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Effect of thinning on growth and shape of *Castanea sativa* adult tree plantations for timber production in Chile

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A B S T R A C T

Chestnut (*Castanea sativa* Mill.) is an interesting species for high-quality timber production. It is well known that the species responds to early thinning, but there is no information on the impact of late interventions. The objective of this study was to assess the effect of a late thinning on the performance of unmanaged adult chestnut plantations in Chile. Future-tree selective thinning and control were compared in adult plantations using a randomized complete block design with three replicates at three sites, Minas, Pillo-Pillo and Pumillahue. Tree growth was evaluated periodically during the first 7 years after thinning in all plantations. Additionally, almost 20 years after the intervention, the Pumillahue plantation was measured for growth and tree shape variables. In this case study, the effect of thinning on tree growth decreased considerably after 5 years, with a maximum DBH increment in the third year after the intervention (45.8 %, 68.6 %, and 42.2 % in Minas, Pillo-Pillo and Pumillahue, respectively). In all plantations, basal area was smaller in the thinned plots in the first years after the intervention, but in Pumillahue, 19 years after thinning, no differences were found among treatments. Height was statistically greater under thinning seven years after the intervention; this effect was also found in Pumillahue plantation 19 years after thinning. Most trees showed high vigor, and were straight and healthy, even in control plots. Late effect of thinning was observed 19 years after thinning on tree shape, with a reduction in the proportion of bifurcated trees from 16 % to 8 %. The results suggest that late thinning is an effective silvicultural intervention to produce high-quality chestnut timber in unmanaged adult plantations. Progressive and frequent thinning should be used to increase growth and improve timber production in chestnut.

1. Introduction

Chestnut (*Castanea sativa* Mill.) is a multipurpose species appreciated for its fruit production and high-quality timber. In Europe, in the species native area, the private sector has been actively involved in chestnut plantation establishment due to the increasing demand for high-quality timber (Patrício and Nunes, 2017), which can be a lucrative investment (Bourgeois et al., 2004); however, most of the plantations lack proper management (Patrício and Nunes, 2017).

The simplest and most ancient chestnut management system is coppicing in short-rotations to produce small and medium-sized poles (Manetti et al., 2010). This technique profits from the species resprouting capacity and the high initial shoot growth rate (Manetti et al., 2001). Another management system for the species refers to high forest, and a third one to a combination of high forest and coppicing, in which coppicing coexists with trees originated from seed in an area (Manetti et al., 2022).

The species was introduced to Chile in the 19th century by European immigrants. It showed an excellent adaptation to the conditions of the central-southern region of the country, especially between 34° and 41° south latitude, where the fruit has been traditionally consumed. Small chestnut plantations have been established for timber production. They are between 15 and 70 years old and have been planted at densities of 1,111 trees ha^{-1} or higher, with scarce or no silvicultural management.

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Thus, these plantations provide information on the adaptation and growth of the species under extensive forest production schemes. Height growth ranges between 0.64 and 1.43 m year^{-1}, and annual diameter growth ranges between 0.65 and 1.24 cm year^{-1} (Benedetti and Saavedra, 2007). The latter values are comparable to those obtained in the species native area (Vieitez and Vieitez, 1996; Bourgeois et al., 2004). In general, trees exhibit high vigor and good health, despite the presence of *Phytophtora cinnamomi* in some plantations (López and Loewe, 2007). However, limited advances have been made regarding the application of late management techniques, such as thinning, to improve growth and timber quality.

The species is internationally recognized for its high-value timber, which is easy to work with, light-colored and uniform, with straight to spiral or interlocked grain, and of attractive appearance (Vieitez and Vieitez, 1996). The timber obtained from plantations in Chile is suitable for structural use, as well as for carpentry and furniture, and noble uses such as veneering; it can be easily turned, drilled, planed and sanded (Juacida et al., 2000). Its quality is similar to that of several appreciated forest species, both native (*Nothofagus alpina, N. pumilio, Podocarpus nubigenus* and *Persea lingue)* and exotic (*Quercus* spp.). Importantly, ringshake in the wood, a serious defect present in its distribution range (Fonti and Macchioni, 2003), has not been reported in Chile (Loewe and Benedetti, 2007). Low apical dominance has a direct incidence on timber quality, since if the tree bifurcates, no quality timber will be generated (Drénou et al., 2020). Chestnut timber quality can be improved by applying silvicultural techniques suitable for the timber production goal (Monteiro and Patrício, 2007).

Silvicultural models alternative to short rotation coppice have been proposed to increase the production of quality assortments and to establish more functional and valuable stands (Amorini et al., 2000). In chestnut coppices, stand density is defined considering a sustained diameter growth rate while avoiding an excessive decrease of the stand productivity and assuring high quality stems (Menéndez-Miguélez et al., 2013). Small diameter round wood from coppices, formerly in high demand, is now less attractive to the market (Patrício et al., 2020). Thus, it is necessary to improve sustainable management techniques to obtain benefits from intermediate to large diameter trunks.

A high sensitivity of chestnut to thinning has been reported (Amorini et al., 2000). Thinning concentrates the yielding capacity on the selected trees and improves growth under drought (Sohn et al., 2016) through a better water use efficiency during summer (Marini et al., 2019) while decreasing stem flow and transpiration (del Campo et al., 2022). It also increases net precipitation and soil moisture, thereby confirming the role of this silvicultural technique in managing chestnut stands under climatic variability (Marini et al., 2019). In particular, selective thinning based on future crop trees releases best trees for future harvest at the end of the rotation (Pretzsch, 2009; Cruz et al., 2018).

It is well known that the species responds to early thinning (FVA, 2018; Manetti et al., 2020); however, scientific studies on late thinning are lacking and the duration of the thinning effect is unknown. Given the limited research on high-forest system management in chestnut (Patrício and Nunes, 2017), developing silviculture techniques like thinning contributes to the optimization of profitable and sustainable management. Therefore, the objective of this study was to assess the effect of late thinning on tree growth and shape of chestnut plantations. The scientific question is whether thinning can increase the production of quality timber in unmanaged adult chestnut forest plantations.

2. Materials and methods

2.1. Experimental trials

The study was conducted in Los Ríos, the region with the greatest presence of chestnut forest plantations in Chile, and where soil and climate characteristics are favorable for the species development. Three plantations with no previous interventions were selected, which had been established with one-year-old seedlings at a density of 1,111 trees ha^{-1} in Minas, Pillo-Pillo and Pumillahue in 1978, 1980 and 1982, respectively (Fig. 1, Table 1).

Site conditions where these plantations were established correspond to parameters reported for the species in the literature: deep, light and well-drained soils, and loamy texture with an organic horizon and litter (Blanco-Andray et al., 2000). Soil analyses in the three plantations showed: silt loam, lumpy sub-polyhedral texture, with an effective soil depth of more than 80 cm. Regarding nutrient content, P and B were deficient in all sites, and in Minas Al content was high (84 mg kg^{-1}).

2.2. Experimental design and field measurements

A silvicultural management trial considering two treatments (late thinning and control) was established in 25-, 23- and 20-year old plantations in Minas, Pillo-Pillo and Pumillahue, respectively, in 2003. Trees were selected considering their DBH, height, apical dominance, straightness, and absence of wounds or rot. The percentage and number of trees and basal area removed is shown in Table 2; final density was 700–800 trees ha^{-1}.

In each plantation, treatments were arranged in a randomized complete block design with three replicates; each plot within blocks was 500 m^2 in area (~40 trees plot^{-1} in thinned plots and ~ 95 trees plot^{-1} in control plots). Diameter-at-breast-height (DBH) at 130 cm above the ground was measured with a caliper and height with a hypsometer in all trees per plot six times after thinning (in 2003, 2004, 2005, 2006, 2008 and 2010); Pumillahue plantation was also measured in 2021, at age 40. Minas and Pillo-Pillo plantations were not measured in 2021 because they were modified by the local community, with several trees being cut in the last 10 years. Thus, the comparative analysis including all plantations was done with data from 2003 to 2010.

Timber quality-related variables (vigor, stem form, and apical

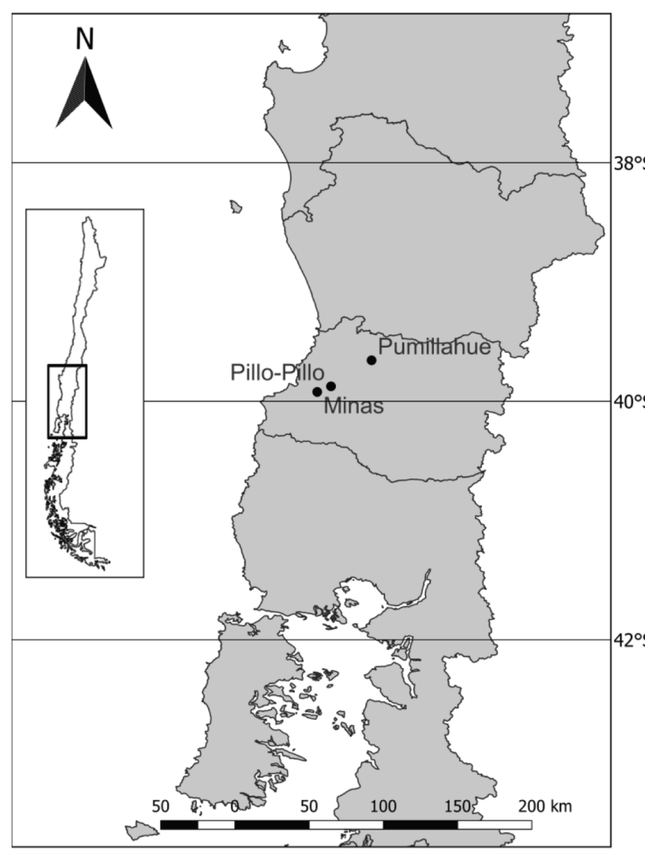

Fig. 1. Location of studied chestnut plantations in Chile, South America.

Table 1
Characterization of the chestnut plantation sites.

Plantation	Minas	Pillo-Pillo	Pumillahue
Geographical location			
Latitude	39°55′S	39°52′S	39°39′S
Longitude	73°13′W	73°06′W	72°46′W
Altitude (m a.s.l.)	58	44	155
Climate			
Annual average temperature (°C)	11.9	11.9	11.4
Maximum temperature of the warmest month (°C)	23.5	24.1	26.0
Minimum temperature of the coldest month (°C)	4.2	4.1	3.7
Annual rainfall (mm)	1,950	1,902	1,763
Frost-free days (days year^{-1})	224	262	184
Solar radiation (Ly day^{-1})	331	331	324
Soil			
Effective soil depth (m)	0.8	> 1	>1
Texture	Silt-loam	Silt-loam	Silt-loam
Structure	Lumpy sub-polyhedral	Lumpy sub-polyhedral	Lumpy sub-polyhedral
pH	5.04	5.01	5.65
Apparent density (g cm^{-3})	0.69	0.59	0.42
Organic horizon (cm)	20	15	30
Litter (cm)	5	5	5
Slope exposure	North-East	South	North
Slope (%)	14	18	4
Organic matter (%)	14.4	14.9	14.5
N (%)	0.40	0.46	0.49
P (Mg/kg)	4.90	4.80	3.10
K (Mg/kg)	67	81	52
Ca (cmol+/kg)	0.11	0.47	1.80
Mg (cmol+/kg)	0.15	0.26	0.59
Na (cmol+/kg)	0.06	0.04	0.07
K (cmol+/kg)	0.17	0.21	0.13
Al (cmol+/kg)	0.93	0.50	0.08
Sum of bases (cmol+/kg)	0.48	0.98	2.59
ECEC (cmol+/kg)	1.42	1.48	2.67
Base saturation (%)	65.9	33.8	2.9
Zn (Mg/kg)	0.41	0.23	0.08
B (Mg/kg)	5.04	5.01	5.65
S (Mg/kg)	22	17	13
Al (Mg/kg)	84	45	7
Ca (Mg/kg)	21	94	359
Mg (Mg/kg)	18	31	71
Na (Mg/kg)	13	10	17

Climate variables were taken from Santibáñez (2017).

Table 2
Trees and basal area removed by thinning in *Castanea sativa* plantations.

Plantation	Number of trees before thinning (trees ha^{-1})	Trees removed (%)	Basal area before thinning (m^2/ha)	Basal area removed (%)
Minas	1,960	25	34.80	39.02
Pillo-Pillo	1,300	36	46.81	35.25
Pumillahue	1,280	31	40.35	13.80

dominance), and phytosanitary status were recorded in Pumillahue in 2021 (19 years after thinning) to enrich the analysis of long-term effect of thinning. Vigor was assessed following Lakatos and Mirtchev (2014): high vigor trees (no defoliation or leaf discoloration); medium vigor trees (slight or no defoliation, and/or slight leaf discoloration); and low vigor (moderate or severe defoliation, and/or moderate or severe discoloration). Stem form was classified as straight, light buckled (curvature lower than the median curvature), heavy buckled (curvature higher than the median curvature), and deformed (several curvatures) (Kuehne et al., 2013). Apical dominance was measured to classify crown shape as monopodial (one dominant apex), forked (two codominant apexes) or brushy (without any dominant apexes). Phytosanitary status assessment consisted of monitoring the presence of any disease or pest in each chestnut tree.

2.3. Statistical analyses

DBH annual growth, height and basal area (average per plot) data for the 2003–2010 period were fitted using a linear mixed model (West et al., 2014) including the effects of treatment (control vs thinning), plantation and year after thinning, as well as their interactions, as fixed, and block within plantation and plot within block as random effects. The model was estimated via Restricted Maximum Likelihood (REML) with heterogeneous variances among plantations and years after thinning. Then treatments were compared in each plantation and year using Fisher's LSD test with a significance level of $\alpha = 0.05$. An individual analysis of growth and quality variables was performed for Pumillahue in 2021 using an ANOVA. The proportion of trees with high vigor and good stem form (straight trees), and without bifurcation was estimated and compared between treatments using a generalized linear mixed ANOVA model for binomial data with a logit function (Stroup, 2013). Statistical analyses were performed using the software InfoStat (Di Rienzo et al., 2022) and its interface with the software R (www.r-project.org).

3. Results

3.1. Tree growth

For diameter growth, the interaction between plantation and treatment was statistically non-significant ($p < 0.2571$) (Table 3). Table 4 presents the average annual DBH growth per treatment and plantation. In all plantations, DBH annual growth was statistically higher under thinning across years than in the control (22.0 % higher; 0.72 vs 0.59 cm year^{-1}). The thinning effect was significant up to the fifth year after thinning, and the maximum increment was recorded three years after the intervention (45.8 %, 68.6 %, and 42.2 % in Minas, Pillo-Pillo and Pumillahue, respectively).

For basal area, statistical differences were found for treatment ($p < 0.0001$), plantation ($p < 0.0001$) and years after treatment ($p < 0.0001$); the interaction between plantation and treatment was statistically significant ($p = 0.0336$) (Table 5). In all plantations, basal area was smaller under thinning than in the control plots. However, in Pumillahue, 19 years after treatment, there was no significant difference between thinning and control.

In all plantations, height was statistically greater in the thinned plots than in the control ones seven years after the intervention (on average, 23.9 vs 22.7 m, respectively) (Table 6). In Pumillahue, 19 years after thinning, statistical differences ($p < 0.0001$) were also observed for height between thinned and control plots (27.9 vs 25.3 m, respectively).

3.2. Timber quality variables

Results obtained for quality variables in Pumillahue plantation 19 years after the intervention are presented in Table 7. The proportion of straight and healthy trees and of trees with high vigor was similar among

Table 3
P-values of effects of treatment (thinning), plantation, years after thinning and their interactions for DBH annual growth in *C. sativa*.

Effect	DF	F-value	P-value
Treatment	1	14.23	0.0004
Plantation	2	0.5	0.6068
Years after thinning	4	6.35	0.0003
Treatment × Plantation	2	1.39	0.2571
Treatment × Year	4	15.77	<0.0001
Plantation × Year	8	3.63	0.0017
Treatment × Plantation × Year	8	5.4	<0.0001

Table 4
Castanea sativa DBH annual growth in different years after thinning.

Plantation	Years after thinning (age)	DBH growth (cm year^{-1})	
		Thinning	Control
Minas	1 (26)	0.61 ± 0.06a	0.70 ± 0.06a
	2 (27)	0.73 ± 0.14a	0.09 ± 0.14b
	3 (28)	1.05 ± 0.21a	0.72 ± 0.21b
	5 (30)	0.98 ± 0.07a	0.70 ± 0.07b
	7 (32)	0.56 ± 0.10a	0.65 ± 0.10a
	Mean	*0.78 ± 0.06a*	*0.57 ± 0.06b*
Pillo-Pillo	1 (24)	0.44 ± 0.05a	0.71 ± 0.05a
	2 (25)	0.61 ± 0.03b	0.82 ± 0.03a
	3 (26)	0.86 ± 0.05a	0.51 ± 0.07b
	5 (28)	1.12 ± 0.14a	0.55 ± 0.11b
	7 (30)	0.40 ± 0.10a	0.55 ± 0.10a
	Mean	*0.68 ± 0.04a*	*0.63 ± 0.04b*
Pumillahue	1 (22)	0.43 ± 0.05a	0.66 ± 0.05a
	2 (23)	0.75 ± 0.03a	0.48 ± 0.03a
	3 (24)	0.91 ± 0.08a	0.64 ± 0.08b
	5 (26)	0.77 ± 0.10a	0.45 ± 0.10a
	7 (28)	0.64 ± 0.05a	0.62 ± 0.05a
	Mean	*0.70 ± 0.03a*	*0.57 ± 0.03b*
	19 (40)	0.57 ± 0.05a	0.70 ± 0.04a

Mean ± SE. For each plantation and year, different letters indicate statistical differences among treatments.

Table 5
Castanea sativa basal area in different years after thinning.

Plantation	Years after thinning (age)	Basal area (m^2/ha)	
		Thinning	Control
Minas	1 (26)	23.7 ± 0.5b	39.0 ± 4.0a
	2 (27)	25.7 ± 0.5b	40.4 ± 3.9a
	3 (28)	28.6 ± 0.7b	40.8 ± 7.2a
	5 (30)	33.6 ± 0.6b	46.4 ± 4.7a
	7 (32)	36.0 ± 0.8b	50.7 ± 3.0a
	Mean	*29.5 ± 1.3b*	*43.5 ± 2.2a*
Pillo-Pillo	1 (24)	32.8 ± 1.8b	43.9 ± 4.6a
	2 (25)	33.9 ± 2.0b	45.7 ± 4.2a
	3 (26)	36.3 ± 2.5b	47.3 ± 3.7a
	5 (28)	42.9 ± 1.3a	52.7 ± 2.5a
	7 (30)	45.6 ± 0.8a	55.3 ± 5.9a
	Mean	*38.3 ± 1.5b*	*49.0 ± 2.0a*
Pumillahue	1 (22)	36.7 ± 3.5b	42.3 ± 3.5a
	2 (23)	38.5 ± 2.8b	44.5 ± 4.8a
	3 (24)	41.6 ± 3.2b	47.4 ± 4.2a
	5 (26)	49.0 ± 3.8b	52.7 ± 1.5a
	7 (28)	53.5 ± 4.2a	56.7 ± 9.8a
	Mean	*43.8 ± 2.2a*	*48.7 ± 2.5a*
	19 (40)	55.8 ± 3.7a	50.4 ± 2.1a

Mean ± SE. For each plantation and year, different letters indicate statistical differences among treatments.

Table 6
Castanea sativa height and DBH before thinning, after thinning and seven years after thinning.

Plantation	Year of thinning		Seven years after thinning	
	Before	After	Thinned	Control
Height (m)				
Minas	16.5 ± 0.8	15.6 ± 0.3	21.0 ± 0.2	19.5 ± 0.4
Pillo-Pillo	20.8 ± 1.6	20.6 ± 0.4	25.8 ± 0.2	25.3 ± 0.6
Pumillahue	18.2 ± 0.3	20.0 ± 0.4	25.0 ± 0.1	23.3 ± 0.3
DBH (cm)				
Minas	14.5 ± 0.5	18.1 ± 0.4	23.5 ± 0.5	18.6 ± 0.7
Pillo-Pillo	18.9 ± 0.8	21.5 ± 0.4	26.0 ± 0.5	23.3 ± 1.0
Pumillahue	19.1 ± 0.5	22.0 ± 0.4	26.8 ± 0.5	23.3 ± 0.7

Mean ± SE.

Table 7
Castanea sativa timber quality in Pumillahue 19 years after thinning.

Variable	Category	Trees [%]	
		Thinning	Control
Vigor	High	87 a	86 a
	Medium-Low	13 a	14 a
Stem form	Straight	64 a	65 a
	Buckled or Deformed	36 a	35 a
Apical dominance	Monopodial	92 a	84 b
	Forked	8 b	16 a
Phytosanitary status	Healthy trees	90 a	90 a

treatments across plantations ($p > 0.05$). However, statistical differences in apical dominance were observed between treatments ($p < 0.0014$). Regarding the quality and the use of the timber derived from the thinning performed at 20–25 years, the following assortments were obtained: firewood (40 %), poles (10 %, 15 cm of DBH) and logs (50 %) destined for sawn timber (20–25 cm of DBH).

4. Discussion

Assessing the impact of thinning on tree growth is useful for planning silvicultural management. Studies on late thinning in chestnut plantations established for timber production are scarce at the international level. In Europe, chestnut is a species considered of rapid growth and suitable for multiple purposes; however, the lack of silvicultural interventions limits the potential use of its timber and, therefore, its commercialization (Fioravanti et al., 2010).

The tested thinning favored big, vigorous trees spatially distributed, named as future trees (Cruz et al., 2018). It has similar characteristics to selective thinning, a technique widely disseminated in Europe, especially in chestnut coppices (Manetti et al., 2010).

Mean DBH growth observed after thinning (0.7 cm year^{-1}) in chestnut plantations in Chile across years is within the range of values observed in Europe. In fact, DBH growth values were lower than those reported in UK (1 cm year^{-1}, Everard and Christie, 1995), Spain (1–2 cm year^{-1}, Vieitez and Vieitez, 1996), France (0.8 to 1.1 cm year^{-1}, Bourgeois et al., 2004) and Italy (1.2 to 1.8 cm year^{-1}, Manetti et al., 2010), but higher than in pure plantations in northern Portugal (~0.5 cm year^{-1}, Nunes et al., 2014). In Pumillahue, at age 40, the average DBH growth (0.64 cm year^{-1}) was similar to growth in a long rotation 37-year-old coppice model proposed by Amorini et al. (2000). The effect of thinning was observed up to year five, with a subsequent decrease of the DBH growth after that year; this result indicates that progressive and frequent thinning is a suitable silvicultural method to increase timber production.

Considering site index curves developed for Portuguese chestnut high-forest stands (Patrício and Nunes, 2017), 19 years after thinning in Pumillahue, at age 40, unthinned stand height corresponded to site index between 24 and 26, whereas thinned stands were above the best site index (27).

To obtain high-quality timber in natural chestnut forests, periodical thinning every 3 to 7 years has been recommended (Everard and Christie, 1995) from the age of 12 years (FVA, 2018) up to 38 years (Bourgeois, 1992). Considering that an irregular diametric growth reduces the quality of logs (Berti et al., 2003), periodic progressive thinning might be a sound silvicultural approach.

In Chile, chestnut plantations for timber production are generally unmanaged, with no pruning or thinning being applied. There was a positive response but not as important as expected and of limited duration. Probably, if thinning had been implemented earlier, the response would have been more important. Late thinning is useful in plantations that were not managed due to neglect or for economic reasons, so the owner performs the technique late to take advantage of the timber extracted. The fact that the trees were performing well despite the lack of early intervention, and the response of trees to the late intervention, could justify the application of management techniques late in the life of the stands. In order to compare early and late thinning, we recommend studying the effect of earlier and frequent thinning in chestnut plantations established for high-value timber production.

Plantation density of up to 1,200 trees ha^{-1} has been proposed for timber production, with 200 trees ha^{-1} being left after 40–50 years, at the end of the rotation (IDF, 1990). Similar final densities have been recommended in France, with periodical thinning being suggested to attain a final density of 120–200 trees ha^{-1} (Bertrand et al., 1995). In the UK, frequent thinning has been recommended until a final density of 100–190 trees ha^{-1} is reached (Crawford, 1995). In our study, the density after the late intervention (700–800 trees ha^{-1}) shows the need to perform a second thinning, which should reach a final density of 300–400 trees ha^{-1} or lower, giving priority to vigorous, healthy, straight and non-bifurcated trees. A second thinning is necessary considering that a final density of 180–220 trees ha^{-1} has been proposed to obtain a target DBH of 40 cm, which decreases to 120–160 trees ha^{-1} if the target DBH increases to 50 cm (Kerr and Haufe, 2011), and that the current density is higher than the optimal range indicated for pure even-aged high-forest in a silviculture oriented to single-stem selection (Patrício and Nunes, 2017).

Reports on thinning involving several species in Europe indicate that interventions at early ages can remove a greater basal area than in adult formations (Müller-Using et al., 2013). It is known that basal area drastically drops under thinning in the short run. As expected, in the three plantations, basal area was smaller in the thinning treatment than in the control, with similar values for coppices reported by Manetti et al. (2010) of similar age in Italy (23.1 m^2/ha), and higher values than those modeled by Patrício et al. (2020) for 24-year-old medium diameter chestnut trees in Portugal (22.7 m^2/ha). In Pumillahue, at the age of 40, the basal area of thinned plots (55.8 m^2/ha) was greater than the value reported for high forests at age 35 after three thinning interventions (34.3 m^2/ha) in Italy (Amorini et al., 2000). To maximize volume production in chestnut stands, Kerr and Haufe (2011) recommended starting thinning when a threshold basal area is reached. For Pumillahue, considering the height reached at 40 years of age, that threshold would be 31–36 m^2/ha for the control stands and 33–35 m^2/ha for thinned stands. This criterion confirms the need to perform a new thinning. In Pumillahue, 19 years after thinning, the basal area decreased in the control treatment due to mortality and cutting of some trees by local people.

The results on growth, vigor and good health status suggest a good adaptation of the species in southern Chile. Indeed, height, the most frequently used indicator of site quality (Senilliani et al., 2019), in Pumillahue trees at the age of 40 years was higher than values reported for the best sites in the UK at a similar age (Everard and Christie, 1995), and higher than those in coppices in Portugal at the age of 24 years (Patrício et al., 2020). Height values were similar to those observed in the best quality sites in France (Bourgeois, 1992).

Thinning did not interfere with health, probably because the species is healthy in Chile, and because the initial density was not high enough to foster fungi disease development. In relation to vigor, thinning generated an increase in growth, but not high enough to be expressed through a greater vigor.

Quality timber is produced from trees that are healthy, vigorous, straight, non-forked and free of defects. One of the features recommended by Coello et al. (2020) to determine the potential of small or intermediate trees is good stem form. In this study, stem form was not impacted by the intervention, since a high proportion of trees had straight trunks in both treatments. However, the proportion of monopodial trees was significantly improved with thinning, increasing the potential quality of the stand final products. Thus, future long-term studies monitoring the impact of late thinning on chestnut timber productivity and quality are recommended to contribute to the recovery of unmanaged adult plantations.

5. Conclusions

Late thinning is an effective silvicultural intervention to produce high-quality chestnut timber in unmanaged adult plantations. The effect of late thinning on tree growth decreased considerably after 5 years. Long-term effect of late thinning was observed 19 years after thinning on tree shape, favoring timber quality. Progressive and frequent thinning should be used to increase growth and improve timber production in chestnut.

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Authors contributions

All authors contributed to the study conception and design. Material preparation and data collection was performed by Barrales and data curation by del Rio; Balzarini was in charge of the formal analyses. Loewe-Muñoz wrote the draft of the manuscript and all authors commented on successive versions of the manuscript. All authors read and approved the final manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2022.120762.

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