FT-IR also differentiated selected cellulose and lignin bands from pith to bark in the samples from each plantation site, confirming the potential of FT-IR for identification of changes of the chemical structure in solid wood.

The adsorbed water (band 1635 cm^{-1}) (Marchessault 1962) showed significant differences between all sites, while Las Vertientes and Catanlí showed significant differences from pith to bark. The most crystalline structure is cellulose, which sorbs the least amount of water, while hemicelluloses, such as glucomanans for example, tend to be more amorphous and sorb more water (Olsson and Salmén 2004). Thus, it can be said, a more crystalline structure will have less adsorption of water, and a more amorphous structure will tend to have a higher adsorption. It has been shown that Pelchuquín presented a difference from pith to bark in the crystalline part of the cellulose and in the polysaccharide band, while it did not show any changes in the amorphous part of the cellulose. On the other hand, Las Vertientes and Catanlí displayed exactly the opposite results, and in addition, the adsorbed water bands showed significant differences in these bands and not in Pelchuquín. The crystalline ratio and the crystallinity index (Table 5) where lower in both plantations with intensive silviculture, which relates to the more amorphous structure of the measured celluloses. These differences between the site closely resembling a secondary growth of the studied species and the ones with intensive silviculture could potentially show an influence of this kind of intervention in a plantation on the crystalline structure of the wood. This could also have an effect on the chemical structure, particularly celluloses and hemicelluloses, and the way the wood adsorbs water, as those properties influence each other.

CONCLUSIONS

The silvicultural conditions of the sites had effects on the studied properties of thinning wood from *Nothofagus alpina* plantations. It was found out that there were statistically significant differences among the studied properties within the trees and between the studied sites. EMC, MOE and relative crystallinity were significantly different between Pelchuquín, the site that was more similar to a secondary growth forest, and Las Vertientes and Catanlí, which were managed sites with intensive silviculture. FT-IR was able to differentiate between within the trees and between the studied sites, and the XRD also showed clear differences in the crystallinity index. Furthermore, it was possible to distinguish that Catanlí, the plantation site with longer intense silvicultural regime, had the more homogeneous, as it had the best correlations between all the measured properties measured of this study.

The mechanical properties of the thinned wood from *Nothofagus alpina* plantations were comparable to the properties of *Pinus radiata*, so it shows that it has industrial value, therefore, that should be considered when making economic evaluations when deciding to plant this species. It is also possible to conclude that this material has a strong potential to be competitive and usable for the Chilean wood industry.

Authorship contributions

M. W.: Conceptualization, data curation, formal analysis, investigation, methodology, visualization, writing - original draft, writing - review and editing. H. P.: Data curation, resources, writing - review and editing. F. D.: Conceptualization, methodology, resources, writing - review and editing. A. R.: Conceptualization, data curation, investigation, methodology, resources, supervision, writing - review and editing.

Acknowledgments

The authors would like to thank the "Agencia Nacional de Investigación y Desarrollo de Chile" ANID, through their FONDECYT Postdoctoral Program 2022 for the financing of the project Nº3220112 "Valorization of native wood from thinning: Study of the characteristics and properties of thermally modified *Nothofagus alpina* wood from plantations with intensive silviculture" and through their FONDEQUIP Program, for the financial support for the acquisition of research equipment: EQM150019 "Strengthening of interdisciplinary research in materials and biomaterials, FT-IR Infrared Imaging System for non-destructive evaluation of surfaces" and the EQM160152 "Attraction of high-impact International Scientific Collaboration using Advanced X-ray Diffraction techniques to integrate interdisciplinary research in the Araucanía Region". They would also like to thank Helmut Huber, Alejandro Martínez, Gerardo Ludwig, Helmut Keim and Manuel Castro for their collaboration in this study.

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