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NOTE

Early response of *Nothofagus antarctica* forests to thinning intensity in northern Patagonia

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Abstract: *Nothofagus antarctica* (G. Forst.) Oerst. stands of northern Patagonia (Argentina) have great potential to provide multiple ecosystem services. Nonetheless, the lack of basic information limits the application of silvicultural treatments to this forest type. This study reports the early response to three systematic strip thinning treatments (30%, 50%, and 70%) carried out during 2013 in a 30-year-old *N. antarctica* stand, where control plots (i.e., no thinning) were also established. Subplots were located within each plot. Basal diameters (BD) of all retained stems were measured in the non-vegetative season (winter) of 2016, 2017, and 2018 to calculate basal diameter annual increment (BDI) and stand volume growth. BDI ranged from 1.9 mm·year^{-1} in the control plots to 2.7 mm·year^{-1} at 70% thinning. Relative BDI also responded positively to thinning intensity. Stand volume growth decreased non-linearly with thinning intensity from 3.36 m^3·ha^{-1}·year^{-1} in the control plots to 0.71 m^3·ha^{-1}·year^{-1} when thinning was 70%. Smaller differences were observed between control plots, 30% thinning, and 50% thinning. Our results show that *N. antarctica* forests, in the stem exclusion stage, respond to strip thinning. Thus, silviculture based on this management system could favor the development of retained trees without losing productivity if it remains under 50% intensity. This outcome represents an important incremental contribution to the design of silvicultural interventions in northern Patagonia.

Key words: silviculture, *Nothofagus antarctica*, northern Patagonia, thinning, growth.

Résumé : Les peuplements de *Nothofagus antarctica* (G. Forst.) Oerst. du nord de la Patagonie (Argentine) ont un grand potentiel pour fournir de multiples services écosystémiques. Toutefois, le manque d'information de base limite l'application de traitements sylvicoles dans ce type de forêt. Cette étude porte sur la réaction précoce à la suite de trois traitements d'éclaircie systématique par bandes (30, 50 et 70 %) réalisés en 2013 dans un peuplement de *N. antarctica* âgé de 30 ans, dans lequel des placettes témoins (c.-à-d. sans éclaircie) ont également été établies. Des sous-placettes ont été établies dans chaque placette. Le diamètre à la souche (DS) de toutes les tiges résiduelles a été mesuré pendant la saison non végétative (hiver) en 2016, 2017 et 2018 pour calculer l'accroissement annuel en DS (ADS) et la croissance en volume du peuplement. L'ADS variait de 1,9 mm·an^{-1} dans les placettes témoins à 2,7 mm·an^{-1} dans les éclaircies à 70 %. L'ADS relatif a aussi réagi positivement à l'intensité de l'éclaircie. La croissance en volume des peuplements a diminué de façon non linéaire avec l'intensité de l'éclaircie, passant de 3,36 m^3·ha^{-1}·an^{-1} dans les placettes témoins à 0,71 m^3·ha^{-1}·an^{-1} dans les éclaircies à 70 %. De plus petites différences ont été observées entre les placettes témoins et les éclaircies à 30 et 50 %. Nos résultats montrent que les forêts de *N. antarctica* au stade d'exclusion des tiges réagissent à l'éclaircie par bandes. Ainsi, la sylviculture fondée sur ce système d'aménagement pourrait favoriser le développement des arbres résiduels sans perte de productivité si l'intensité de l'éclaircie ne dépasse pas 50 %. Ce résultat représente une contribution supplémentaire importante à la conception des interventions sylvicoles dans le nord de la Patagonie. [Traduit par la Rédaction]

Mots-clés : sylviculture, *Nothofagus antarctica*, nord de la Patagonie, éclaircie, croissance.

1. Introduction

Among all South American species of *Nothofagus*, *Nothofagus antarctica* (G. Forst.) Oerst. covers the widest range of habitat types. Its latitudinal range extends from 36°30′S to 56°S in the mountainous regions of Chile and Argentina (Steinke et al. 2008). Accordingly, it has different morphotypes linked to distinctive habitat types (Premoli and Steinke 2008; Ramirez et al. 1985). For example, in areas with topographic depressions (Veblen et al. 1996), *N. antarctica* grows as a shrub type (Ramirez et al. 1985), denoting a great capacity to tolerate extreme conditions through morphological variants (Veblen et al. 1996; Steinke et al. 2008; Gargaglione et al. 2010).

In some regions and in the absence of fire and cattle disturbance, *N. antarctica* stands can be displaced by longer-lived species and obligate seed dispersers such as *Austrocedrus chilensis* (D. Don) Pic-Serm. & Bizzarri. or *Nothofagus dombeyi* (Mirb.) Oerst., forming pure forests (Kitzberger and Veblen 1999). Nonetheless, this successional dynamic is usually affected by fire, owing to fire-prone characteristics of *N. antarctica* communities (i.e., fire-adapted forests). Under high fire frequency or severity, these communities might remain in a flammable state and might be unable to mature and transition to a less flammable community dominated by tall *A. chilensis* or *N. dombeyi* trees (Tiribelli et al. 2019; Kitzberger et al. 2012).

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Fig. 1. Left panel shows Los Repollos site location. Dark grey color represents *Nothofagus antarctica* distribution along Rio Negro province, which has ~91 000 ha of this forest type (Oddi et al. 2020). The map was created using QGIS version 3.10 (QGIS Development Team 2019), and the classification of forest types and land cover in the region is from CIEFAP, MAyDS (2016). Upper right is a photo from an unmanned aerial vehicle (UAV) of one of the plots (70% thinning intensity). Lower right photo shows one of the six strips on a 70% thinning intensity plot. [Colour online.]

In northern Patagonia, Argentina, native forest management has been scarcely explored. In contrast, extensive information is available for southern Patagonia (Martínez Pastur et al. 2018 and references therein), and vast knowledge has been developed for fast-growing exotic coniferous plantations across the whole region (Grosfeld et al. 2019). Today, silvicultural practices such as thinning might be applied in *N. antarctica* stands under new use policy (Law No. 26.331, LP 4331), and could be in accordance with the current extensive livestock production in this ecosystem (Kitzberger et al. 2005). Thinning could favor provisioning ecosystem services by shortening the cutting cycles of wood and posts, thus generating an extra-economic income to foresters (Goldenberg et al. 2018). Also, it could improve silvopastoral efficiency by promoting understory grass growth. Additionally, thinning could favor fire control by reducing flammability and fire hazard, thus promoting forest conservation (Pausas et al. 2015). This is a key factor, as this forest type is the most fire-prone in the region (Kitzberger and Veblen 1999). Therefore, thinning is an important aspect of management that could address multiple objectives ranging from solely economic-based to conservation-related.

The response of the remaining trees to thinning is an important aspect of silviculture. When removing trees, resources are released and become available for the remaining crop trees. This ultimately increases their growth rate, and they consequently attain larger dimensions in shorter periods (Assmann 1970). Nonetheless, tree removal can also diminish wood volume growth at the stand level, thus forest management is usually based on minimizing this. The "thinning response hypothesis" postulates that volume growth at the stand level is independent of thinning in a range from an unthinned stand to a residual basal area of ~50% (Skovsgaard and Vanclay 2008; Langsaeter 1941). Therefore, testing the applicability of this hypothesis has implications for intensely managing this species.

Previous reports have shown that in northern Patagonia, coppice growth after cutting is low in *N. antarctica* stands under harsh environment (Goldenberg et al. 2020*a*). Moreover, few reports have evaluated the response of *N. antarctica* to thinning in the region (e.g., Sarasola et al. 2008), and none of them have considered a gradient of systematic thinning. We believe this is important, but absent, information for native forest silviculture of the region. Thus, the objective of this study is to determine the effect of increasing systematic strip thinning intensities on the growth of *N. antarctica* in northern Patagonia, at the individual tree and stand levels. Based on this, we discuss our results within the context of the thinning response hypothesis.

2. Materials and methods

2.1. Study area and experimental site

In northwestern Patagonia (Argentina), the vegetation forms temperate forests. *Nothofagus antarctica* is distributed where annual rainfall (occurring mainly during autumn and winter) ranges

Table 1. Environmental and stand characteristics.

Environmental site characteristics	
Latitude	41°46′30.7″S
Longitude	71°28′26.0″W
Elevation (m a.s.l.)	856.2
Annual mean temp. (°C)	9.4
Summer mean temp. (°C)	15.9
Winter mean temp. (°C)	2.3
Annual precipitation (mm)	950
Soil group	Udivitrants
Soil depth (cm)	90
Soil carbon (%)	6.3
Soil nitrogen (%)	0.4
Soil phosphorus (μg·g^{-1}; Olsen method)	2
Stand characteristics	
Age (years)	30
Stand density (stems·ha^{-1})	37 129 ± 500
Dominant height (m)	2.5 ± 0.1
Mean basal diameter (cm)	3 ± 1
Basal area (m^2·ha^{-1})	33.5 ± 10

Note: Mean ± standard deviation.

from 920 to 1300 mm (Reque et al. 2007). Only 11% of the rainfall occurs during summer (Jobbágy et al. 1995). Average annual temperature ranges between 8 and 9 °C, with a maximum average annual temperature of 15 °C and a minimum temperature of 1.5 °C. There are 120 frosts days per year, annual relative humidity is 65%, and annual dew temperature is 2 °C (Gyenge et al. 2009; Reque et al. 2007). The accumulation of cold air in the bottom valley and the extreme summer water deficit presents one of the most severe situations for tree development, thus *N. antarctica* usually grows as a shrub there (Veblen et al. 1996).

A 30-year-old *N. antarctica* shrubby stand under optimal growing phase (Soler 2012) close to Los Repollos (LR), Río Negro province, was chosen as the experimental site (Fig. 1). The stand is a *N. antarctica* pure shrubland with small-sized and multi-stemmed individuals (Table 1), and use history is associated to intense grazing, firewood extraction, and frequent fire occurrence. Stand density was approximately 30% of maximum Reineke's stand density index (max-SDI) when thinning, at which competition is already established (Tejera and Letourneau 2016). It is located in a bottom valley characterized by poor soil, cold winters, and intense summer drought, which implies extreme environmental conditions throughout the year.

2.2. Thinning treatments

On the experimental site, eight permanent 31.5 m × 45.0 m plots protected from livestock were established in 2013. In this same year, six plots were thinned geometrically in six strips of increasing width (1.5, 2.5, and 3.5 m along the plot (45 m)), leaving the two remaining plots unthinned (i.e., control). This resulted in a thinning intensity (i.e., basal area removal) gradient of approximately 0%, 30%, 50%, and 70% (Fig. 1). Therefore, stand density went from 30% to approximately 21%, 15%, and 9% of max-SDI, respectively. Thinning removed stems within a genet and entire genets randomly, depending on whether they were placed completely or partially in the thinning strip. The objective of this thinning design was to favor the development of retained trees through a relatively inexpensive thinning system. Additionally, leaving intervention strips could also be compatible with silvopastoral use, as grass species can establish and develop in the cleared strips.

2.3. Measurements

To measure stand growth, a circular 8 m diameter subplot was established in each plot. All retained stems were counted and marked inside the subplots. During the winter of 2016, 2017, and

Table 2. Fitted models for each of the analyzed response variables.

Response	Fitted model	AIC	ΔAIC null model
Stand density	$39\,221.16 - 474.62t$	160.5	16.67
Basal diameter increment	$1.92 + 0.011t$	781.6	8.40
Stand volume growth	$3.36 + 0.016t - 7.70 \times 10^{-4}t^2$	27.0	4.05

Note: Stand density was modeled with a binomial negative error structure (log-link) because (count) data were over-dispersed. For basal diameter increment, a gamma error distribution was assumed (identity-link) because (continue) data showed positive asymmetry. *t*, thinning intensity (% basal area removed).

2018, the basal diameters (BD, approximately 3 cm from the ground) of all the subplot stems were measured with a measuring tape and divided by two years, to calculate basal annual diameter increment (BDI). These diameters were used to estimate volume using eq. 1, which is a local equation previously developed for the study site (Gonzalez-Musso et al. 2020).

$$\text{SV} = 2.84 - 27.15\text{BD} + 74.46\text{BD}^2 \quad (1)$$

where SV is stem volume (in cm^3) and BD is basal diameter (in cm). Then, volume increase in all individual stems of each subplot where summed and extrapolated to a hectare to estimate stand volume growth (in m^3·ha^{-1}·year^{-1}).

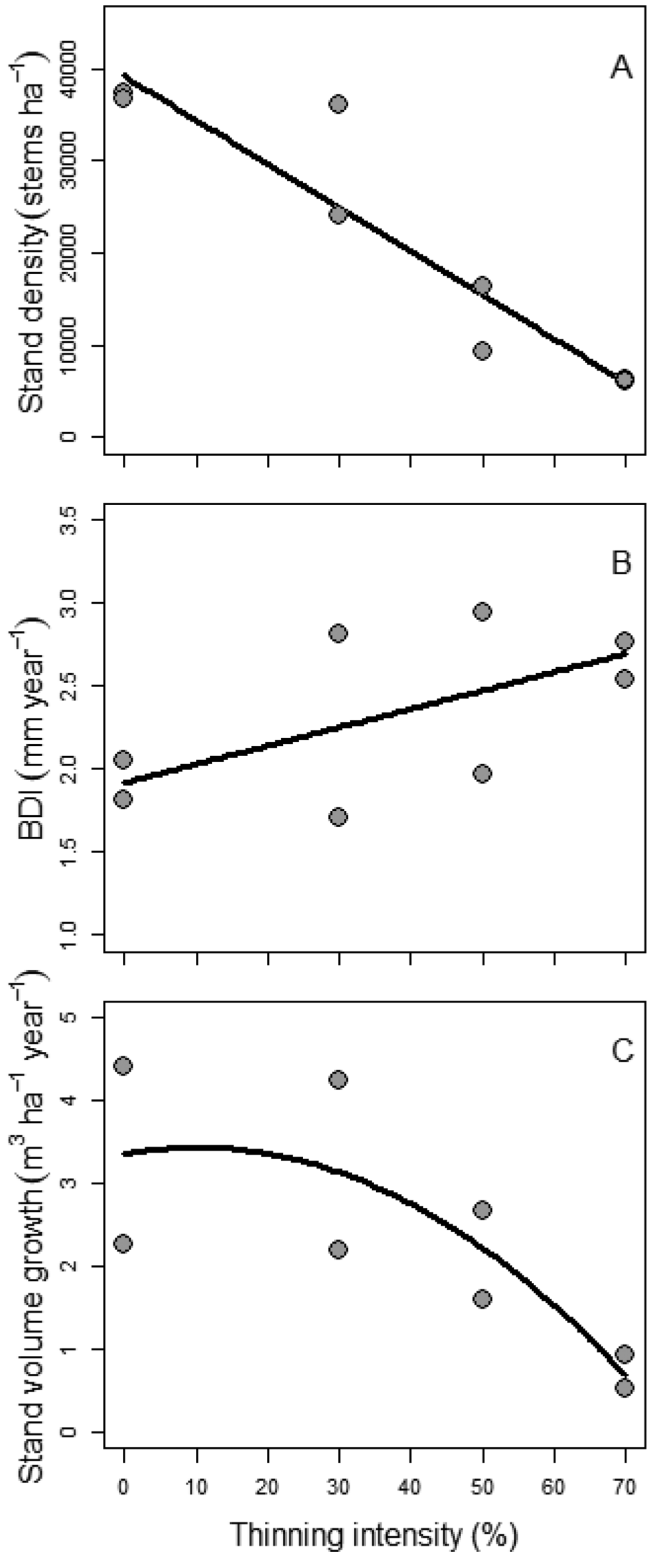
2.4. Statistical analysis

To analyze the effect of thinning on growth, general and generalized linear models were fitted. This effect was evaluated on three growth variables (i.e., response variables of the models): stand density (number of stems·ha^{-1}), BDI (mm·year^{-1}) (as the average of the 2016–2017 and 2017–2018 annual periods), and stand volume growth (m^3·ha^{-1}·year^{-1}). Because data were over-dispersed, stand density (count data) was modeled with a binomial negative error structure (log-link). A gamma error distribution was assumed for BDI (identity-link) because data showed positive asymmetry. In the case of stand volume growth, a normal distribution was used. In all models, the linear predictor included thinning intensity (the percentage of removed basal area: 0%, 30%, 50%, and 70%), and linear and squared terms were also used to account for possible non-linear responses. The AIC criteria was used to determine the importance of thinning predictors (Burnham and Anderson 2002). Model assumptions were verified by visual evaluation of residual scatter plots (residual values vs. predicted values). Additionally, to remove possible differences owing to the initial size of individuals, the relative growth of individual basal diameter (i.e., as a percentage of the initial size) was described through histograms as a function of growth period and thinning intensity. Also, histograms were used to describe absolute individual volume growth as a function of thinning intensity. All analyzes were performed in R software 3.6.3 (R Core Team 2020). Models were fitted using the *lm()* and *glm()* functions of the base package and the *glm.nb()* function of the MASS package (Venables and Ripley 2002).

3. Results

Stand density responded linearly to thinning intensity, causing an average decrease of ≈475 stems per 1% increment in thinning intensity (Table 2; Fig. 2A). Thinning intensity exhibited a linear but positive effect on individual basal diameter growth from 1.9 mm·year^{-1} in the control plots (30% of max-SDI) to 2.7 mm·year^{-1} at the maximum thinning intensity (70%, 9% of max-SDI) (Fig. 2B). In other words, when 70% thinning was applied, stems grew 42% more than in unthinned plots. In addition, the response to thinning intensity was similar when growth was assessed as a function of initial size, but higher during the second period (Fig. 3). Volumetric growth at the stand level in the control plots was ≈4.7-fold than in the 70% thinning plots (3.36 m^3·ha^{-1}·year^{-1} vs. 0.71 m^3·ha^{-1}·year^{-1}), but similar to plots under 30% (21% of max-SDI)

Fig. 2. Effect of systematic strip thinning intensity on (A) stand density, (B) basal diameter increment, and (C) total stand (over bark) volume growth. The points indicate the mean values per plot, and curves are the predicted values from general and generalized linear models.



and 50% (15% of max-SDI) of removal. Thus, productivity decreased non-linearly with thinning intensity (Fig. 2C; Table 2).

4. Discussion

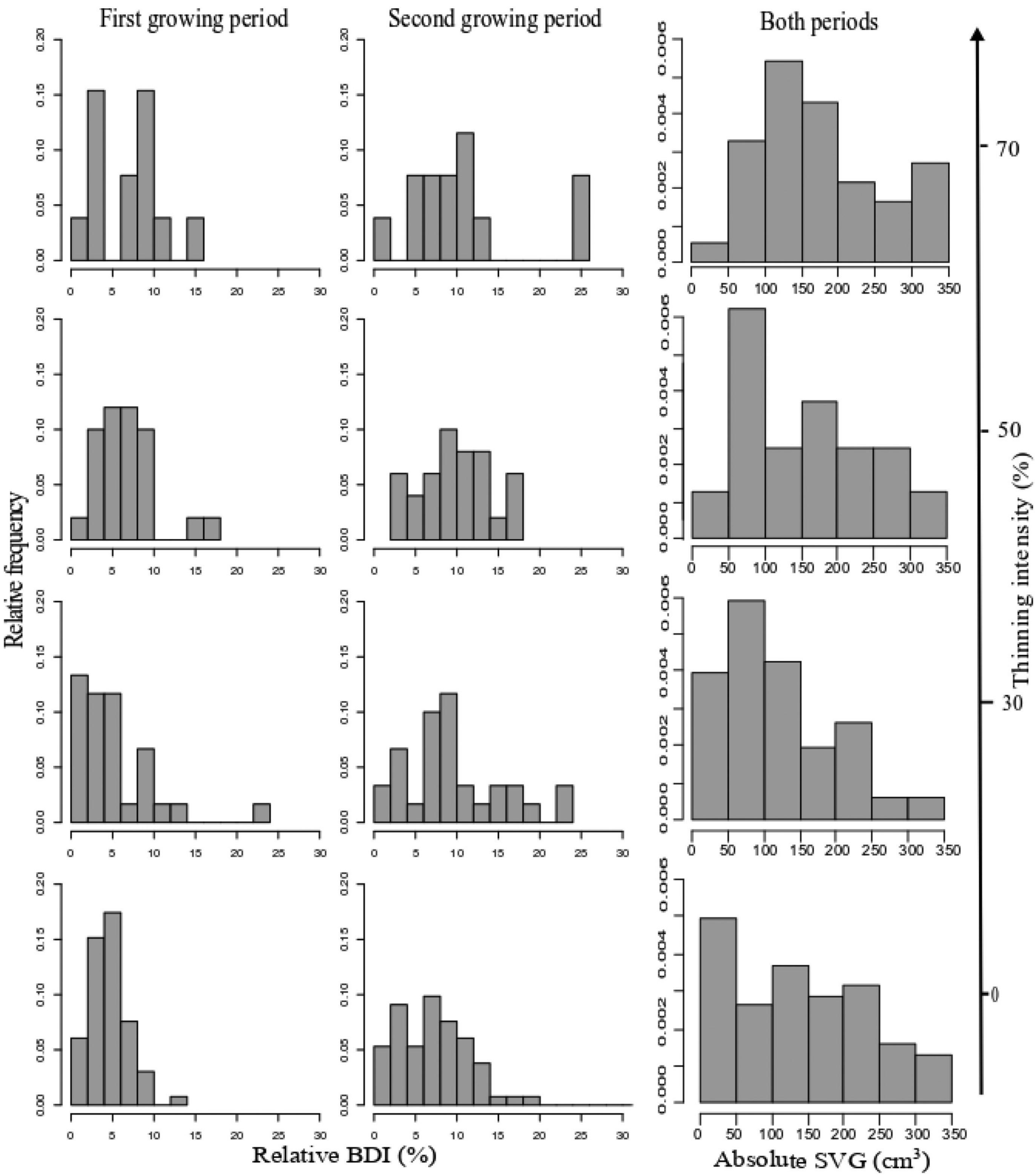
Our results agree with those reported by Sarasola et al. (2008), who found a high response to thinning in *N. antarctica*, and who estimated an approximate 200% increase in radial growth after strong thinning treatments compared with the pre-thinning situation. In that study, the authors assessed 65- to 90-year-old stands at the El Foyel basin, near our study site, and found that typically the number of stems was 86.2% lower in stands that had been thinned. However, unlike Sarasola et al. (2008), strip thinning had increasing widths, which were designed geometrically. This allowed us to analyze changes across a thinning gradient. Gyenge et al. (2011) discussed that thinning has a major effect on water availability of remnant trees, which might be important on sites similar to our study site, due to summer water deficit.

In a high-quality site of southern Patagonia, Peri et al. (2016) analyzed unthinned stands and stands with two thinning intensities: 53% (low) and 65% (high) removal from the basal area. When analyzing the annual diametric growth at breast height, they found a 78.9% increase in the low thinning intensity and 110.5% increase in the high thinning intensity when compared with the control plots, in which breast diameter increment was around 1.9 mm·year^{-1}. At the basal height, our fitted model predicted a 30% and 37.2% increase in the low and high thinning intensity, respectively, when compared with control plots, where basal diameter increment was around 1.9 mm·year^{-1}. Thus, we found lower stem growth and lower responses to thinning intensity. This could be expected, as we worked in a low-quality site and performed a completely systematic thinning, in which more dominant trees were removed. Further, the available resources for tree growth were unevenly distributed among the remaining trees (Mäkinen et al. 2006). Also, thinning strips randomly removed entire genets and stems within a genet, for which greater variability is expected in this thinning system. This is due to different mechanisms favoring the growth of the retained stems, such as diminishing competition within a genet (e.g., more starch for retained sprouts) and between genets that compete for the same resources (Quevedo et al. 2013).

At the stand level, Peri et al. (2016) also found that the average volumetric growth of the unthinned stand was 4.86 m^3·ha^{-1}·year^{-1}, and a 19.3% reduction of stand growth in low thinning stands (53%), and a 20.4% reduction when it went from low to high thinning intensity (65%). This confirms that southern Patagonian *N. antarctica* stands have higher growth rates, but the same type of response (i.e., non-linear) to thinning intensity. In other words, responses to thinning seem to be similar in *N. antarctica* forests, even considering forests with different physiognomy (trees of greater size and lower stems density), as those studied by Peri et al. (2016). In this study, our model predicts a 39.1% decreased in stand growth at low thinning intensity and a 43.8% decrease when thinning intensity increases from low to high. This major decrease in stand growth is likely because the thinning effect on stand density is less compensated by the response of stem growth to thinning. Therefore, *N. antarctica* growing in high-quality sites could tolerate higher thinning intensities without compromising stand productivity compared to low-quality sites. Nonetheless, future studies should carry out other thinning systems in *N. antarctica* stands of northern Patagonia. For example, these could include selective thinning from below or removing entire genets in higher competition situations to evaluate whether higher responses are feasible in other thinning systems, and under higher levels of stand competition.

Thinning is performed to increase growth rate at the tree level, although it could be reduced at the stand level, as few trees are maintained (Assmann 1970). We found that an intermediate thinning intensity (~50% and 15% of max-SDI) increases individual

Fig. 3. Annual relative basal diameter increment (BDI) of *Nothofagus antarctica* stems for two growing periods and absolute stems volume growth (SVG) during both periods in plots with different thinning intensities.



growth compared with the controls, and does not considerably affect stand productivity (Fig. 2C). Thus, our results support the thinning response hypothesis (Skovsgaard and Vanclay 2008; Langsaeter 1941) and constitute the first empirical demonstration of this hypothesis in northern Patagonia temperate forests of Argentina. Although it is necessary to bring ones attention to the limitations of this preliminary assessment (8 plots in a single stand of relative low-competition situation (30% of max-SDI) and short-term response), our results indicate that keeping strip thinning levels under 50% or 15% of max-SDI would allow the acceleration of harvesting cycles, reaching more valuable firewood and poles in a shorter period. Further, a ~50% thinning would allow the maintaining of productivity and ecosystem integrity (Peri et al. 2016).

Peri et al. (2009) found that 50% thinning in *N. antarctica* forests favors grass productivity in sites with limiting conditions (extreme summer drought), such as our study site. Thus, a 50% thinning intensity would be compatible with silvopastoral systems, through favoring grass development in the intervention strips and maintaining growth rates of the retained tree component. In addition, fuel load and continuity (and thus flammability at the community level) is reduced by removing trees (Goldenberg et al. 2020*b*). As *N. antarctica* forests are among the most fire-prone woody communities in Patagonia (Tiribelli et al. 2018), this strategy could reduce fire occurrence and magnitude in northern Patagonian forests. Moreover, another study carried out in our study site reported that while local plant abundance and richness may diminish with thinning intensities, pollinator abundance and richness are enhanced after the intervention (Coulin et al. 2019). Additionally, in similar systems, intermediate forest intensities (30% and 50%) can maximize herbivore diversity and tree sapling survival rate (Nacif et al. 2020). Therefore, intermediate thinning intensities could be suitable for biodiversity conservation, fire prevention, and silvopastoral systems, thus advancing sustainable forest management practices for this species.

5. Conclusions

This is the first study that quantifies stand growth under a strip thinning gradient in *N. antarctica* forests of harsh northwestern Patagonia environments. In this area, silvicultural interventions are infrequent, despite new forestry legislation demands of sustainable management plans. We found that *N. antarctica* forests growing in limiting conditions responded favorably to thinning, with response patterns consistent with the thinning response hypothesis. Potentially, according to our results, thinning in other sites and stands similar to those described in this study could be carried out under a 50% thinning intensity without losing productivity. This thinning level would favor the development of future trees, contribute to maintaining stand productivity, increase biodiversity, and possibly enhance grass productivity for livestock production.

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