Radial growth response to long-term thinning strategies in *Nothofagus pumilio* forests of Tierra del Fuego

Respuesta del crecimiento radial a estrategias de raleo de largo plazo en bosques de *Nothofagus pumilio* de Tierra del Fuego

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SUMMARY

New silvicultural proposals based on long-term trials are needed to develop forest management strategies. Radial growth response was the preferred proxy for managers to define thinning levels and best years for intervention. We analyzed long-term thinning strategies in secondary *Nothofagus pumilio* forests (55 years old) in Tierra del Fuego (Argentina) to determine and quantify the effect on radial growth. Samplings were conducted in a trial area established in 1965 where three interventions (17, 33 and 44 years after harvesting) with different thinning strategies were applied. We employed dendrochronological techniques to measure and co-date ring widths, comparing 19 different thinning strategies (n = 100 slices x 2 reading sections). Average ring width (RW), basal area increment (BAI), and periodic annual increment every five years (PAI_5) were calculated and compared through univariate comparisons. Radial growth responses were directly related to thinning intensity; however, a differential response was found according to thinning strategy (*e.g.* selective and systematic cuttings) and always significantly higher than the control (3 vs. 1 mm year^{-1}). The maximum growth occurred between 2 and 4 years after thinning (YAT), and progressively decreased until reaching pre-cutting levels (5 to 8 YAT). The analyses of the thinning strategies showed that initial systematic thinning followed by at least light thinning when growth rates recover their pre-intervention values is the most convenient combination of intermediate treatments for *Nothofagus pumilio* forests. These results can contribute to better silvicultural decision-making in secondary forests and provide information to analyze the feasibility of their implementation.

Keywords: dendrochronology, secondary forests, selective and systematic cuttings, Patagonia.

RESUMEN

Las propuestas silvícolas basadas en ensayos a largo plazo son necesarias para desarrollar estrategias de manejo forestal. La respuesta de crecimiento radial ha sido el proxy preferido por los gestores para definir los niveles de raleo y los años de intervención. Analizamos estrategias de raleo a largo plazo en bosques secundarios de *Nothofagus pumilio* (55 años) en Tierra del Fuego (Argentina) para determinar y cuantificar el efecto sobre el crecimiento radial. Los muestreos se realizaron en un área de ensayo establecido en 1965 donde se aplicaron tres intervenciones (17, 33 y 44 años después de la cosecha) con diferentes estrategias de raleo. Se emplearon técnicas dendrocronológicas, donde se midieron y co-fecharon anchos de anillos definiendo 19 estrategias de raleos diferentes (n = 100 rodajas x 2 secciones de lectura). Se calculó el ancho medio de los anillos (RW), el incremento del área basal (IAB) y el incremento periódico anual cada cinco años (PAI_5), comparando valores mediante pruebas univariadas. Las respuestas de RW estuvieron relacionadas con la intensidad del raleo y se encontró una respuesta diferencial según la estrategia aplicada (por ejemplo, cortas selectivas y sistemáticas), siendo siempre significativamente mayor que el control (3 vs 1 mm año^{-1}). El crecimiento máximo ocurrió entre 2 y 4 años después del raleo (ADR), y disminuyó hasta alcanzar los niveles previos a los raleos (5 a 8 ADR). Los análisis mostraron que una primera intervención sistemática seguida de al menos un raleo suave cuando las tasas de crecimiento recuperan los valores previos a la intervención, es la combinación de tratamientos intermedios más conveniente para los bosques de *Nothofagus pumilio*. Estos resultados pueden contribuir a una mejor toma de decisiones silvícolas en los bosques secundarios, proporcionando herramientas para analizar la viabilidad de su aplicación.

Palabras clave: dendrocronología, bosques secundarios, raleos selectivos y sistemáticos, Patagonia.

INTRODUCTION

Silviculture of secondary forests is a long-term complex process, essential for developing effective forest management strategies to meet the local industry's needs. The most important intermediate treatment is thinning, where trees can be left or removed according to different strategies, such as selective or systematic cutting that regulates the available natural resources in the managed stand (light, water, nutrients) and influences tree growth and intra-tree competition (Cruz *et al.* 2018). It is a challenge to establish a full-cycle prescription of interventions to optimize forest production (Allen 2008), as long-term research is necessary to define the best practical solutions for managers.

In Tierra del Fuego, *Nothofagus pumilio* (Poepp. *et* Endl.) Krasser (lenga) forests are the main resource for timber in the sawmill industry (Martínez Pastur *et al.* 2009), and are harvested and managed through various practices. From the 1960s to the present day, several large-scale trials have been established (Alonso *et al.* 1968), promoting the implementation of new silvicultural strategies (Gea-Izquierdo *et al.* 2004) including selective and clear-cuttings (Mutarelli and Orfila 1973), shelterwood cuts (Martínez Pastur *et al.* 2000) and variable retention cuts (Martínez Pastur *et al.* 2009). These systems open the canopy and stimulate the establishment of natural regeneration (Martínez Pastur *et al.* 2009) by modifying microclimate and natural cycles (Martínez Pastur *et al.* 2009, 2013, Soto *et al.* 2019). Therefore, established regeneration leads to an even-aged secondary forest with high density that is generally unmanaged (Gea-Izquierdo *et al.* 2004) and follows a natural dynamic with a rotation length that varies from 110 to 170 years depending on site quality (Martínez Pastur *et al.* 2004). Aggressive self-thinning occurs, making implementation of intermediate treatments (intermediate cuts - thinning) necessary to open the canopy and advantageously transform the secondary forest into high-productivity managed forests, reducing the time needed to produce larger and higher priced logs. In effect, growth is concentrated in selected trees, and an intermediate yield is harvested, considering that it would otherwise be lost due to the high intra-tree competition and the consequent natural mortality (Cruz *et al.* 2018).

Most of the harvested lenga forests were not managed after logging (Gea-Izquierdo *et al.* 2004). However, several theoretical proposals (*e.g.* Schmidt and Urzúa 1982, Uriarte and Groose 1991) and a few long-term studies were carried out to improve and manage lenga secondary forests (Martínez Pastur *et al.* 2001, 2013, Contreras 2004, Mundo *et al.* 2020). Several advantages and trade-offs were identified for thinning practices. For example, high-intensity selective thinning improves tree quality and growth, reduces forest longevity, but encourages the growth of lateral branches. Meanwhile, low intensity thinning reduces the negative visual impact, increases stability, and leaves a branch-free stem, but increases operation costs (Peri *et al.* 2013). Many authors described outputs in the short-term (Contreras 2004), but more long-term studies that quantify the effect of different intensities and thinning strategies are needed, such as evaluation of the periodicity between interventions and the effects of combining different thinning strategies (selective and systematic cuttings).

Radial growth response was the preferred proxy for managers to define levels of thinning and annual growth of trees through measurement of rings. Using this methodology, effects of thinning on annual radial growth have been reported for different species around the world (Misson *et al.* 2003, Pérez-de-Lis *et al.* 2011). In Tierra del Fuego, Franco *et al.* (2019) analyzed the response to different combinations of thinning in secondary forests of *Nothofagus betuloides* (Mirb.) Oerst. (guindo, coihue de Magallanes), and Mundo *et al.* (2020) researched the effects of two thinning levels in secondary lenga forests.

This study presents cases of long-term thinning strategies for secondary forests, however little is known about their effects nor the best recommendations for its application. Therefore, the objective was to determine and quantify the radial growth response to long-term thinning strategies in lenga forests in Tierra del Fuego and provide tools for the development of intermediate treatments in the long term. We sought to answer the following questions: (i) What is the response of trees' radial growth to each combination and intervention strategy (selective or systematic cuttings) as a function of years-after-thinning (YAT)?; (ii) What is the growth response time of the remaining trees as a function of applied thinning intensity?; (iii) Which is the recommended strategy for secondary lenga forests based on the studied treatments? It is hypothesized that the effect of thinning on growth will be positive and highly correlated, and that response time and annual growth rates will be proportionally higher according to thinning intensity. Furthermore, the impact of different thinning strategies on growth as well as potential costs must be evaluated, as selective cuts can be more effective at stimulating individual growth but more expensive than systematic cutting.

METHODS

History of management of the study area. The study was carried out in a long-term permanent plot of the PEBANPA network (Parcelas de Ecología y Biodiversidad de Ambientes Naturales en Patagonia Austral, INTA-UNPA-CONICET, Argentina) (Peri *et al.* 2016). The study area is located in Tierra del Fuego province, 14 km from the town of Tolhuin, in the Aguas Blancas forests (54° 36’ 35” S, 67° 15’ 43” W) which is characterized by a subantarctic oceanic climate (Cfc by Köppen), an elevation of 200 meters above sea level, and the presence of inceptisols. The studied stands are pure lenga forests of medium site quality (Martínez Pastur *et al.* 1997) with dominant heights fluctuating between 22 and 26 m at maturity, which is reached around 200 - 250 years old (Schmidt and Urzúa 1982).

Site history. In the 1960s, the University of Buenos Aires (UBA) began a series of research studies in Andean-Patagonian forests with the purpose of evaluating the necessary elements to ensure the rational management of these native forests. Through these studies, they aimed to establish the most convenient silvicultural treatments and the best timing and intensity of the interventions in order to grow the productive stands to harvesting age with the maximum possible value according to the technological criteria to balance growth and quality (Mutarelli and Orfila 1973). These investigations were supported by the National Forestry Administration (ANB) and later by the National Forestry Institute (IFONA), and were gradually abandoned, as the last monitoring and trials were carried out in the mid-1980s.

Between 1965 and 1967, the ANB and UBA established one permanent plot at the Aguas Blancas forests in 16 ha of unmanaged lenga forests with high homogeneity in terms of composition and structure of vegetation, soil type, and topography. This forest was harvested for timber purposes using clear cuts in alternating NE-SW oriented strips, 35 meters wide and 400 meters long (Cozzo *et al.* 1967). Within the harvested strips, all the woody material was removed (> 5 cm), allowing the establishment of natural abundant regeneration of the harvested areas. During the following years, the remnant strips were partially harvested (selective cuts), and then the entire area was abandoned and no management was conducted for 15 years. In 1984, IFONA carried out different commercial thinning systems on harvested strips. The regeneration presented forests of approximately 2 meters of height, 2.5 cm DBH, and a tree density of 80,000 - 100,000 ind ha^{-1} (Mundo *et al.* 2020). These start-up trials were applied at one per strip without replications (selective or systematic cuttings): (i) heavy thinning from below (HT), (ii) light thinning from below (LT), (iii) extraction of competitors through selection thinning (S), (iv) 2 meter strips parallel to the mother strips (longitudinal strips, LS), (v) 2 meters strips perpendicular to the mother strips (transverse strips, TS), and (vi) checkerboards (with parallel and perpendicular strips every 2 meters, D) (figure 1). Control areas (C) without cuttings were left in every strip.

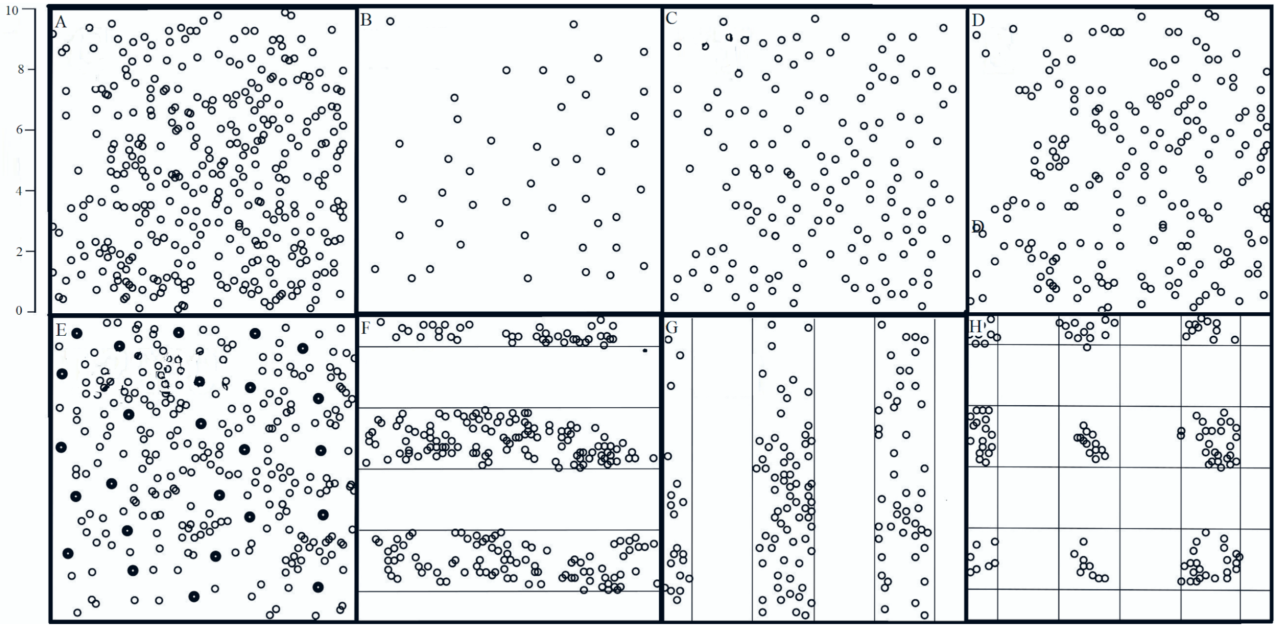

Figure 1. Start-up thinning treatments (1984) in Aguas Blancas permanent plots. A = control, B = heavy thinning, C = light thinning, D = selection, E = selection strip by competitors, F = transversal strips, G = longitudinal strips, H = checkerboard. Scale in meters.

Tratamientos de la primera intervención (1984) en las parcelas permanentes de Aguas Blancas. A = control, B= raleo fuerte, C = raleo suave, D = selección, E = extracción de competidores, F = franjas transversales, G = franjas longitudinales, H = damero. Escala en metros.

New monitoring and management of the permanent plot was conducted starting in 1999, led by Centro Austral de Investigaciones Científicas (CADIC CONICET), Facultad de Ciencias Agrarias y Forestales (UNLP), the Forest Office (Government of Tierra del Fuego) and private companies. New trials and cuttings for thinning were applied in 1999 - 2000, 2010, and 2020 in the harvested strips. During 1999 - 2000, new subtreatments were installed without replications of the analyzed treatments, and one new treatment was established in an undisturbed sector. In the start-up trials, the areas were subdivided into three sectors, where subtreatments were defined during the second thinning: (i) heavy thinning (> 50 % basal area was removed), (ii) light thinning (< 50 % basal area was removed), and (iii) a thinning control, where no new cuttings were applied on the areas thinned in 1985. Both thinning levels removed individuals of low crown class with poor health and deformations in the stem, prioritizing an equivalent distance among remnant individuals. The objective of these treatments was to promote the growth of remnant trees by increasing rainfall and temperature at the understory level, as well as reducing competition for nutrients.

The new trial established in 2000 defined a new thinning strategy based on selective cuttings in two stages (T2000). For this purpose, target trees were selected across the plot (3 x 3 m; 1,111 trees ha^{-1}). During the first stage all the crown competitors of the target trees were removed (year 2000), and in the second stage the remaining non-target trees were removed (year 2010). The target trees were dominant and presented good health and forest stem quality. The objective of this treatment was to promote the crown development of the target trees before the final cut, in which the canopy was abruptly opened. In 2010, the third intervention was conducted, where all subtreatments were thinned in order to homogenize remnant forest structure. Finally, in 2021, the fourth intervention was implemented, applying heavy thinning (50 - 60 % of the BA was removed), removing individuals with poor health and deformations in the stem, and prioritizing an equivalent distance among remnant individuals (not analyzed in this study). This thinning homogenizes the area without consideration of the previously established subtreatments of each harvested strip. A total of 19 thinning strategies were considered. Evolution over years of treatments and its subdivisions are presented in table 1, representing thinning intensities as compared to BA of the control. Combinations with their abbreviations are presented in annex 1.

Sampling and dendrochronological analysis. Forest structure was measured for all treatments prior to cuttings and samplings. We used the Bitterlich point sampling method with a forest caliper and a Criterion RD-1000 (Laser Technology, US), applying a K coefficient between 1 and 6. We obtained: (i) height (H, m), (ii) basal area (AB, m^2 ha^{-1}), (iii) tree density (individuals ha^{-1}), and (iv) average diameter at breast height (DBH, cm). After cutting, slides were obtained from harvested trees during thinning in 2021. A total of 100 slices at DBH were collected considering trees of good quality (straight shafts without bifurcations), DBH of 17 - 23 cm and dominant heights of up to 16 meters (6 treatments x 3 subtreatments x 5 replicates + 5 replicates of C + 5 replicates of T2000), resulting in the 19 different thinning strategies and combinations of treatments across the years reported in table 1. The slides were air-dried and polished in order to obtain smooth surfaces to facilitate the identification of growth rings under magnification (10x - 50x).

Cross sections were processed using standard dendrochronological techniques (Stokes and Smiley 1968) and two perpendicular radii were measured per sample. Growth rings were dated according to the Schulman convention (Schulman 1956) for the southern hemisphere, and the year of each growth ring was assigned according to the year it began to form. Ring widths were measured with a digital caliper to the nearest 0.01 mm. COFECHA software was used to evaluate the quality of the dating and to calculate Mean Intercorrelation (MI) and Mean Sensitivity (MS). For analyses, average ring width (RW), basal area increment (BAI) assuming circular sections, and periodic annual increment (PAI) were calculated, using the average of 5-year periods before and after the interventions, grouping dendrochronological series in treatments and subtreatments. The difference between the means of PAI_{pre} and PAI_{post} was calculated by statistical tests to compare growth before and after the interventions. Thus, the periods were established as such: for the 1984 intervention (first one, 17 YAH), pre (1980 - 1984), post (1985 - 1989); for 1999 (second one, 33 YAH), pre (1995 - 1999), post (2000 - 2004); for 2010 (third one, 44 YAH), pre (2006 - 2010), post (2011 - 2015). The year 2020 was discarded because cuts were conducted during ring growth. The Kruskal-Wallis non-parametric test was applied to detect differences between means with a significance level of $P < 0.05$, and the Mann-Whitney U test was applied for comparison between means. Statistical analyses were performed using STATGRAPHICS Centurion XVI.I software (USA, StatPoint Technologies, Inc). Further, the response time of the interventions was estimated as the number of years with RW values greater than the average of the 5 years prior to thinning.

RESULTS

Regarding forest structure in 2021 (table 2), the lowest average DBH value corresponded to C (11.2 cm), but with the highest basal area (52.2 m^2 ha^{-1}) and density (7,420 ind ha^{-1}). The treatments presented average DBH between 18.3 and 28.1 cm, with the highest value corresponding to LS followed by D (21.9 cm) and the lowest to S. Basal area fluctuated between 30.4 and 34.9 m^2 ha^{-1} and density between 919 and 1,239 ind ha^{-1} in treatments thinned. Regarding T2000, and considering that its structure was the result of two thinning treatments, it reached lower values

Table 1. Classification of treatments and subtreatments. Percentages represent the proportion of BA remnants compared to C.

Clasificación de los tratamientos y subtratamientos. Los porcentajes representan la proporción de AB remanente en comparación con C.

Treat.	T17	T33	T44	T17-POST	T33-PRE	T33-POST	T45-PRE	T-45POST	T54-PRE
C	no	no	no	35.0	35.6	35.6	40.4	40.4	52.2
HT	H	L/P	H	14.0 %	68.6 %	53.3 %	76.0 %	36.1 %	46.4 %
	H	H	H	14.0 %	68.6 %	44.7 %	73.3 %	27.7 %	39.8 %
	H	no	H	14.0 %	68.6 %	68.6 %	95.5 %	31.9 %	44.1 %
LT	L	L	H	56.0 %	102.7 %	62.3 %	100.7 %	44.3 %	65.9 %
	L	H	H	56.0 %	102.7 %	42.5 %	80.7 %	42.8 %	62.8 %
	L	no	H	56.0 %	102.7 %	102.7 %	101.5 %	45.5 %	62.8 %
S	L	L	H	56.0 %	98.6 %	69.4 %	98.5 %	34.4 %	50.6 %
	L	L	H	56.0 %	98.6 %	66.6 %	98.0 %	33.4 %	67.4 %
	L	no	H	56.0 %	98.6 %	99.4 %	95.5 %	28.7 %	76.6 %
TS	L	H	H	50.0 %	99.4 %	45.8 %	90.1 %	45.3 %	73.6 %
	L	H	H	50.0 %	99.4 %	40.7 %	86.9 %	41.6 %	64.4 %
	L	no	H	50.0 %	99.4 %	98.0 %	98.3 %	34.4 %	67.4 %
LS	L	L	H	50.0 %	76.9 %	58.1 %	61.6 %	24.5 %	55.2 %
	L	H	H	50.0 %	76.9 %	40.4 %	62.4 %	34.7 %	62.8 %
	L	no	L	50.0 %	76.9 %	76.9 %	99.5 %	60.1 %	69.0 %
D	H	L	H	25.0 %	95.6 %	67.8 %	99.0 %	46.5 %	72.0 %
	H	H	H	25.0 %	95.6 %	33.7 %	77.0 %	43.1 %	69.0 %
	H	no	H	25.0 %	95.6 %	95.6 %	82.7 %	30.7 %	73.6 %
T2000	no	L	H	100.0 %	100.0 %	85.1 %	87.1 %	25.3 %	42.4 %

Where: T17= thinning 17 YAH (first, 1984), T33= thinning 33 YAH (second, 1999), T44= thinning 44 YAH (third, 2010), T54= thinning 54 YAH (fourth, 2021). H= heavy thinning, less than 50% of BA of Control. L= light thinning, more than 50% of BA of Control. No= no thinning applied. Row values of C represent BA (m^2.ha^{-1}). PRE= values previous to thinning. POST= values post thinning. C= control, HT= heavy thinning, LT= light thinning, S= selection, TS= transversal strips, LS= longitudinal strips, D= checkerboard, T2000= thinning year 2000.

of basal area (28.0 m^2 ha^{-1}) and average DBH (18.4 cm) than the other treatments with three interventions. Heights fluctuated between 13.83 and 16.46 m, where higher values corresponded to LS, LT and D. The highest gross BAI corresponded to HTHT and DHT, being the subtreatments with the biggest trees (so highest response to thinning). No mortality was reported in thinned sites, but it was reported in control sites due to natural stand dynamics (self-thinning, 6 % annually on average). Exceptional cases of wind throw were reported. The slides sampled presented a diameter of 22.5 ± 6.3 cm, considering the different sizes of samplings.

The dendrochronological series showed a year of onset that varied between 1960 and 1977, considering the initial age at DBH, and indicated that several individuals were probably part of the seedling bank prior to clear-cutting. Likewise, there was evidence of an established cohort after harvesting in all treatments. Regarding the common variability between individual series depending on treatment, the average MI prior to the first intervention was relatively low (0.23 across all series, varying between 0.23 and 0.53 if divided by treatments), increasing to 0.52 after the first intervention, 0.62 after the second, and 0.71 after the third. The number of series varied among treatments according to the age of the trees studied (table 3).

The analysis of the effects of thinning using δPAI comparisons showed positive effects on radial tree growth for the 3 interventions. The greatest effects were observed for the first and third thinning treatments, with values close to 0 in δPAI_{RW} for the second thinning, and negative values for the control. Similarly, significant differences were observed when treatments were compared between the 3 interventions, finding for all cases that the control presented the lowest values, negative for the second and third interventions (figure 2). For the first intervention, the treatment with the greatest effect corresponds to HT, showing significant differences with the rest of the treatments when δPAI_{RW} ($P < 0.001$) and δPAI_{BAI} ($P < 0.001$) were com-

Table 2. Forest structure in 2021 for subtreatments.

Estructura forestal para los subtratamientos, año 2021.

Tr	BA	DEN	DBH	QMD	Gross BAI
C	52.2	7,420	11.1	11.5	26.4
HTC	32.0	1,381	18.3	18.6	69.4
HTHT	29.6	1,056	20.1	20.5	110.9
HTLTP	32.0	969	23.6	25.3	96.8
LTC	32.8	1,246	23.0	26.9	105.1
LTLT	34.4	1,523	24.8	29.4	58.3
LTHT	32.8	876	25.7	27.4	99.8
SC	40.0	1,584	21.8	24.1	59.1
SLT	26.4	997	19.3	19.6	53.2
SHT	35.2	992	27.9	34.8	71.1
TSC	35.2	1,242	26.1	30.9	63.5
TSLT	38.4	1,264	27.6	32.7	83.4
TSHT	33.6	1,105	20.6	20.8	100.3
LSC	36.0	1,077	23.2	24.1	64.1
LSLT	28.8	806	26.7	28.3	93.6
LSHT	32.8	884	28.1	32.8	94.5
DC	38.4	1,385	24.5	28.6	53.4
DLT	37.6	1,110	25.9	29.5	106.1
DHT	36.0	1,245	25.1	30.1	110.9
T/2000	28.0	1,242	18.4	18.8	83.1

Where: Treatment (Tr), basal area (BA, m^2 ha^1), density (DEN, ind ha^{-1}), diameter at breast height -130cm- (DBH, cm), quadratic mean diameter (QMD, cm), Gross BAI (sum of BAI from 45 to 54 YAH -after 3rd thinning-, cm^2).

pared. Analyzing the results of δPAI_{BAI} for the second intervention, the different thinning treatments did not show significant differences. However, when analyzing the third intervention, significant differences between treatments both for δPAI_{RW} ($P < 0.001$) and δPAI_{BAI} ($P < 0.001$) were found, where the largest effects correspond to T2000, HT and systematic treatments.

The evolution of the effects after the first thinning (figure 3, 17 YAH) is consistent with those previously mentioned, showing similar response patterns for all treatments. HT was the treatment with the highest response and growth for RW and IAB, considering also that at the time of thinning it started from lower values than the rest of the treatments. This was the only one that differed from systematic treatments. When compared with C, all treatments followed similar patterns, and after 25 YAH, RW values kept constant, but with higher rates (excepting for S).

When subtreatments (2nd thinning) were applied, the responses were differential according to the intensity of thinning applied (figure 4). First, all thinned subtreatments showed positive effects and differed in C growth values. For heavy thinning, the highest response was for LT (subT = LTHT), followed by HT (subT = HTHT). Systematic treatments showed similar patterns, with D (subT = DHT) showing the greatest growth rates, not only after the second thinning, but also after the third one. For light thinning, systematic treatments differed from non-systematic ones in higher growth, except HT (subT = HTLT). For controls, values remained constant until the application of the third thinning (44 YAH), where all subtreatments showed similar effects. However, when compared with subtreatments that were applied in 1999, RW and IAB values were lower for controls, highlighting the successive effect of thinning application. Finally, T2000 highlights a behavior similar to C, modifying this pattern considerably at the time of the second intervention (1999), reaching similar rates to the other subtreatments.

The response time (lag) of the positive effects of the first intervention varied between 1 and 13 YAT, with variability according to the treatment applied and the % BA removed. In this case, the greatest effect was observed in HT, followed by D and LT. Regarding the effects of the second intervention, the application of subtreatments highlighted the difference between controls and interventions. In the controls, growth rates remained below the pre-intervention average. In contrast, heavy and light thinning for each treatment had positive effects on radial tree growth in all cases, with the year of greatest growth ranging from the third to the seventh year after thinning, with lags of 6 to 10 YAT (table 4). For all treatments, the average ring widths post-intervention were larger than before the intervention, except for HT pruned. Finally, for the third intervention, where all the subtreatments were applied, the effects were positive in all cases, and the largest growth occurred between the second and third year after thinning, with a lag between 7 and 10 YAT, considering that at the time of the last intervention (4th thinning, 2021) the trees still presented higher average rates than those prior to the intervention. In the case of C, a drop in average growth rates was observed throughout the entire period studied.

DISCUSSION

As expected, the results of the present work show that the effects of thinning are positive, considering that they generate more growth in the remaining forest stand when compared with control sites. Additionally, the evaluation of the effects by statistical analysis and interpretation of graphs seems to be more sensitive when BAI is applied. The present findings are consistent with those of Mundo *et al.* (2020), who conducted a study at the same site but applied only HT and its subtreatments. In the present work, the study was expanded with the incorporation of a new intervention and the remaining treatments, comparing systematic and non-systematic interventions.

The mean intercorrelation values obtained are similar to those presented by Mundo *et al.* (2020), highlighting the increase of these values as the interventions elapse. These values indicate that thinning produces a homogeneous growth effect among the remaining trees in the stand, a condition that can be modified when competition for resources increases.

Analysis of the effects of thinning shows that more intense interventions generate more annual radial growth and a longer response period. Similar results were found by Pérez-de-Lis *et al.* (2011) where the effects of heavy thinning were greater than those of light thinning for *Pinus canariensis* Sweet *ex* Spreng. This is due to fewer individual trees that are able to take advantage of more resources for a longer period (McDowell *et al.* 2003). The time limit seems to be the moment of crown closure, when greater inter-tree competition for light is triggered, and annual growth rates return to pre-intervention values. Annual growth surveys could allow for determination of opportune moments for interventions, and the results of the present work could be used as a reference, considering the varying situations studied. However, the intensity of thinning can also have consequences on the stability of the remaining canopy (Peri *et al.* 2002) and the excessive formation of lateral branches (Martínez Pastur *et al.* 2001).

When the treatments are analyzed separately, a gradual increase in growth rates is observed, reaching a peak that varies between year 2 and 6 after the interventions. Similar patterns of the effects of thinning were found by Franco *et al.* (2019) for *Nothofagus betuloides*. It is a challenge to determine whether it is best to apply thinning once these maximum values are reached, or at the time when previous values are recovered. Economic aspects

Table 3. Ring width statistics for periods between interventions.

Estadísticas de ancho de anillos para los períodos entre intervenciones.

		X - 1984			1985 - 1999			2000 - 2010				2011 - 2019		
Tr	Fy(X)	MI	MS	NS	MI	MS	NS	Sub-T	MI	MS	NS	MI	MS	NS
C	1977	0.53	0.28	10	0.59	0.31	10	C	0.92	0.45	10	0.71	0.41	10
HT	1969	0.35	0.26	28	0.70	0.33	30	HTC	0.53	0.29	10	0.81	0.29	10
								HTHT	0.75	0.32	10	0.79	0.28	10
								HTHTP	0.56	0.28	10	0.78	0.27	10
LT	1970	0.34	0.24	22	0.59	0.28	30	LTC	0.64	0.31	10	0.40	0.27	10
								LTLT	0.54	0.23	10	0.45	0.26	10
								LTHT	0.58	0.30	10	0.79	0.29	10
S	1971	0.24	0.27	26	0.50	0.29	28	SC	0.53	0.34	10	0.70	0.28	10
								SLT	0.68	0.29	10	0.58	0.24	10
								SHT	0.62	0.28	10	0.86	0.22	10
TS	1964	0.25	0.28	24	0.47	0.30	28	TSC	0.45	0.25	10	0.68	0.29	10
								TSLT	0.54	0.25	10	0.74	0.28	10
								TSHT	0.59	0.35	10	0.61	0.28	10
LS	1960	0.25	0.26	26	0.68	0.24	30	LSC	0.72	0.27	10	0.53	0.27	10
								LSLT	0.66	0.26	10	0.73	0.23	10
								LSHT	0.58	0.24	10	0.73	0.26	10
D	1974	0.23	0.27	22	0.57	0.26	30	DC	0.78	0.28	10	0.83	0.22	10
								DLT	0.52	0.29	10	0.68	0.24	10
								DHT	0.69	0.30	10	0.57	0.23	10
C/T2000	1973	0.31	0.28	10	0.62	0.25	10	T2000	0.68	0.33	10	0.74	0.25	10
ALL	1960	0.23	0.27	168	0.52	0.28	196	ALL	0.62	0.30	200	0.71	0.27	200

Where: Treatment (Tr), First year (Fy), mean intercorrelation (MI), mean sensitivity (MS), number of series (NS), subtreatment (Sub-T). C= control, HT= heavy thinning, LT= light thinning, S= selection, TS= transversal strips, LS= longitudinal strips, D= checkerboard, T2000= selection strip by competitors.

and social context that are not considered in this work should be discussed.

It may be considered that the second thinning should have been implemented with greater intensity to observe more effects on the trees. Thus, it is estimated that four thinning treatments are sufficient to complete the silvicultural system in a rotation of approximately 80 years, maintaining radial growth rates of ≈ 2 mm per year (finally, sawn logs with a diameter of 40 cm, forest density of ≈ 600 ind ha^{-1}). These intermediate treatments are suitable for application after logging (in this case, 17 YAH, but it could be years later, depending on site quality and height of saplings), both for shelterwood cuts and retention strategies. Furthermore, thinning generates products (smaller than timber products) that can potentially be used by farmers without having to wait for the final felling year. Considering differences between systematic and non-systematic interventions, a primary systematic interven-

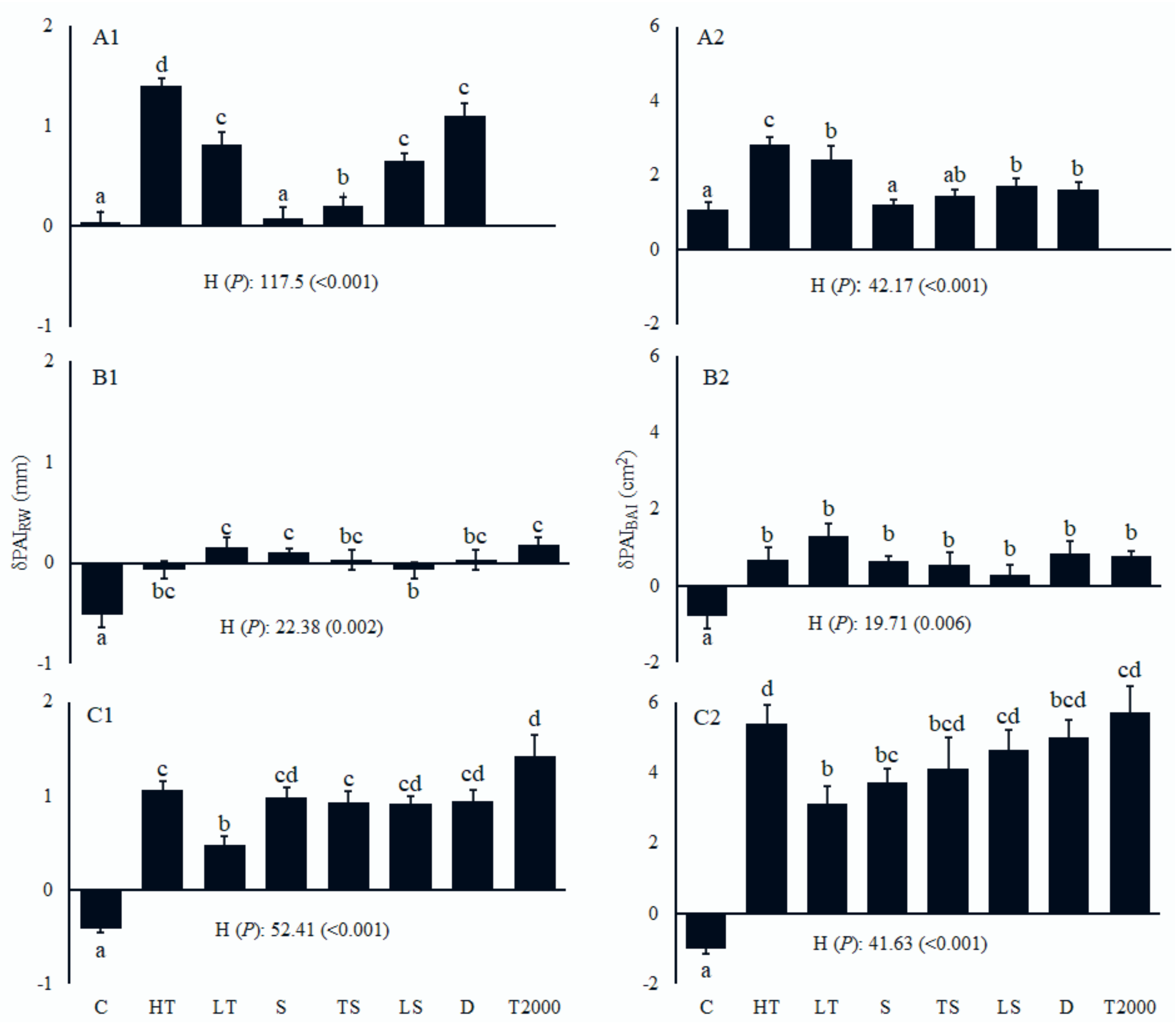

Figure 2. Differences in periodic annual increment (δPAI) for 5 years before and after 3 interventions for ring width (RW, left panels) and basal area increment (BAI, right panels). A (A1 and A2): for first thinning (1980 - 1984) - (1985 - 1989). B (B1 and B2): for second thinning (1995 - 1999) - (2000 - 2004). C (C1 and C2): for third thinning (2006 - 2010) - (2011 - 2015). Bars represent mean values, with their corresponding standard errors of the mean. Different letters show significant differences by the Mann-Whitney U test (P < 0.05 based on Kruskal-Wallis test). C = control, HT = heavy thinning, LT = light thinning, S = selection, TS = transversal strips, LS = longitudinal strips, D = checkerboard, T2000 = selection strip by competitors.

Diferencias en el incremento periódico anual (δPAI) durante 5 años antes y después de 3 intervenciones para anchos de anillo (RW, paneles de la izquierda) y el incremento del área basal (BAI, paneles de la derecha). A (A1 y A2): para 1ra intervención (1980 - 1984) - (1985 - 1989). B (B1 y B2): para 2da intervención (1995 - 1999) - (2000 - 2004). C (C1 y C2): para 3ra intervención (2006 - 2010) - (2011 - 2015). Las barras representan la diferencia de medias, con su correspondiente error estándar de la media. Letras diferentes indican diferencias significativas de acuerdo a Mann-Whitney U test (P < 0,05 según la prueba de Kruskal-Wallis). C = control, RF = raleo fuerte, RS = raleo suave, S = selección, TS = franjas transversales, LS = franjas longitudinales, D = damero, T2000 = extracción de competidores.

tion (scripts or checkerboarded) seems to be successful in terms of logistics and effects on growth rates, which are similar to non-systematic treatments (except for HT), as evidenced in figure 2. Pruning does not make a big difference in radial growth after the second intervention, but it does after the third one, comparable with results found by Mundo (2020), due to more carbon accumulation in the stem and not in the branches. Therefore, other interventions should be conducted, considering that the effects of thinning decay and growth rates recover to previous values 6 - 10 years after thinning. It is then appropriate to apply a second thinning treatment in which about 50 % of the remaining basal area is removed from those that were thinned systematically in the first intervention. In this way, canopy release is achieved, which was not completed during the first intervention. If second thinning is not applied, effects on systematic treatments will be lower than non-systematic ones after third interventions, as evidenced in figure 4. This combination of interventions generates similar effects at the time of a third thinning treatment, when compared to originally non-systematic thinning. In addition, in the year 2020 (54 YAH), these combinations reached higher average DBH values. The threshold of interventions results in a combination of pe-

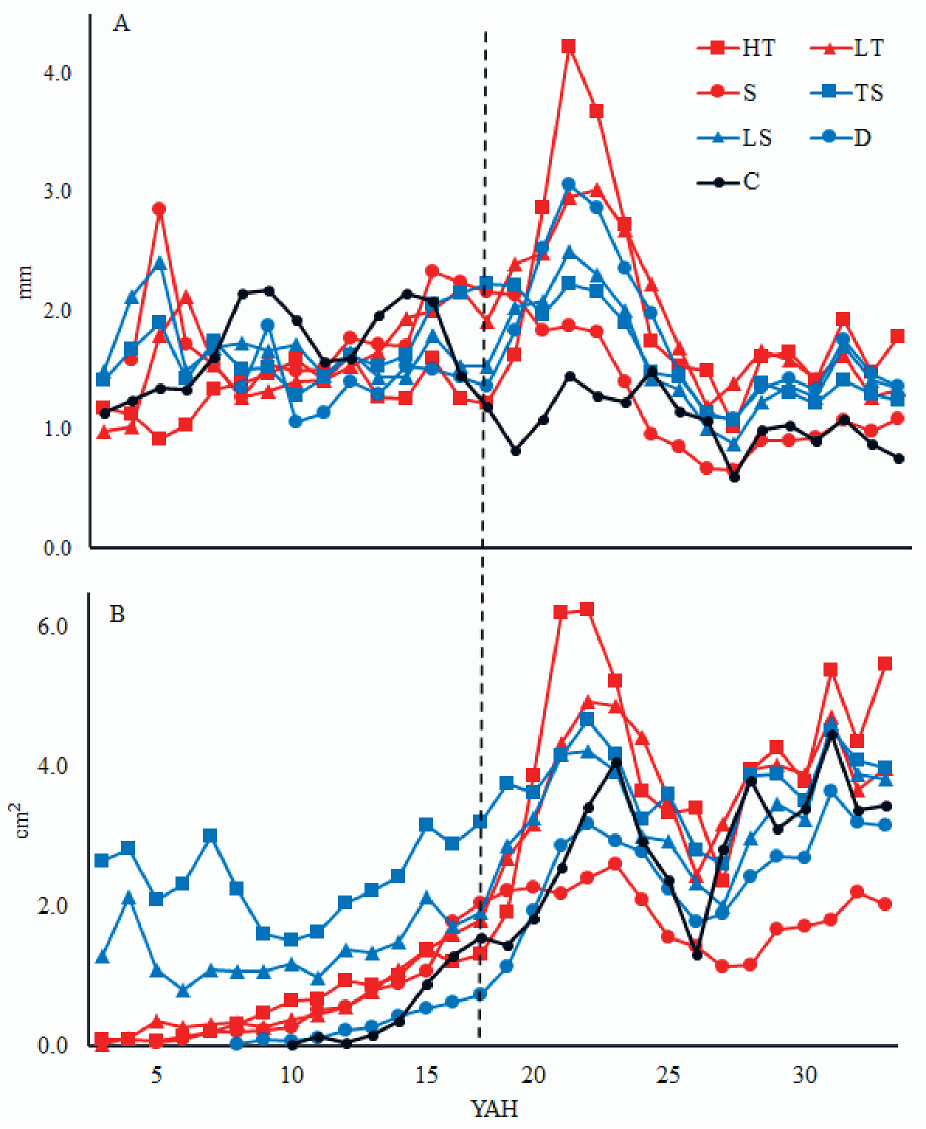

Figure 3. Mean RW (A) and BAI (B) mean series for treatments for period 3 to 33 YAH. The intervention year is marked with dashed lines (17 YAH, 1st intervention). HT = heavy thinning, LT = light thinning, S = selection, TS = transversal strips, LS = longitudinal strips, D = checkerboard, C = control.

Series medias de RW (A) y BAI (B) para los tratamientos del período 3 a 33 YAH. El año de intervención está marcado con líneas discontinuas (1984, 1ra intervención). HT = raleo fuerte, LT = raleo suave, S = selección, TF = franjas transversales, LF = franjas longitudinales, D = damero, C = control.

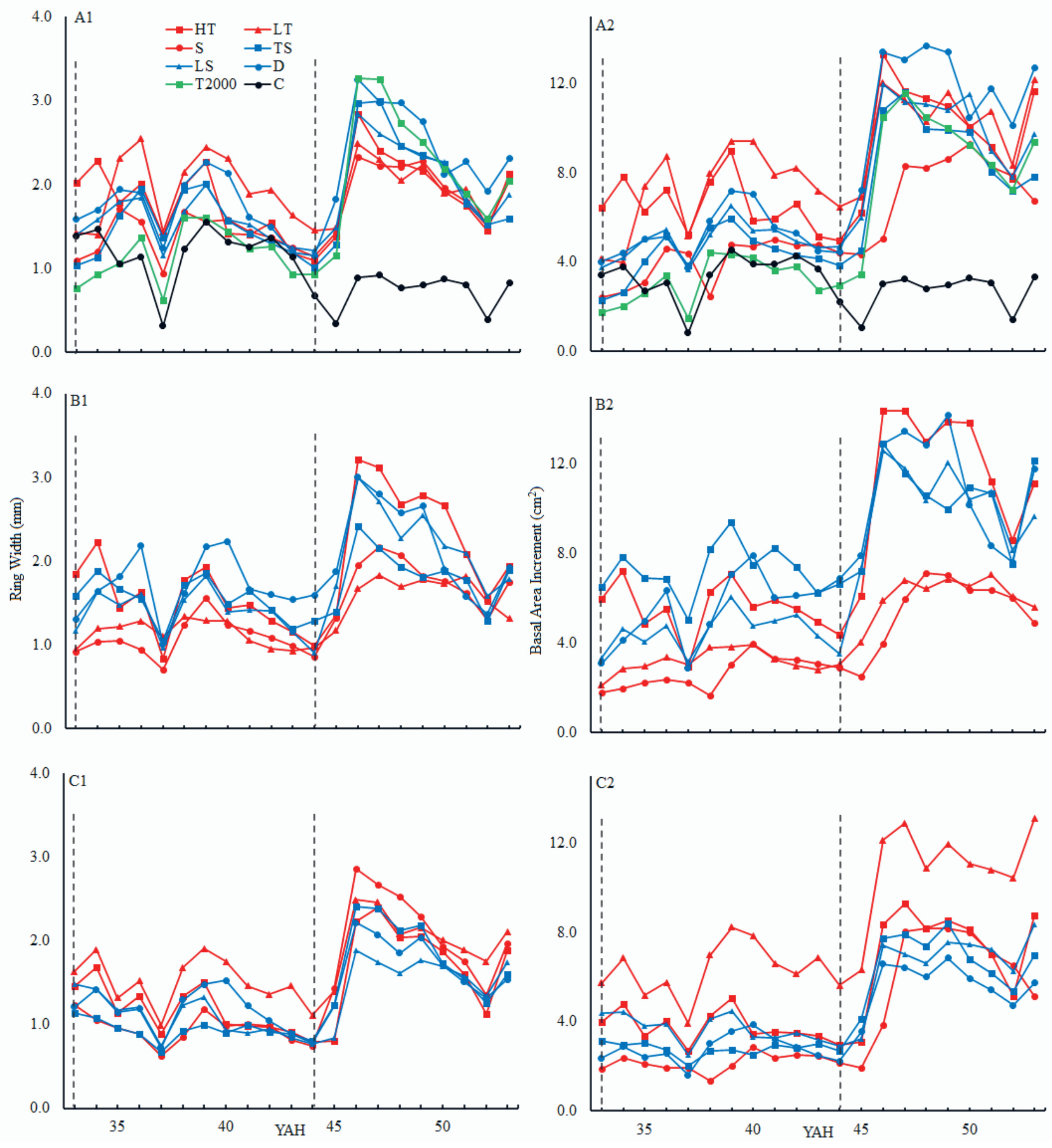

Figure 4. RW (left) and BAI (right) mean series for subtreatments for period 33 to 53 YAH, classified as heavy thinning (A1 and A2), light thinning (B1 and B2) and control (C1 and C2). Intervention years are marked with dashed lines (33 YAH, 2nd intervention; 44 YAH, 3rd intervention). HT = heavy thinning, LT = light thinning, S = selection, TF = transversal strips, LS = longitudinal strips, D = checkerboard, T2000 = selection strip by competitors, C = control.

Series medias de RW (izquierda) y BAI (derecha) para los subtratamientos para el periodo 33 a 53 YAH, clasificado en raleo fuerte (A1 y A2), raleo suave (B1 y B2) y control (C1 y C2). Los años de intervención están marcados con líneas discontinuas (1999, 2da intervención; 2010, 3ra intervención). HT = raleo fuerte, LT = raleo suave, S = selección, TF = franjas transversales, LF = franjas longitudinales, D = damero, C = control, T2000 = extracción de competidores.

riods between thinning and intensities applied, reaching a final density before shelterwood cuts. In summary, a combination similar to DHT and DLT appears to be the most convenient to apply, considering both growth rates and operability. Considering that the results of this study are from experimental plots, it is expected to be useful as a tool for real application on a larger scale, taking advantage of the abundance of secondary forest resources available in the province of Tierra del Fuego.

Finally, repeated situations in all the subtreatments were observed in 2003 (31 YAH), 2011 (45 YAH) and 2018 (52 YAH), moments in which the growth rates decreased noticeably and punctually, recovering previous growth values in the following years. This can be explained by years with adverse climatic conditions (*e.g.* low rainfall) (Franco *et al.* 2019) or mast years where photo assimilates are mostly used to synthesize reproductive organs instead of carbon fixation in growth rings (Hadad *et al.* 2021). Although it has been shown that the application of intermediate treatments generates effects on ring widths, annual variation due to climatic variations cannot be eliminated by these silvicultural practices (Spiecker 2002). Indeed, these variations must be considered to characterize the effectiveness of thinning after interventions.

CONCLUSIONS

Results show that thinning generates positive effects on the radial growth of remnant trees in secondary forests of *Nothofagus pumilio*. These interventions produce releases of remnant trees in all treatments, and the effects are quantified as compared to control sites. Indeed, the application of dendrochronological techniques makes it possible to

Table 4. Treatment (Tr), intensity of thinning represented as percentage of basal area thinned (% AB), average of ring width (mm) 5 years before thinning (X_{RW} pre), average of ring width (mm) 5 years after thinning (X_{RW} post), year of highest growth and value (Year (Max)), response time (Lag), subtreatment (Sub-T).

Tratamiento (Tr), intensidad del raleo representado como porcentaje del área basal raleado (% AB), media de anchos de los anillos (mm) 5 años antes del raleo (X_{RW} pre), media de anchos de los anillos (mm) 5 años después del raleo (X_{RW} post), año de mayor crecimiento y valor (Año (Max)), tiempo de respuesta (Lag), subtratamiento (Sub-T).

1st Thinning (17 YAH)							2nd Thinning (33 YAH)					3rd Thinning (44 YAH)				
Tr	% AB	X_{RW} pre	X_{RW} post	Year (max)	Lag	Sub-T	% AB	X_{RW} pre	X_{RW} post	Year (max)	Lag	% AB	X_{RW} pre	X_{RW} post	Year (max)	Lag
C	0	1.96	2.16	-	-	C	0	1.62	1.12	-	-	0	1.15	0.76	-	-
HT	77	1.38	2.62	3 (4.23)	13	HTC	0	1.54	1.27	-	-	35	1.03	1.78	3 (2.40)	10
						HTHT	24	1.66	1.88	1 (2.29)	6	51	1.48	2.03	2 (2.85)	9
						HTLTP	33	1.72	1.61	1 (2.23)	6	39	1.38	2.38	2 (3.21)	9
LT	44	1.80	2.49	4 (3.01)	6	LTC	0	1.83	1.58	-	-	68	1.51	2.04	2 (2.49)	9
						LTLT	34	1.08	1.24	5 (1.34)	7	61	1.08	1.61	3 (1.83)	10
						LTHT	61	1.54	2.09	3 (2.55)	9	47	1.94	1.99	2 (2.49)	9
S	44	1.92	1.55	1 (2.13)	1	SC	0	0.95	0.93	-	-	76	0.95	2.09	2 (2.86)	10
						SLT	39	0.87	1.11	6 (1.57)	9	65	1.15	1.75	3 (2.17)	10
						SHT	52	1.12	1.46	2 (1.72)	10	66	1.39	1.98	2 (2.34)	10
TS	50	1.80	1.91	3 (2.22)	5	TSC	0	1.27	0.92	-	-	52	0.91	1.83	2 (2.41)	10
						TSLT	29	1.58	1.60	1 (1.88)	6	44	1.48	1.84	2 (2.42)	7
						TSHT	48	1.08	1.66	6 (2.01)	10	48	1.41	2.13	3 (3.00)	9
LS	50	1.55	1.95	3 (2.49)	5	LSC	0	1.60	1.15	-	-	68	0.95	1.58	2 (1.89)	10
						LSLT	54	1.16	1.49	6 (1.83)	9	50	1.35	2.21	2 (3.00)	9
						LSHT	66	1.41	1.66	6 (2.00)	9	52	1.49	2.14	2 (2.85)	9
D	75	1.38	2.30	3 (3.05)	7	DC	0	1.38	1.26	-	-	63	1.16	1.72	2 (2.21)	9
						DLT	38	1.35	1.81	7 (2.23)	10	57	1.80	2.19	2 (3.00)	9
						DHT	49	1.62	1.88	6 (2.27)	7	44	1.64	2.49	2 (3.26)	9
						T2000	48	0.94	1.23	5 (1.61)	5	90	1.23	2.29	2 (3.27)	10

demonstrate the periodic impact of thinning. According to analysis of these effects, non-systematic interventions did not differ from systematic ones, so the application of the latter is considered more convenient, though it is also necessary to apply others to maintain higher growth rates than control sites. Annual growth surveys could allow for determination of opportune moments for interventions, and the values of the present work could be considered as a reference, taking into account the combined effect of the situations studied. Finally, these results can contribute to better silvicultural decision-making for sustainable forest management in secondary forests, improving the management of resources and their abundance. It is important to continue research in such a valuable sample site, as it could be a model for application in other sites and *Nothofagus* forests.

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AUTHOR CONTRIBUTIONS

Guillermo Martinez Pastur, Juan Manuel Cellini and Pablo Luis Peri conceived and designed the experiments; Guillermo Martinez Pastur, María V Lencias, Dardo Paredes, Jimena E Chavez, Fidel A Roig and Julián Rodríguez-Souilla collaborated in fieldwork and data analysis, and all the authors collaborated in writing the manuscript. All authors have read and agreed to the published version of the manuscript.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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Annex 1. Combinations: C = control, T2000 = thinning year 2000, HTC= heavy thinning - control, HTHT= heavy thinning-heavy thinning, HTLTP= heavy thinning – light thinning - pruned, LTC= light thinning - control, LTLT= light thinning - light thinning, LTHT= light thinning - heavy thinning, SC= selection - control, SLT= selection - light thinning, SHT= selection - heavy thinning, LSC= longitudinal strips - control, LSLT = longitudinal strips - light thinning, LSHT= longitudinal strips - heavy thinning, TSC= transversal strips - control, TSLT= transversal strips - light thinning, TSHT= transversal strips - heavy thinning, DC= checkerboard - control, DLT= checkerboard - light thinning, DHT= checkerboard - heavy thinning.

Combinaciones: C= control, T2000= extracción de competidores, HTC= raleo fuerte - control, HTHT= raleo fuerte – raleo fuerte, HTLTP= raleo fuerte - raleo suave - podado, LTC= raleo suave - control, LTLT= raleo suave - raleo suave, LTHT= raleo suave – raleo fuerte, SC= selección - control, SLT= selección – raleo suave, SHT= selección – raleo fuerte, LSC= fajas longitudinales - control, LSLT= fajas longitudinales – raleo suave, LSHT= fajas longitudinales – raleo fuerte, TSC= fajas transversales - control, TSLT= fajas transversales – raleo suave, TSHT= fajas transversales – raleo fuerte, DC= damero - control, DLT= damero – raleo suave, DHT= damero – raleo fuerte.

1967-1983	1984-1999	1999-2010	2010-2019
0-16 YAH	17-33 YAH	34-44 YAH	45-55 YAH
C	C	C	C
	C	T2000	T2000
	HT	HTC	HTC
		HTHT	HTHT
		HTLTP	HTLTP
	LT	LTC	LTC
		LTLT	LTLT
		LTHT	LTHT
	S	SC	SC
		SLT	SLT
		SHT	SHT
	TS	TSC	TSC
		TSLT	TSLT
		TSHT	TSHT
	LS	LSC	LSC
		LSLT	LSLT
		LSHT	LSHT
	D	DC	DC
		DLT	DLT
		DHT	DHT