RESEARCH PAPER

Growth responses after a future crop tree thinning and a thinning from below in a second-growth *Nothofagus pumilio* forest in Tierra del Fuego, Chile

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Abstract

G.E. Cruz, F.A. Rodríguez, P.A. Tapia, and H.E. Bown. 2018. Growth responses after a future crop tree thinning and a thinning from below in a second-growth *Nothofagus pumilio* forest in Tierra del Fuego, Chile. Cien. Inv. Agr. 45(3): 263-276. *Nothofagus pumilio* (lenga) is the most important native species for timber production in southern Patagonia both in Chile and Argentina. Thinning application to second-growth *N. pumilio* forests has been limited in Patagonia, probably because of the long time necessary for the investment to be recovered. In addition, experimental trials have focused mostly on thinnings from below, leaving a high residual stand density, which has led to a modest growth response. Using measurements (1995–2014) obtained from a thinning trial carried out in a second-growth *N. pumilio* forest located in Tierra del Fuego (Chile), the objective of this case study was to analyze whether selective thinnings with future crop trees (in the sense of Z-Bäumen thinning) promote greater growth responses than those from a thinning from below. In addition, we explored the associations between climatic factors and age on *N. pumilio* tree growth. Trial treatments comprised a control, a thinning from below and a future crop tree thinning. The growth response after a future crop tree thinning was greater and lasted for a longer period (10 yrs) than did the thinning from below (4 yrs). The tree basal area and diameter at breast height (dbh) growth increased with dbh and annual absolute minimum temperature and decreased with age for the unthinned treatment during the period from 1977–2014 (~70–110 yrs old). Our results suggest that the future crop thinning might be a better alternative than the thinning from below for secondary *N. pumilio* forests in Patagonia due to the greater growth response while being a less intensive silvicultural method.

Key words: Climatic factors, lenga, Patagonia, thinning treatments

Introduction

Nothofagus pumilio (Poepp. et Endl.) Krasser (lenga) is the most important native species for timber production in southern Patagonia both in

Chile and Argentina. In Chile, *N. pumilio* forest covers an area of approximately 3.6 million ha, concentrated mainly in the regions of Aysén and Magallanes. In Magallanes, primary *N. pumilio* forests cover approximately 735 thousand ha, while second-growth forests cover approximately 131 thousand ha, which have originated from adult forests partially or totally destroyed by old fires

or unregulated logging since the colonization period in the 19th century. In southern Patagonia and Tierra del Fuego, approximately 200–300 thousand ha were transformed into pasture (Lara and Cruz, 1987, Cruz and Schmidt, 2007). In many cases, the pastures were abandoned, and a secondary forest was re-established. In Tierra del Fuego, second-growth forests cover an area of approximately 61 thousand ha (CONAF, 2011).

Thinnings and improvement cuttings in young *N. pumilio* forests have only been applied experimentally or in small extensions in Patagonia (Uriarte y Grosse, 1991, Chávez, 2002, Schmidt *et al*., 2003, Contreras, 2004, Maulen, 2015), despite the existence of state subsidies for their application (Neira y Rivas, 2013). Thinnings in secondary forest stands would reduce the time required to yield larger and better-priced logs, concentrate growth on selected trees, and harvest an intermediate yield that would otherwise be lost by natural mortality.

In Central European forestry, a variation of a selective thinning (Schädelin, 1942), commonly referred to as crop tree thinning in the sense of the German term Z-*Bäumen (*Abetz, 1979*)* or the American term *free thinning* (Helms, 1998, Nyland, 2016), has been frequently used. These healthy and vigorous future crop trees are promoted in the long term by removing a defined number of competitors (Pretzsch, 2009). By future crop tree thinning (FCT henceforth), we mean the selective thinning in young stands (pole timber stage), where final crop trees are chosen and permanently marked and kept until reaching a desired target diameter at breast height (dbh). Trees other than future crop trees are kept alive and may represent a fair proportion of the total basal area.

There are several reasons for the lack of interest in applying thinnings in young *N. pumilio* forests in the Magallanes Region in Chile. Thinning trials in the region have dealt mostly with thinning from below, testing different intensities in spacing and basal area. The current thinning from below

scheme considers leaving a residual stand with a high density of young trees, which leads to high intraspecific competition resulting in a modest growth response and low-quality timber in the future (Cruz, 1997). In addition, a thinning from below would generally involve felling the small-diameter trees, which would be generally left in the forest as a result of the low demand for small logs and the high logging and transport costs.

In contrast, selective thinnings based on a small number of future crop trees (100–300) prevent an excessive harvest of low-quality trees, thus reducing the costs of the intervention in line with the government subsidies available (Cruz, 2017). Additionally, wind damage and windthrow are common in *N. pumilio* forests (Rebertus *et al*., 1997; Peri *et al*., 2002), affecting stand stability and threatening the success of silvicultural operations (Peri *et al*., 2002). Therefore, low-intensity thinning practices that eliminate only the effective competitors (such as FCT thinning) could prevent large-scale windthrow and reduce the negative visual impact of managed forests (Peri *et al*., 2013). FCT thinning may also lead to rapid growth and the production of quality wood, which would better contribute to carbon sequestration at the tree and stand level and to the long-term storage of carbon into end products. Despite the apparent advantages of future crop tree thinning over thinning from below, silvicultural trials focused on the growth responses of the former on young *N. pumilio* forests are scarce, usually covering relatively short periods of time (Contreras, 2004; Peri *et al*., 2013; Maulen, 2015).

To the best of our knowledge, the trial reported in this study is one of a few with a longer monitoring time (19 yrs), allowing us to describe the medium-term growth responses of a control, a thinning from below and an FCT thinning treatments. We analyzed whether selective thinnings with future crop trees could bring about greater growth responses than those from a thinning from below for second-growth *N. pumilio* forests in Tierra del Fuego. In addition, we explored the

associations between climatic factors and age on *Nothofagus pumilio* stem growth in the unthinned treatment to better separate the effects of thinnings from other factors controlling the growth of *N. pumilio* forests. These results and discussion may contribute to better silvicultural decision-making for sustainable forest management.

Materials and methods

Study area

The study was conducted in a second-growth *N. pumilio* forest located in the "Cazuelas" property (53° 44´ 08" S; 69°06'46"; 160 m a.s.l.), owned by the company Forestal Russfin Ltda., Tierra del Fuego Island, in the Magallanes Region, Chile (Figure 1). Trials were established in a second-growth stand with two cohorts coexisting in 1995. At that time, the older, overmature cohort was approximately 250-300 yrs old, with approximately 48 trees per hectare, a basal area of 12.1 m^2 ha^{-1}, and an average dbh of 58 cm. The younger cohort was approximately 80–100 yrs old, with 1,820 trees per hectare, a 56.3 m^2 ha^{-1} basal area, and an average dbh of 21 cm. A future crop tree thinning (FCT) in the sense of the German term Z-*Bäumen (*Abetz, 1979*)* was carried out on 1.2 ha, a thinning from below on 2.4 ha, and 1.6 ha were left unthinned as a control. The treated areas were no more than 500 m apart and were similar in terms of vegetation composition and structure, soil type and topography.

The climate of the area is southern antiboreal subzone (oceanity sector O$_2$; humid province h) (Tuhkanen, 1992), having a mean air temperature between 8.5 and 9.5 °C for the warmest month of the yr and below zero for the coldest month. The mean annual rainfall ranges between 350 and 600 mm, and the length of the growing season ranges between 150 and 170 days. The wind
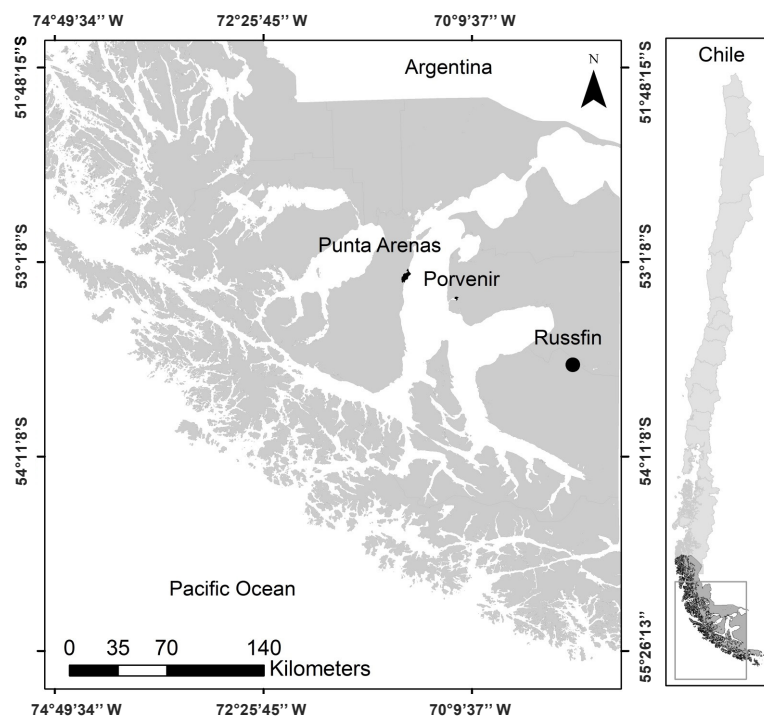

Figure 1. Study area showing the location of the secondary *N. pumilio* forests in Russfin (Cazuelas property), Tierra del Fuego, Chile.

direction is commonly west to southwest, with speeds averages between 14 and 22 km h^{-1}, and the maximum speeds in summer are above 100 km h^{-1} (Tuhkanen, 1992).

The topography is rolling terrain, with slopes lower than 5%. Soils have no apparent erosion and are classified within the group of humic podzols. The soils have thin to moderate depths (<50 cm), with sandy to loamy textures that are slightly acidic (pH 5.2-5.7) and have low fertility (Caldentey, 1995). The natural vegetation is characterized by pure *N. pumilio* deciduous forest belonging to the formation of the Patagonic Andean Forest Region (Gajardo, 1994).

Thinning treatments

All thinning treatments were applied for the younger cohort (80–100 yrs old). Overmature trees (250-300 yrs old) of the older cohort were left uncut in the thinning treatment areas. The FCT thinning released 138 young trees per ha that were dominant, straight, without excessive branching, with good vitality and with the best possible spacing by eliminating one to eight competitors for each selected tree. A competitor was defined as a dominant or codominant tree with a crown that compresses or touches the crown of a future crop tree. The basal area was reduced from 68.4 to 58.7 m^2 ha^{-1}, while the stand density was reduced from 1,868 to 1,598 trees ha^{-1}.

The thinning from below left the 1,320 best trees per ha (straight, without excessive branching, vigorous), maintaining an equivalent distance between them as far as possible. The basal area was reduced from 61.7 to 51.0 m^2 ha^{-1}, while the stand density was reduced from 1,568 to 1,320 trees ha^{-1}. The thinning intensity was defined according to the silvicultural system model proposed by Schmidt and Urzúa (1982) and Cruz and Schmidt (2007) for *N. pumilio* forests.

In 2002, the forest structure was characterized through a census for the FCT thinning, and through 5 randomly located 500 m^2 plots for the thinning from below. Fallen trees and stumps were also measured to reconstitute the stands before and after thinning in 1995. Within the FCT thinning, trees were also classified as *future crop trees*, corresponding to the 138 selected trees that were directly released by the thinning in 1995; *influenced trees* that were indirectly released by the thinning because they were closer (<5 m) to the cut trees (stumps); and *non-influenced trees* that were apparently unaffected by the thinned trees. The average dbh, tree height (h), tree density (N), basal area (G), and total overbark volume (V) were calculated. The structure of the unthinned stand was also characterized using 5 randomly located 500 m^2 plots. In 2014, the future crop thinning, the thinning from below and the control area were remeasured using 5 random plots of 500 m^2 per treatment area and assessed with the same parameters as in 2002. Values of the stand density, basal area and stem volume in the younger cohort before and after thinning in 1995 and 2014 are shown in Table 1.

Tree core sampling

In 2014, increment cores were taken from tree trunks at 1.3 m for each treated area and the control to assess the radial growth response. All of the suitable cores were dried, mounted, sanded using sandpaper of increasingly finer grain until the growth rings were clearly visible and processed, following the standard procedures outlined by Stokes and Smiley (1996). The ring widths were recorded to the nearest 0.01 mm using a LINTAB measuring system and TSAP-Win ™ 4.69b analysis software (RINNTECH e.K., Heidelberg, Germany). The dbh increment (mm yr^{-1}) both 19 yrs before and 19 yrs after the thinning were measured. A total of 250 increment wood cores were obtained: 130 from the FCT thinning treatment (70 from the future crop trees, 35 from the influenced and 25 from the non-influenced

Table 1. Stand density (N), basal area (G) and total overbark volume (V) for the younger stratum of *Nothofagus pumilio* secondary forest before and after thinning treatments in 1995 and 2014.

Thinning treatments	N (trees ha⁻¹)			G (m² ha⁻¹)			V (m³ ha⁻¹)		
	Stand before thinning in 1995	Stand after thinning in 1995	Stand after thinning in 2014	Stand before thinning in 1995	Stand after thinning in 1995	Stand after thinning in 2014	Stand before thinning in 1995	Stand after thinning in 1995	Stand after thinning in 2014
Future crop tree thinning	1,868	1,598	1,140	68.4	58.7	61.0	554	475	513
Future crop trees		138	135		5.7	9.6		45	81
Influenced and Non-influence trees		1,460	1,005		53.0	51.4		430	432
Thinning from below	1,568	1,320	1,048	61.0	51.0	61.7	503	432	520
Control	1,379	1,379	1,110	65.5	65.5	63.6	562	562	539

trees), 60 from the residual trees in the thinning from below treatment, and 60 from the control treatment. The cored trees were evenly distributed across dbh classes for each category of trees, i.e., future crop, influenced and non-influenced trees from the FCT treatment, the remaining trees from the thinning from below and the control trees.

Climatic influences on diameter growth

To test the association between climatic variables and annual dbh growth, we compiled the data from those weather stations with the longest and most complete instrumental temperature and precipitation records within the study area (data downloaded from explorador.cr2.cl) for the common interval, 1975–2017. This included records for the Russfin (53.75° S, 69.18° W, and 225 m altitude) and Punta Arenas weather stations (53.12° S, 70.8° W, and 5 m altitude). To complete the missing records, we fitted linear regression models for the daily minimum temperature, maximum temperature and precipitation for the intervals where these variables were available for both stations and applied the model fittings to the incomplete series

at the Russfin station using the records from the Punta Arenas station. Consequently, correlations between the dbh increment and the climate data were calculated for trees within the unthinned control treatment over 38 yrs (from 1977 to 2014). We calculated the Pearson correlation between the dbh increments and the total annual precipitation, mean monthly maximum temperature, absolute maximum temperature, mean minimum monthly temperature and absolute minimum temperature for the yr, growing season (September to April) and leafless season (May to August) and considered whether the variables lagged from the previous yr.

All statistical analyses were performed using R (R Core Team, 2013). Descriptive statistics were used to compare stand-level values. At the tree level (cores), we used linear mixed models to test the relationship between the current annual increment in dbh and the tree basal area against the tree state variables (e.g., dbh and age) and environmental variables (annual air temperatures and annual rainfall). Trees were considered a random effect. P-values were obtained by likelihood ratio tests of the full model with and without the fixed factor.

Results

Overall effect of thinnings

The FCT thinning performed in 1995 promoted the growth of the 138 most vigorous and high-quality trees selected per hectare by eliminating competition around them (an average of 1.96 competitors were cut around each future crop tree), representing 14.2% of the stem basal area of the original stand (Table 1). The thinning from below removed predominantly the dominated trees, representing 16.4% of the stem basal area of the original stand.

After the thinning treatments were applied during the summer of 1994/1995, from 1995 to 2014, the stand density within the FCT thinning decreased as a consequence of natural mortality by 28.7% (from 1,598 trees ha^{-1} in 1995 after thinning to 1,140 trees ha^{-1} in 2014), although mortality was almost exclusively confined to the influenced and non-influenced trees (28.5% pooled together). The stand density within the thinning from below treatment decreased by 20.6% (from 1,320 trees ha^{-1} in 1995 to 1,048 trees ha^{-1} in 2014) due to mortality (Table 1). This showed that competition-induced mortality occurred at a mean rate of 14.3 trees ha^{-1} yr^{-1}, affecting primarily the codominant and intermediate trees of the stand. The tree density for the unthinned stand decreased by 19.5% (from 1,379 trees ha^{-1} in 1995 to 1,110 trees ha^{-1} in 2014), similar to the mortality rate of the thinning from below treatment (Table 1).

After the thinning treatments were applied during the summer of 1994/1995, between 1995 and 2014, the basal area increment in the selective thinning treatment exhibited a slight increase (3.9%) that was concentrated mainly on the future crop trees (68.4%). The basal area of influenced and non-influenced trees decreased by 3.0%, which was attributed to the mortality that occurred during that period. The values of the mean quadratic diameter (D_g) of the future crop trees increased by 31.8% (from 17.9 cm in 1995 to 23.6 cm in 2014),

with almost null mortality. The basal area in the thinning from below treatment increased by 21.0% (from 51.0 m^2 ha^{-1} in 1995 to 61.7 m^2 ha^{-1} in 2014), distributing this growth in the basal area to trees of different sizes, social classes and stem qualities. Consequently, the mean quadratic diameter (D_g) of the stand increased 22.9% (from 17.4 cm in 1995 to 21.4 cm in 2014) during the same period. The basal area of the unthinned stand decreased by 2.9% due to mortality, while the mean quadratic diameter (D_g) increased by 9.9% (from 19.2 cm in 1995 to 21.1 cm in 2014) during the same period.

The total overbark volume (V) of the FCT-thinning treatment increased by only 8.0% (from 475 in 1995 to 513 m^3 ha^{-1} in 2014), with an average of 2.0 m^3 ha^{-1} yr^{-1}. However, 94.7% of the growth rate was attributed to the growth of the selected future crop trees alone (11.8% of the trees). The relative participation of the future crop trees to the total overbark volume (V) of the stands increased by 66.3% (from 9.5 to 15.8%). During the same period, the total overbark volume (V) from the thinning from below treatment increased from 432 in 1995 to 520 m^3 ha^{-1} in 2014 (20.4%) at a mean growth rate of 4.6 m^3 ha^{-1} yr^{-1}. The total overbark volume (V) of the unthinned stand decreased by 4.1%, which was attributed to mortality in that period.

Individual tree growth in dbh and basal area

The current annual increments in dbh (g_{dbh}) and basal area (g_{ba}) ranged from 0.04 to 10.20 mm and from 0.12 to 43.8 cm^2 yr^{-1}, respectively, during the time of the study (1977–2014, stand ages 52–89 yrs). Overall, the g_{dbh} was similar before (1977–1995) and after (1995–2014) the treatments were applied for the unthinned (1.85 ± 0.99, before; 1.82 ± 1.03 mm yr^{-1}, after), the thinning from below (2.59 ± 1.22, before; 2.41 ± 1.03 mm yr^{-1}, after), and the FCT thinning (2.58 ± 1.34 mm, before; 2.52 ± 1.09 mm yr^{-1}, after). For the basal area, the g_{ba} values were similar for the unthinned (7.9 ± 5.2, before; 7.2 ± 5.1 cm^2 yr^{-1}, after) and the thinning from below

(7.7 ± 4.9, before; 7.2 ± 5.1 cm² yr⁻¹, after) when comparing the period before and after 1995, while for the FCT, the g_{ba} values drastically increased from 7.8 ± 4.6 cm² yr⁻¹ before 1995 to 10.1 ± 6.4 cm² yr⁻¹ after 1995.

The future crop trees from the FCT-thinning after 1995 exhibited the greatest g_{dbh} compared to the influenced and non-influenced trees of the FCT, the trees from the thinning from below and the control, in that order. The effect of the FCT thinning treatment on the g_{dbh} exceeded the growth response in both magnitude and length compared to the thinning from below. Visually, the effect of the FCT thinning treatment lasted for approximately 10 to 11 yrs, with an average diameter

growth for that period of 3.85 mm yr⁻¹, compared to the growth before (2.34 mm yr⁻¹) and after (2.01 mm yr⁻¹) that period (Figure 2a). In contrast, the effect of the thinning from below lasted for approximately 4 yrs after the thinning in 1995 (in absolute terms, from 2.23 in 1995 to 2.31 mm yr⁻¹ in 1999). The magnitude of the effect of the thinning from below was very modest. The trees in the control, the unthinned treatment, gradually decreased in diameter growth from 2.23 in 1995 to 1.36 mm yr⁻¹ in 2014, which was clearly associated with natural decline with age (Figure 2a). Visually, the tree growth in the basal area (g_{ba}) did not seem to decrease with age (Figure 2b), although statistically it did, as shown in the next section.
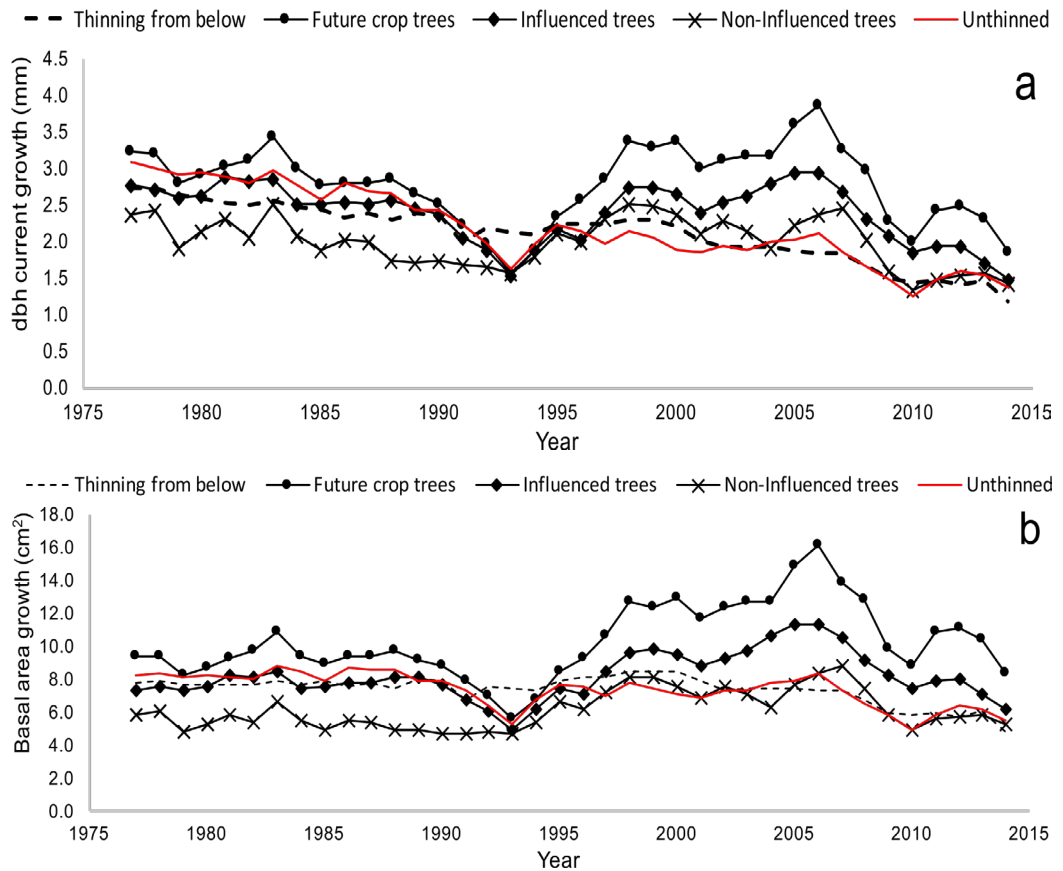

Figure 2. Current annual increment in (a) dbh and (b) tree basal area across thinning treatments. Values are the means for the future crop (n=69) and the influenced (n=34) and non-influenced trees (n=20) within the FCT thinning, thinning from below (n=59) and control (n=52) trees.

Growth drivers of dbh and tree basal area

The current annual increment in dbh (g_{dbh}, mm yr^{-1}) increased with dbh (cm) (P<0.001) and absolute annual minimum temperature (ºC) (P<0.001) and decreased with age (yrs) (P<0.001) (Table 2, Figure 3), i.e., g_{dbh} = 6.277+ 0.029 dbh - 0.048 age + 0.026 Tmin. The same pattern was observed for the current annual increment in the tree basal area (g_{ba}, cm^2 yr^{-1}); g_{ba} = 13.28+0.44 dbh -0.15 age + 0.12 Tmin (P<0.001 for all three variables). Rainfall, air mean and maximum annual temperature did not influence the g_{dbh} or g_{ba} values. The values of g_{dbh} would then increase by 0.029 mm for each additional 1 cm in dbh, would decrease by -0.048 mm for each additional yr of age and would increase by 0.026 mm for each additional 1ºC increase in the absolute minimum annual temperature (Table 2). The directions of change of the g_{ba} and g_{dbh} values against the predictors were the same, i.e., values increased with dbh and annual absolute minimum temperature and decreased with age (Table 2).

Discussion

The thinning trial in this study lacks a robust experimental design, but it is probably one of the few studies on second-growth *N. pumilio* forests in Patagonia, monitored for 19 yrs after the treatments were applied. Therefore, we do not attempt to extrapolate these results to the region and do not expect the reader to do so without a warning.

However, the unique character of this case study allows us to infer the overall growth responses of this forest to an FCT thinning and a thinning from below. These results may inform silviculturalists, forest ecologists and forest managers about the outcomes, although uncertain, about the advantages of using FCT for sustainable forest management of the second-growth forests of *N. pumilio* in Patagonia.

The slight growth increase in dbh and basal area of the residual trees after the thinning from below was applied is likely due to the low intensity of the first thinning (16.4% in the basal area, G) and the lack of successive thinnings for the last 20 yrs that led to excessive crown competition among the dominant and codominant trees. Several thinning trials in *N. pumilio* forests of low intensity have shown a small growth response (Schmidt *et al.*, 2003). A thinning severity of 7.9% in the basal area (1,167 N ha^{-1}; 76.4 m^2 ha^{-1} G) exhibited a null increase in mean dbh growth after four yrs, and a severity of 21.1% in the basal area (1,056 N ha^{-1}; 71.1 m^2 ha^{-1} G) showed an increase of 26.6% (from 1.5 to 1.9 mm yr^{-1}) in mean dbh growth after three yrs (Schmidt *et al.*, 2003). The results from a thinning from below in a 100-yr-old *N. pumilio* stand showed that the dbh growth after 20 yrs was 2.0 mm yr^{-1} for the unthinned treatment (1,317 N ha^{-1}; 24.7 m^2 ha^{-1} G) compared to 4.9 mm yr^{-1} when G was reduced by 74% (400 N ha^{-1}; 6.4 m^2 ha^{-1} G) without considering the wood quality of the residual trees and the stability of the stand (Schmidt *et al.*, 2003). This reinforces

Table 2. Current annual increment in dbh and basal area as explained by dbh, age and absolute minimum annual temperature for *Nothofagus pumilio* secondary forests. Only records from the unthinned stand were considered. Only significant variables were kept in the model.

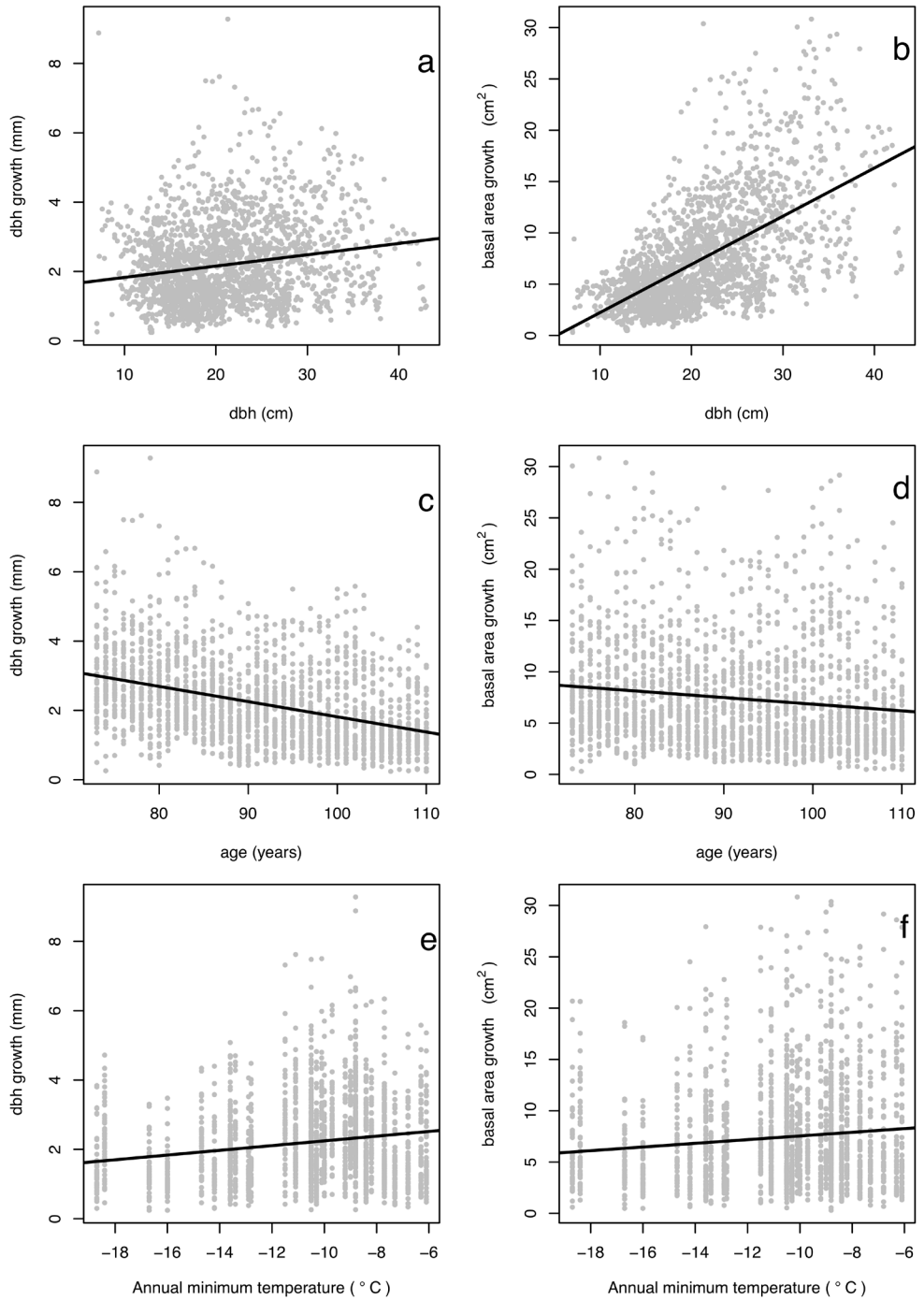| Variable	Current annual increment			
	dbh (mm yr -1)		basal area (cm^2 yr -1)	
	Coefficient	P-value	Coefficient	P-value
(Intercept)	6.1895	< 0.001 ***	12.8949	< 0.001 ***
dbh	0.0671	< 0.001 ***	0.5812	< 0.001 ***
Age	-0.0561	< 0.001 ***	-0.1795	< 0.001 ***
Tº min	0.0251	< 0.001 ***	0.1184	< 0.001 ***

Figure 3. Significant relationships between the current annual increment in dbh (left panel) and basal area (right panel) and the dbh (a, b), age (c, d) and the absolute annual minimum temperature (ºC) (e, f) for the unthinned control treatment.

the idea that the thinning from below should be more severe and periodic to increase the growth of the thinned trees and maintain the productive capacity of the site.

In this study, future crop trees within the FCT-thinning exhibited a mean current annual increment in dbh of 3.16 ±1.18 mm yr⁻¹ (58.8% higher than the control trees) between 1995 and 2005 (Figure 4). Contreras (2004) found that for the 5 yrs following the FCT for the same trial reported in this study, there was a current dbh increment of 3.9 mm yr⁻¹, which is approximately 24% greater than dbh increment observed for the FCT after ten yrs. Therefore, we may speculate that a periodic release every 10 yrs would be needed to maintain the growth potential of the future crop trees.

Maulen (2015) found slow growth of selected trees under low intensity selective thinning. In a 50 yr old *N. pumilio* secondary forest (15,401 Nha⁻¹; 63 m² ha⁻¹ G), they found a nonsignificant increase in dbh of 4.5% (from 2.2 mm yr⁻¹ before to 2.3 mm yr⁻¹ after thinning) when the 606 young selected trees were released from their direct competitors. Peri *et al.* (2013) found that removing one, two and three or more competitors around each selected

tree in a 40-yr-old secondary *N. pumilio* forest in Tierra del Fuego, Argentina, increased the dbh growth rate by 6.3%, 31.3% and 37.5%, respectively, when compared to the control following the 10 yrs after thinning. Our mean annual increment in dbh (58.8%) was greater than that observed by Maulen (2015) (4.5%) and Peri et al. (2013) (<38.0%) compared to the unthinned control treatment. In contrast, our dbh increments were smaller than those reported by Schmidt *et al.* (2003), where dbh growth was 63.6% and 68.2% greater when removing one or two competitors, respectively, from a 30 yr old stand in Magallanes (compared to a control over 10 yrs). This would indicate a greater thinning growth response in younger trees after future crop tree release. However, *N. pumilio* trees as young as 30 yrs old may have not yet differentiated their crowns, rendering them unfeasible for carrying out an FCT.

Future crop tree thinning caused significant changes in the forest structure during the 19-yr thinning trial. One of the major changes in the thinned plots, compared to the thinning from below and the control plots, was the concentration of the stand mortality on the influenced and non-influenced trees (99.3%), which showed a
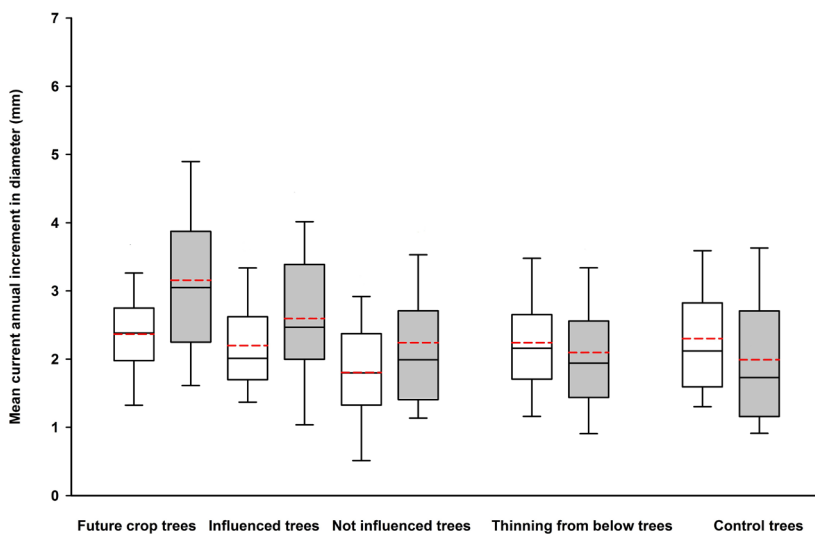

Figure 4. Mean current annual increment in diameter before (1985–1995; left box) and after (1996–2005; right box) thinning treatments were applied. The thinning treatments were FCT thinning (future crop tree, influenced and non-influenced trees), thinning from below and the control. The central black line in the boxes represents the median, while the red dashed lines represent the mean annual increment in dbh.

mortality rate 51.5% and 60.0% higher than that for the thinning from below trees and the control trees, respectively. In contrast, the mortality rate of the future crop trees was very low (0.7%), and the diameter growth increased drastically over the 19-yr period after the FCT. The strict selection of a small number of future crop trees meeting the recommended criteria of vitality, quality and distance (Abetz, 1979) likely limited the mortality and maintained an adequate number of future crop trees. The above contrasts with the idea of selecting a large number of elite trees (or candidates to be final crop trees) and gradually selecting a smaller number of the best trees at each thinning cycle according to the traditional selective thinning method (Schädelin, 1942). This has been frequently controversial because FCT- thinning is commonly associated with considerable uncertainty and the risk of a negative change in the quality of the future crop trees due to this early and strict selection mechanism (Abetz, 1989). Despite the initial high quality of the future crop trees being selected, they could reverse their quality due to an insufficient thinning growth response (Milinsek *et al*., 1992, Maulen, 2015), damage caused by windthrow (Peri *et al*., 2013) or mechanical damage caused by felling and logging during the thinning cycles (Cruz,2017).

In an oak stand (*Quercus robur* L.) in Opočno, Czech Republic, it was shown that the selection of candidates and target trees at the small pole stage is a premature and risky decision (Chroust, 2007). They concluded that in a traditional selective thinning with an early selection of individuals, it is advisable to focus only on the vital and straight trees or to implement a selective thinning variant (*sensu* Abetz, 1979) in the form of future crop trees. Furthermore, Boncina *et al.* (2007) determined that in beech forest (*Fagus sylvatica* L.) in southeastern Slovenia, selective thinning was not beneficial to all the selected trees when too many crop trees were selected relative to the thinning intensity.

The alternative of selecting a greater number of future crop trees to ensure their quantity in the final stand to be harvested is not advised, since in no case would it lead to a decrease in the incidence of damage to future trees. The selection of the best trees in the course of stand development requires much more experience than a one-time determination and marking of the future crop trees that are to be promoted (Abetz, 1979). We propose that thinning protocols in secondary *N. pumilio* forests should consider a careful identification of a set of future crop trees, assuming that such a set would not appreciably change qualitatively over time.

The only environmental variable significantly explaining the annual growth rate in dbh and the basal area for the site was the absolute minimum annual temperature. For each 1°C increase in the annual absolute minimum temperature, the growth rate in dbh would increase by 0.025 mm yr^{-1}, while the growth in the tree basal area would increase by 0.12 cm^2 yr^{-1}. Aravena *et al.* (2002) analyzed 21 tree ring width chronologies of *N. pumilio* distributed between latitudes 51–55º S in Chile and found that tree growth positively correlated with the minimum annual air temperatures, and they used the correlation to reconstruct the climate of the time series. In contrast, Álvarez *et al.* (2015) found that the radial growth of *N. pumilio* was negatively correlated with precipitation in late spring (November-December) and positively correlated with air temperature in late spring and early summer (November-January) in humid high-elevation environments. Similarly, Norton (1984) found that tree growth was strongly related to air temperature during the austral summer months (December to March) for *Nothofagus menziesi* and *N. solandri* trees in the South Island of New Zealand. Ledgard and Norton (1988) similarly found that air temperature but not rainfall was positively correlated with the rate of shoot growth of seedlings of three New Zealand *Nothofagus*. Suarez *et al.* (2015) studied the ring chronosequences of *Nothofagus dombeyi* along a west-east precipitation gradient in Nahuel Huapi National Park, Argentina, showing that the critical factor regulating tree growth is a spring–summer

water deficit brought about by above-average temperatures and reduced precipitation during the growing season. At high elevations, however, tree growth was less sensitive to water deficit but comparatively more sensitive to air temperature increases. Rubino and McCarthy (2000) found that the ring widths and basal area growth of *Quercus alba* L. from an old-growth forest in southeastern Ohio, USA, correlated well with growing season (April-July) precipitation and drought severity. Therefore, interpreting the above, dbh growth will be limited by either water or temperature. In the case of the *N. pumilio* forest under study, water seems to be less limiting than temperature, and therefore, dbh growth would scale with air temperature. We may speculate that for yrs in which the absolute minimum annual temperature is much lower, the growing season might be shorter and colder, limiting *N. pumilio* development. In contrast, when the absolute minimum annual temperature is higher, the yrs may be expected to be warmer with a longer spring-summer growing season.

In summary, future crop tree thinning (in the sense of Z-Bäumen thinning) seems to be a better option for the management of second-growth *N. pumilio* forests in Southern Patagonia compared to thinning from below. The growth response of the FCT thinning was greater, lasted for a longer period (10 yrs) and involved less intensive silviculture than the thinning from below (4 yrs). The annual dbh and tree basal area growth was observed to increase with dbh and absolute minimum temperature and decrease with age across the studied range (90–110 yrs old).

Acknowledgements

Resumen

G.E. Cruz, F.A. Rodríguez, P.A. Tapia y H.E. Bown. 2018. Respuestas en crecimiento después de un raleo con árboles futuro y un raleo por lo bajo en un bosque secundario de *Nothofagus pumilio*, en Tierra del Fuego, Chile. Cien. Inv. Agr. 45(3): 263-276. *Nothofagus pumilio* (lenga) es la especie nativa más importante para la producción maderera del sur de la Patagonia (Chile y Argentina). Raleos en bosques secundarios *de N. pumilio* no han sido de interés probablemente debido al largo tiempo de recuperación de la inversión. Además, mayoritariamente se han ensayado raleo por lo bajo, dejando un rodal residual denso y con bajo crecimiento diamétrico. Usando mediciones (1995–2014) de un ensayo de raleo instalado en 1995 en un bosque secundario de *N. pumilio*, en Tierra del Fuego (Chile), el objetivo de este estudio de caso fue analizar, si raleos selectivos con árboles futuro (en el sentido de Z-Bäumen), originan un mayor crecimiento diamétrico que un raleo por lo bajo. Además, se exploran asociaciones entre factores climáticos y la edad en el crecimiento diametral de *N. pumilio*, para interpretar los efectos del raleo en los bosques. Los ensayos consistieron en un testigo, un raleo por lo bajo y un raleo selectivo con árboles futuro. La respuesta en crecimiento diametral del raleo selectivo con árboles futuro fue mayor y se prolongó por más tiempo (10 años), respecto del raleo por lo bajo (4 años). El crecimiento diamétrico y en área basal para el testigo se incrementó con el diámetro y la temperatura mínima absoluta y disminuyó con la edad a lo largo del período 1977–2014 (~70–110 años de edad). El raleo selectivo con árboles futuro representaría una mejor opción para el manejo de los bosques secundarios de *N. pumilio*, respecto del raleo por lo bajo.

Palabras clave: Factores climáticos, lenga, métodos de raleo, Patagonia.

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