Forest Systems
27 (1), e01S, 10 pages (2018)
eISSN: 2171-9845
https://doi.org/10.5424/fs/2018271-11928
Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria O. A., M. P. (INIA)

RESEARCH ARTICLE

OPEN ACCESS

Long-term monitoring of thinning for silvopastoral purposes in *Nothofagus antarctica* forests of Tierra del Fuego, Argentina

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Abstract

Aim of the study: To analyse the effectiveness of thinning on tree growth, forest structure and microclimatic variables along seven years after cuttings in a secondary *Nothofagus antarctica* forest in Southern Patagonia.

Area of study: Five hectares of homogeneous stand of secondary forests (54º15'46" SL, 66º59'41" WL) in Tierra del Fuego, Argentina.

Material and methods: One control and two thinning levels were established, and forest structure, growth, crown dynamic and microclimate variables in long-term permanent plots were evaluated. Main comparisons were made using multiple ANOVAs.

Main results: Intensive thinning in secondary forests allowed to increase tree individual growth rates by doubling the radiation levels at the understory level that enhances the silvopastoral management. These forests showed a desirable resilience to the forest interventions and natural disturbances (*e.g.* heavy defoliator attack), with a rapid reaction in the canopy cover growth.

Research highlights: Monitoring of thinning for silvopastoral management must include easy and cheap measuring variables, *e.g.* diameter growth as a proxy for timber production objectives and hemispherical photos (crown cover and radiation) as a proxy for pasture production. Long-term monitoring allowed to identify reliable indicators that assist new sustainable management alternatives.

Additional keywords: crown cover; leaf area index; radiation; insect plague; growth; forest structure.

Abbreviations used: BA (basal area); C (control); CC (crown cover); DBH (diameter at breast height); DIF (diffuse radiation); DIR (direct radiation); HT (heavy thinning); LT (light thinning); RLAI (relative leaf area index); SI_{50} (site index with a base age of 50 years); TD (tree density); TOBV (total over bark volume); TR (total radiation).

Authors´ contributions: Conception and design of the plots: GMP and PLP. Acquisition, analysis and interpretation of data: GMP, RS, JMC. Statistical analysis: MVL. All authors wrote and approved the final manuscript.

Citation: Martínez Pastur, G.; Soler, R.; Lencinas, M. V.; Cellini, J. M.; Peri, P. L. (2018). Long-term monitoring of thinning for silvopastoral purposes in *Nothofagus antarctica* forests of Tierra del Fuego, Argentina. Forest Systems, Volume 27, Issue 1, e01S. https://doi.org/10.5424/fs/2018271-11928

Received: 21 Jun 2017. **Accepted:** 09 Apr 2018.

Funding: INTA Argentina (PNFOR-1104082); CONICET Argentina (P-UE 2016).

Competing interests: The authors have declared that no competing interests exist.

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Introduction

Nothofagus antarctica (G. Forster) Oerst. (commonly named ´ñire´) is one of the main deciduous native tree species in Tierra del Fuego. It covers more than 200,000 ha (Soler, 2012; Martínez Pastur *et al.*, 2013), and naturally occur in different environments near drier northern areas close to the ecotone with the Fuegian steppe. These forests are mainly used for sheep and cattle production (Peri *et al.*, 2016a). In this context, silvopastoral systems have become an economical, ecological and productive alternative for these forests (Martínez Pastur *et al.*, 2012). These systems combine trees and natural grasslands or pastures under grazing in the same unit of land, and provide a diversification of farm income, either directly from the sale of timber and animals and/or indirectly by the provision of stock shelter and beneficial effects due to its potential on ecosystem service provisioning (Peri *et al.*, 2016b).

For silvopastoral systems in secondary forest stands, planned thinning may reduce the time required to yield products of a desired quality, concentrate growth on selected trees, increase wood production by utilizing trees that would die due competition (self-thinning) and also improve the understorey biomass production (and consequently increase animal production) by increasing incoming radiation. In Tierra del Fuego (dominant tree height >8 m, and rainfall >350 mm/yr) intensive thinning were proposed, leaving a 30-40% of canopy cover (Peri *et al.*, 2016a, 2016b). This remaining crown cover provides protection from desiccating strong winds, improving the microclimatic conditions for understorey plants growth and tree regeneration. However, the thinning not only provides synergies with other forest components, but also produce greater trade-offs with other ecosystem services (Gyenge *et al.*, 2011; Martínez Pastur *et al.*, 2017; Peri *et al.*, 2017) and biodiversity components (Lencinas *et al.*, 2008, 2015; Quinteros *et al.*, 2010; Peri *et al.*, 2016a). These changes are poorly studied in the long-term, and can be influenced by changes in the climate conditions (Kreps *et al.*, 2012) or biological threats (*e.g.* attacks of defoliators) (Paritsis & Veblen, 2010; Piper *et al.*, 2015).

To date, there is enough information to support most of the silvopastoral proposals, including forest component, natural cycles, regeneration, understorey and biodiversity (Lencinas *et al.*, 2008, 2015; Quinteros *et al.*, 2010; Gyenge *et al.*, 2011; Ivancich *et al.*, 2011, 2014; Soler, 2012; Soler *et al.*, 2013; Bahamonde *et al.*, 2013, 2015; Martínez Pastur *et al.*, 2013; Gargaglione *et al.*, 2014; Echevarría *et al.*, 2014; Gönc *et al.*, 2015; Peri *et al.*, 2016a,b, 2017). However long-term results along the forest cycle, and its resilience deserve special attention. These long-term data can allowed to design new management alternatives (Martínez Pastur *et al.*, 2016; Peri *et al.*, 2016c). In this sense, long-term plots are essential to determine the economic feasibility of the intermediate treatments, define baselines and impacts of different silvicultural treatments and provide monitoring methodologies (Peri *et al.*, 2016b). For this, the objective of the present work was to analyse the effectiveness of the different levels of thinning on tree growth, remnant forest structure and microclimatic variables along seven years after the cuttings in a secondary *Nothofagus antarctica* forests in Tierra del Fuego, Argentina.

Material and methods

Study site and long-term plots

The study was carried out in San Pablo Ranch located in Tierra del Fuego province (Argentina). Almost half of the ranch area is covered by native *N. antarctica* forests with different degree of previous human impacts, *e.g.* clear-cuts of old-growth stands which derived in secondary young forests. The rancher manages the forests following silvopastoral system proposals (*e.g.* see Martínez Pastur *et al.*, 2013; Peri *et al.*, 2016a,b) that includes thinning to promote understory development (*e.g.* pastures and native forage species). In the framework of PEBANPA network (Peri *et al.*, 2016c), an experimental assay was established in early winter of 2009 in a 5-ha homogeneous stand of secondary forests (54º15’46” SL, 66º59’41” WL). This area was divided into four contiguous areas, two of them were left as control treatments (C) (1.0 ha each) and the other two were thinned at two intensities: one heavy thinning (HT) with a remnant basal area (BA) of 12 m²/ha (1.5 ha) and one light thinning (LT) where the remnant BA was 18 m²/ha (1.5 ha). The stand belongs to a middle site quality (mean dominant height of 10.1 m and 48 years old) with a SI_{50} (site index with a base age of 50 years) of 10-12 m (Ivancich *et al.*, 2011).

Forest structure monitoring

Forest structure were monitored in 15 permanent plots (5 per treatment) located in the control and thinned stands (n = 5 per treatment) with different area according the final tree density: 154 m² in C, 314 m² in LT and 452 m² in HT. Prior to the cuts the original structure (base line) was measured (winter 2009) including diameter at breast height (DBH) of all trees, health characterization and crown classes. After the cuts, the remnant trees were identified with number tags and snails, and survival and DBH were measured annually at the end of each season (2010-2016). After cutting total over bark volume (TOBV) was measured in 48 trees belonging to different diameter (4 to 35 cm) and crown classes (suppressed to dominant): diameter every 1 m from the base to the top, including branches up to 1 cm. Smalian formula was used to integrate the volume of each tree. Non-linear regression technique was used to obtain the TOBV equation (r^2 = 0.838, average error of estimation = 0.0027 m^3, and average absolute error = 0.0164 m^3).

$$\text{TOBV (m}^3\text{)} = 0.000113621 \times \text{DBH}^{2.43623} \text{ (cm)}$$

Crown cover and microclimate monitoring

The centre of each permanent plot was marked with an iron stick, and there hemispherical photographs of forest canopy were taken at 1 m above the ground level with an 8 mm fish-eye lens (Sigma, Japan) mounted on a 35 mm full-frame digital camera (Nikon, Japan) with a tripod levelling head. Each photograph was orientated with the upper edge towards the magnetic north. Photographs were taken when there was no direct sunshine (Roxburgh & Kelly, 1995). Gap Light Analyzer software v.2.0 (Frazer *et al.*, 2001) was used to calculate: (i) crown cover (CC), (ii) relative leaf area index (RLAI) defined as the effective amount of leaf surface area per unit ground area integrated over the zenith angles 0° to 60° (Stenberg *et al.*, 1994), and (iii) total radiation (TR) at the understory level as the amount of direct (DIR) and diffuse (DIF) radiation transmitted through the canopy along the growing season (October to March), expressed as the percentage of the radiation received above the forest canopy. The parameters employed for the modelling were described by Martínez Pastur *et al.* (2011). Photographs were taken in summer (end January) during the maximum expansion of the tree leaves (2010-2016). Finally, nine data loggers (3 per treatment) were located at 1 m above the ground level for 7 months during the first year to assess the effect of the thinning on: air temperature (°C), air humidity (%) and soil temperature (°C) at 30 cm depth.

Statistical analyses

Multiple ANOVAs were conducted to compare tree growth variables, analysing growth in diameter at breast height (G-DBH), growth in basal area (G-BA), growth in total over bark volume (G-TOBV) and ratio of G-TOBV and G-BA (G-ratio) using thinning treatments (C, LT, HT) and seasons (09/10 to 15/16) as main factors. Data were log-transformed when normality assumption was not achieved. Tukey test was applied to separate the means at a significance level of $p < 0.05$. Beside this, Kruskal-Wallis were conducted to compare forest structure, crown cover dynamic and microclimate variables, analysing (i) tree density (TD), DBH, BA and TOBV of the original structure using thinning treatments (C, LT, HT) and years (2009-2016) as comparison factors; and (ii) CC, RLAI, DIF, DIR, and TR, using thinning treatments (C, LT, HT) and years (2010-2016) as comparison factors. Box-and-whisker plot analyses was used to separate the means. For all the test, we used Statgraphics Centurion XVI software (Statpoint Technologies, USA).

Results

Original forest structure belongs to a typical secondary forests with 71-82% BA of dominant and co-dominant trees, with different degrees of health (28% BA of healthy trees, 51% BA of trees with minor damages and 21% BA of unhealthy trees). Trees were mostly affected by fungi and *Misodendrum* sp. attack. The measured forest parameters did not present significant differences (data not shown) prior thinning among the areas selected for each treatment: TD=2183-2793 trees/ha, DBH=12.4-14.3 cm, BA=34.0-38.7 m²/ha, and TOBV=163.0-190.5 m^3/ha. After thinning, these variables presented significant differences over time due to the growth of remnant trees (Fig. 1). TD, BA and TOBV were significantly reduced from C > LT > HT, while DBH increased from C < LT < HT, and only DBH presented differences among the years. LT reduced in 75% TD, but only reduced 45% BA and 36% TOBV, while HT reduced in 87% TD, and 63% BA and 56% TOBV. Beside this, average DBH of the thinned stand increased 48% in LT and 73% in HT.

These changes in the forest structure influenced tree growth at individual and the stand levels (Table 1). An increase in the G-DBH (33% and 71% compared to C in LT and HT, respectively), and a decrease in G-BA and G-TOBV were observed in the control compared with thinned treatments (-12% and -8% for LT, and -38% and -32% for HT for G-BA and G-TOVB compared to C, respectively) (Fig. 2). The ratio between G-TOBV and G-BA greatly increased in thinned treatments compared with the control (70% in LT and 90% in HT). There was a great variation in growth over time, where the highest values occurred in the second year after thinning, and decreased in the following years to date. These growth rates influenced the class diameter distribution of the managed stands compared to the control (Fig. 3) where the individual size increased with the thinning intensity. Beside this, the recorded heavy attack of one defoliator, *Ormiscodes amphimone* (Fabricius), during the growing season of 2012-2013 greatly impacted on tree growth by decreasing the main studied variables (-18% G-DBH, -44% G-BA, -34% GTOBV, and -39% for G-ratio compared with the average of previous and following seasons). The impact of the defoliation mainly impacted HT (Fig. 1). However, other variables recovered the expected values in the following growing seasons.

After thinning, the crown cover and radiation presented significant differences due to the changes in the forest structure and tree growth (Figs. 4 and 5). CC and RLAI were significantly reduced from C > LT > HT, while radiation (DIR, DIF and TR) increased C < LT < HT (Fig. 4). LT reduced in 11% CC and 25% RLAI, increasing near 40% the radiation values. On the other hand, HT reduced in 27% CC and 57% RLAI, increasing more than 100% the radiation values inside the forests. Along the years, crown development increased the canopy cover and the RLAI, decreasing 25% of the radiation levels measured just after the thinning. These variables also were impacted by the attack of the defoliator obtaining -8% CC, -15% RLAI, and 12-19% radiation levels compared with the average of previous and following years (Fig. 6). The crown dynamic and radiation recovered the expected values in the following growing seasons as well as the growth variables.

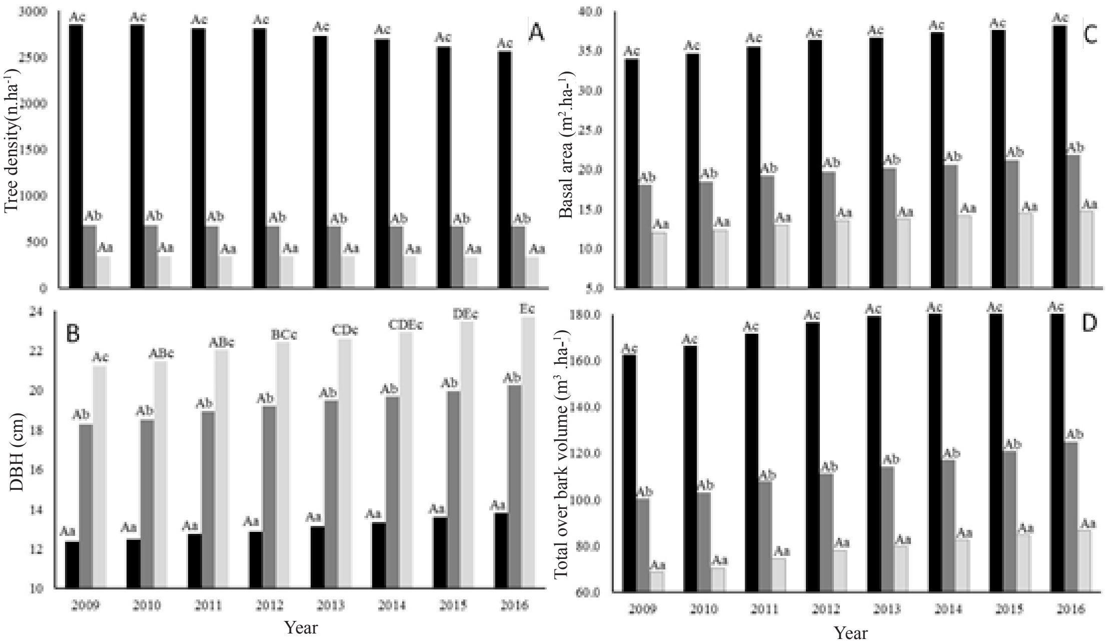

Figure 1. Kruskal-Wallis comparisons considering treatments (C: control, LT: light thinning, HT: heavy thinning) and years (2009 to 2016) as factors, and tree density (TD), diameter at breast height (DBH), basal area (BA) and total over bark volume (TOBV) as variables. Different letters indicate differences by box-and-whisker plot analyses. Capital letters indicates differences among years for each treatment, and lowercase letters indicates differences among treatments for each year.[1]

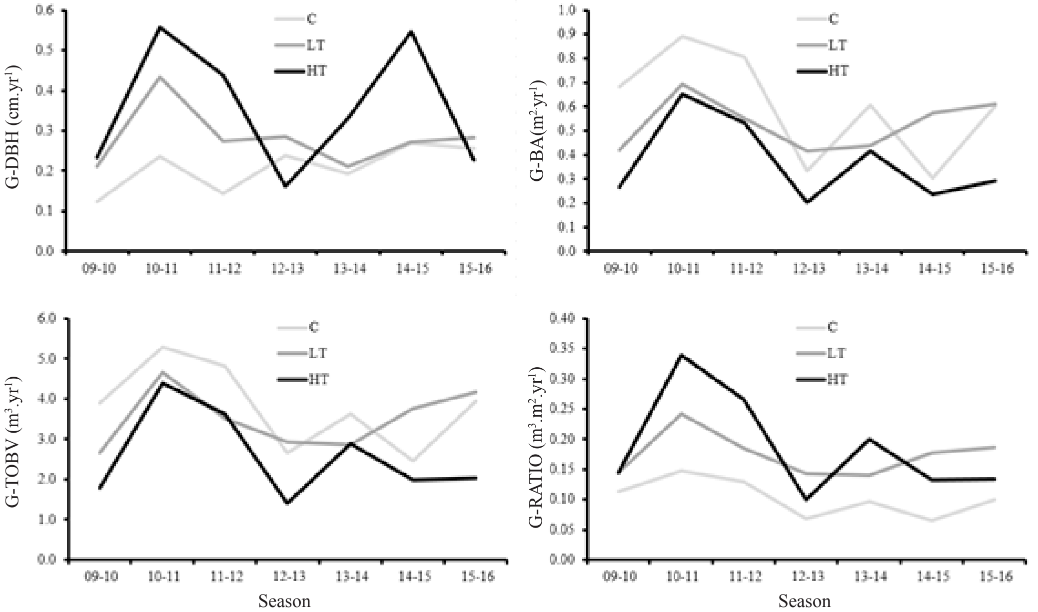

Figure 2. Growth in diameter at breast height (G-DBH), growth in basal area (G-BA), growth in total over bark volume (G-TOBV) and ratio of G-TOBV and G-BA (G-ratio) along the growth seasons (2009/2010-2015/2016) and treatments (C: control, LT: light thinning, HT: heavy thinning).

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[1] Statistics and p-values among years: C × TD = 2.99 (0.885), C × DBH = 6.24 (0.511), C × BA = 4.77 (0.687), C × TOVB = 4.78 (0.686); LT × TD = 0.54 (0.999), LT × DBH = 6.72 (0.457), LT × BA = 6.38 (0.496), LT × TOVB = 4.83 (0.680); HT × TD = 0.33 (0.999), HT × DBH = 14.53 (0.040), HT × BA = 11.71 (0.110), HT × TOVB = 13.38 (0.060). Statistics and *p*-values among treatments: 2009 × TD = 12.56 (0.002), 2010 × TD = 12.56 (0.002), 2011 × TD = 12.54 (0.002), 2012 × TD = 12.54 (0.002); 2013 × TD = 12.52 (0.002), 2014 × TD = 12.52 (0.002), 2015 × TD = 12.50 (0.002), 2016 × TD = 12.50 (0.002); 2009 × DBH = 12.02 (0.002), 2010 × DBH = 12.02 (0.002), 2011 × DBH = 11.58 (0.002), 2012 × DBH = 12.02 (0.002); 2013 × DBH = 12.02 (0.002), 2014 × DBH = 12.02 (0.002), 2015 × DBH = 12.02 (0.002), 2016 × DBH = 12.02 (0.002); 2009 × BA = 12.50 (0.002), 2010 × BA = 12.50 (0.002), 2011 × BA = 12.50 (0.002), 2012 × BA = 12.50 (0.002); 2013 × BA = 12.02 (0.002), 2014 × BA = 12.02 (0.002), 2015 × BA = 12.02 (0.002), 2016 × BA = 12.02 (0.002); 2009 × TOBV = 9.26 (0.009), 2010 × TOBV = 9.68 (0.007), 2011 × TOBV = 8.82 (0.014), 2012 × TOBV = 8.82 (0.014); 2013 × TOBV = 8.82 (0.014), 2014 × TOBV = 8.42 (0.015), 2015 × TOBV = 8.42 (0.015), 2016 × TOBV = 8.42 (0.015).

Table 1. Multiple ANOVAs considering treatments (C: control, LT: light thinning, HT: heavy thinning) and seasons as main factors, and growth in diameter at breast height (G-DBH), growth in basal area (G-BA), growth in total over bark volume (G-TOBV) and ratio of G-TOBV and G-BA (G-ratio) as variables.

Factor		G-DBH* (cm/yr)	G-BA (m^2/ha·yr)	G-TOBV (m^3/ha·yr)	G-ratio (m^3/m^2)
A: Treatment	C	0.21 a	0.60 b	3.80 b	0.10 a
	LT	0.28 b	0.53 b	3.51 b	0.17 b
	HT	0.36 b	0.37 a	2.58 a	0.19 b
	F *(p)*	*21.2* *(<0.001)*	*7.1* *(0.001)*	*6.7* *(0.002)*	*25.4* *(<0.001)*
B: Years	09-10	0.19 a	0.46 abc	2.77 ab	0.13 a
	10-11	0.41 c	0.75 c	4.77 c	0.24 c
	11-12	0.29 ab	0.62 bc	3.98 bc	0.19 bc
	12-13	0.22 a	0.31 a	2.33 a	0.10 a
	13-14	0.25 ab	0.49 abc	3.12 ab	0.14 ab
	14-15	0.36 bc	0.37 ab	2.74 ab	0.12 a
	15-16	0.26 ab	0.50 abc	3.37 abc	0.14 ab
	F *(p)*	*8.7* *(<0.001)*	*4.7* *(<0.001)*	*4.9* *(<0.001)*	*11.7* *(<0.001)*
A × B	*F* *(p)*	*5.0* *(<0.001)*	*0.9* *(0.589)*	*0.8* *(0.636)*	*2.6* *(0.006)*

F(p): Fisher test and probability. Different letters indicate differences by Tukey test ($p = 0.05$). * = Log transformed, but untransformed means are presented in the table.

These changes in the forest structure and the crown variables influenced on other micro-climatic variables (Fig. 7). Air temperature was the less influenced, however, it was observed that C treatment mitigate the extreme values during summer (low average values) and winter (high average values). Soil temperature and air humidity did not greatly changed between the C and LT treatments, while HT presented differences of -2°C and 15% compared with C, respectively.

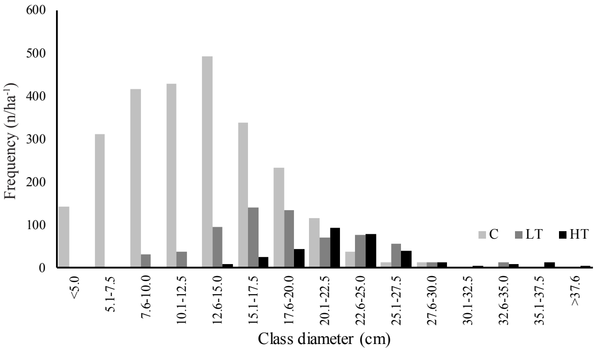

Figure 3. Class diameter distribution for the different treatments (C: control, LT: light thinning, HT: heavy thinning) after 6 years after the thinnings (year 2016).

Discussion

Nothofagus antarctica forests are characterised by a lower timber values in Tierra del Fuego forests due to over-mature forest structures growing in low site quality (Ivancich *et al.*, 2011, 2014; Peri *et al.*, 2016b), but greatest amount of understory biomass due to lower canopy closeness is produced (Lencinas *et al.*, 2008; Soler, 2012). These characteristics determine that these forests were mainly used for sheep and cattle breeding. However, human activities during the last 100 years greatly changed the forest structure of many over-mature stands. Clear-cuts and human fires convert large areas in over-stocked secondary forests with low amount of understory biomass (Soler, 2012; Soler *et al.*, 2013). These forest structures must be managed to recover the desired characteristics for silvopastoral management that appears as the most attractive economical alternative through thinning practices/intervention (Peri *et al.*, 2016a).

Thinning objectives varied with the silvicultural management defined for each forest type, *e.g.* in southern Patagonia thinning had been applied in *N. pumilio* and *N. betuloides* to increase specifically the quantity and quality of timber-wood (Martínez Pastur *et al.*, 2001, 2002; Peri

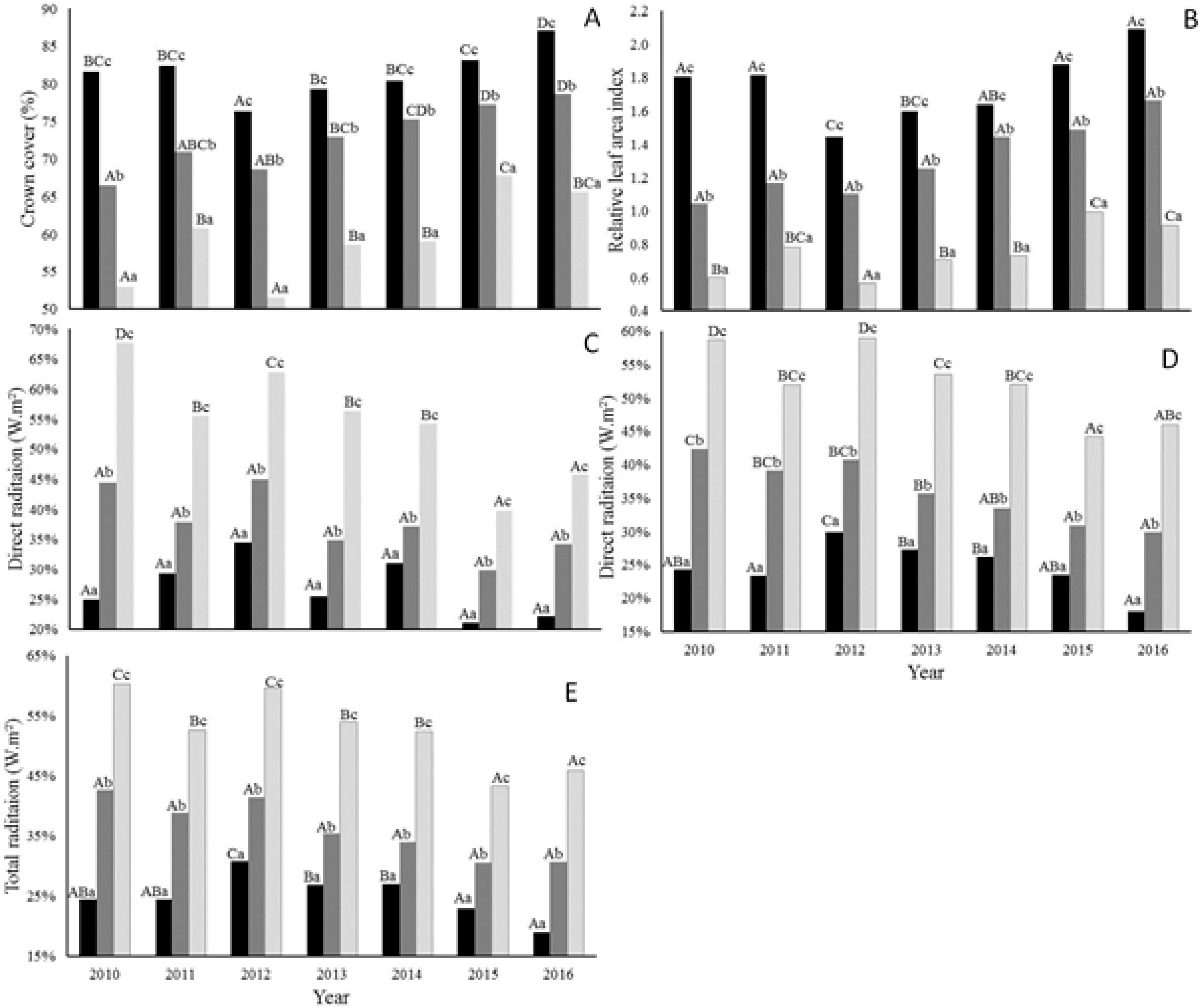

Figure 4. Kruskal-Wallis comparisons considering treatments (C: control, LT: light thinning, HT: heavy thinning) and years (2009 to 2016) as factors, and crown cover (CC), relative leaf area index (RLAI), transmitted direct radiation (DIR), transmitted diffuse radiation (DIF) and transmitted total radiation (TR) as variables.[2]

et al., 2002, 2013). However, thinning for silvopastoral management must consider multiple objectives, *e.g.* in *N. antarctica* forests the interventions try to improve both the quality and quantity of timber, and at the same time enhance pastures biomass by increasing the radiation levels (Martínez Pastur *et al.*, 2013; Peri *et al.*, 2016a,b).

The proposed thinning levels for the studied secondary forests can be considered very intensive (75-87% tree removal) compared with other thinning proposals in the region (Martínez Pastur *et al.*, 2001, 2002; Peri *et al.*, 2002, 2013), because the need of increase the radiation levels into the forests (50-100%). Also, at these latitudes, the thinning allows rainfall to reach the forest floor by reducing the canopy interception (Caldentey *et al.*, 2005). These two variables (light and soil moisture availability) were the most influential ones over understory biomass growth (Lencinas *et al.*, 2008; Quinteros *et al.*, 2010; Soler, 2012; Gönc *et al.*, 2015).

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[2] Different letters indicate differences by box-and-whisker plot analyses. Capital letters indicates differences among years for each treatment, and lowercase letters indicates differences among treatments for each year. Statistics and *p*-values among years: C × CC = 20.86 (0.002), C × LAI = 15.09 (0.019), C × DIR = 12.14 (0.058), C × DIF = 13.17 (0.040), C × TR = 13.48 (0.036); LT × CC = 19.19 (0.004), LT × LAI = 11.45 (0.075), LT × DIR = 7.21 (0.301), LT × DIF = 15.45 (0.017), LT × TR = 12.27 (0.056); HT × CC = 23.35 (0.001), HT × LAI = 19.18 (0.004), HT × DIR = 26.96 (<0.001), HT × DIF = 19.20 (0.004), HT × TR = 21.24 (0.002); Statistics and *p*-values among treatments: 2010 × CC = 12.50 (0.002), 2011 × CC = 12.50 (0.002), 2012 × CC = 12.50 (0.002), 2013 × CC = 12.02 (0.002), 2014 × CC = 10.22 (0.003), 2015 × CC = 11.58 (0.003), 2016 × CC = 10.82 (0.005); 2010 × RLAI = 12.50 (0.002), 2011 × RLAI = 12.50 (0.002), 2012 × RLAI = 11.66 (0.003), 2013 × RLAI = 10.85 (0.004), 2014 × RLAI = 8.90 (0.012), 2015 × RLAI = 10.46 (0.005), 2016 × RLAI = 9.37 (0.009); 2010 × DIR = 12.02 (0.002), 2011 × DIR = 10.51 (0.005), 2012 × DIR = 10.22 (0.006), 2013 × DIR = 10.22 (0.006), 2014 × DIR = 7.02 (0.029), 2015 × DIR = 9.74 (0.008), 2016 × DIR = 8.00 (0.018); 2010 × DIF = 12.50 (0.002), 2011 × DIF = 12.50 (0.002), 2012 × DIF = 12.50 (0.002), 2013 × DIF = 12.02 (0.002), 2014 × DIF = 10.26 (0.006), 2015 × DIF = 11.58 (0.003), 2016 × DIF = 9.74 (0.008); 2010 × TR = 12.50 (0.002), 2011 × TR = 12.50 (0.002), 2012 × TR = 12.50 (0.002), 2013 × TR = 12.02 (0.002), 2014 × TR = 9.62 (0.008), 2015 × TR = 11.06 (0.004), 2016 × TR = 9.74 (0.007).

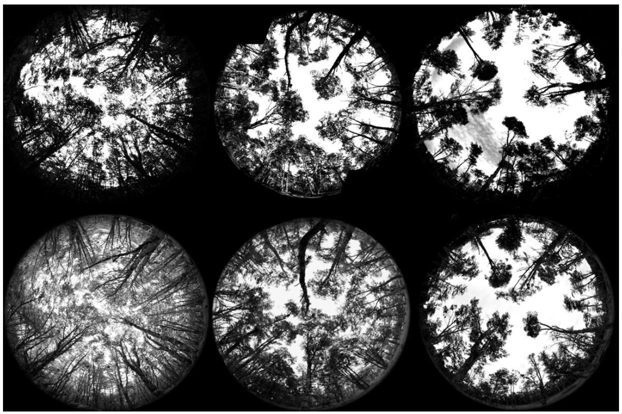

Figure 5. Crown cover for the different treatments (left: control, centre: light thinning, right: heavy thinning) at the year 2010 (up) and 2016 (bottom).

Canopy of *N. antarctica* quickly reacted to the cuttings by recovering the original levels in the light thinning treatment 4 years after cutting, as well as it was observed for other *Nothofagus* species (Martínez Pastur *et al.*, 2002; Peri *et al.*, 2013). Heavy thinning favoured greatest diametric growth (tree variable) with the best G-ratio (stand variable) which maximized the performance of individual trees and increased by 100% the radiation levels. Considering these individual tree growth rates, the timber volume can be increased in the stand (Ivancich *et al.*, 2014) and the radiation levels is enough to develop good-quality pastures for cattle breading (Peri *et al.*, 2016b). For this, heavy thinning levels offered the best combination for silvopastoral management purposes, maintaining for longer periods the benefits of the silvicultural interventions.

The value of resilience in forest ecosystem management has been widely accepted (Yan *et al.*, 2011). Ecosystem resilience is one of the key target for sustainable management. This represents the ability of one ecosystem to absorb impacts before a threshold is reached where the ecosystem changes into a different state (ecological point of view), or the capacity of one ecosystem to return to its more-or-less exact pre-disturbance state (engineering point of view) (Gunderson, 2000; Carpenter *et al.*, 2001). *Nothofagus* in general and particularly *N. antarctica* forests were described as resilient ecosystem considering a wide range of natural and anthropogenic disturbances (*e.g.* Frangi *et al.*, 2015; Peri *et al.*, 2017). The studied forests were converted to pastures in the 50s of the last century by clear-cuts, but abundantly regenerated in the following years resulting in a secondary forests with complete crown cover. After thinning, trees quickly reacted in diameter and crown development. This determines frequent interventions to maintain the open degree of the canopy (*e.g.* LT recover the canopy cover almost completely to date, while HT still present an appropriate openness degree). This reaction is desirable in terms of timber production, but increase the costs of interventions for silvopastoral purposes.

The recover after the caterpillar attack which significantly reduced the alive canopy is another good example of resilience of these forests, where after

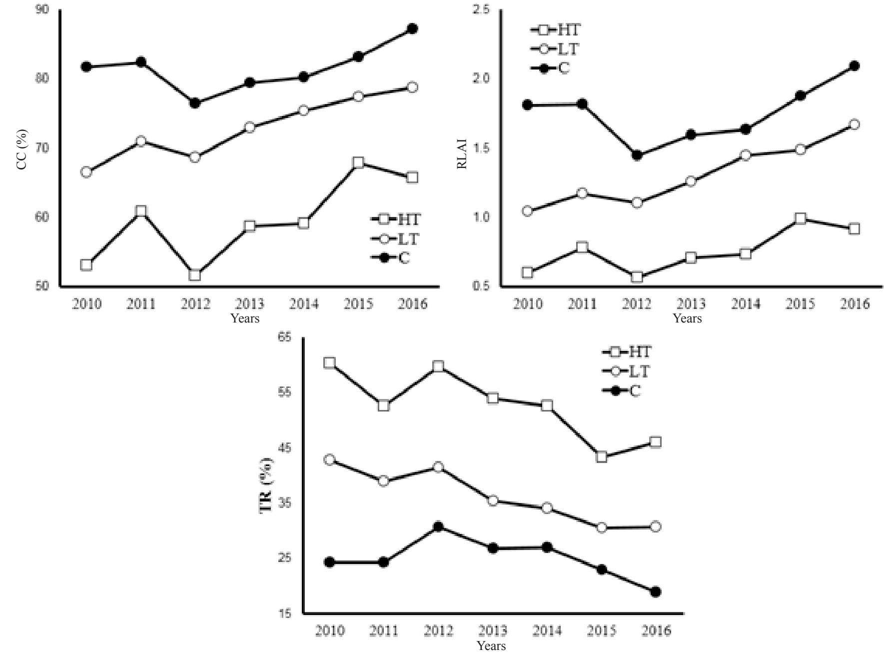

Figure 6. Crown cover (CC), relative leaf area index (RLAI) and transmitted total radiation (TR) along the years (2010-2016) and treatments (C: control, LT: light thinning, HT: heavy thinning).

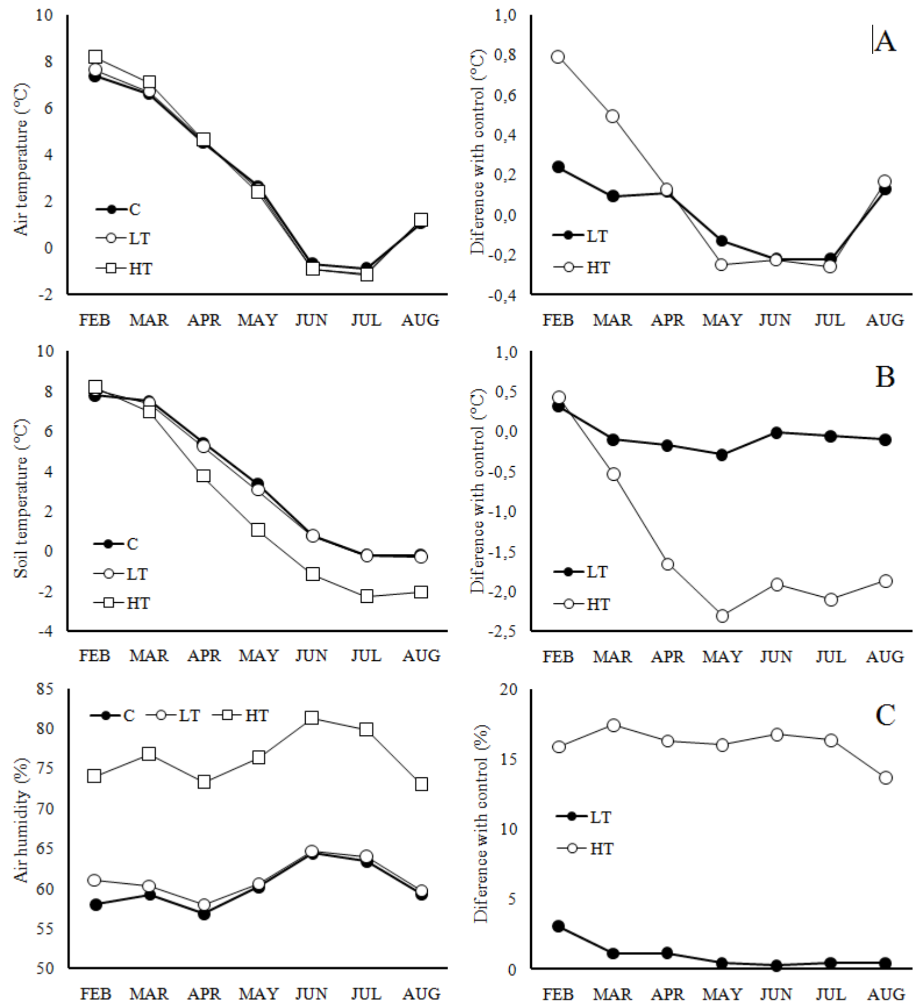

Figure 7. Microclimate data considering months and treatments (C: control, LT: light thinning, HT: heavy thinning). Differences between the thinning treatments and the control are also presented.

disturbance, the values arrived to the expected pre-disturbance levels. This kind of attacks can be related with a loss of growth, accelerating the die-back processes and mortality, related to C and N storage (Piper *et al.*, 2015). Beside this, it is also interesting to observe (Fig. 4) that the attack was higher in the more intensive thinning, producing greater losses and lower recovery rate in the following season compared to LT. This can be explained by the changes in the microclimatic conditions (*e.g.* increase of temperature) favouring higher consumption rate by the *Ormiscodes amphimone* larvae (Paritsis & Veblen, 2010). These authors also relate an increase in the population of defoliators due to foliage quality, and the higher thinning can produce and increase in the quality of the tree leaves due to major availability of limiting resources (*e.g.* soil nutrients, soil moisture and light) (Soler *et al.*, 2011).

Tree diameter was the most useful variable for monitoring growth in forests with timber production purposes (*e.g.* Martínez Pastur *et al.*, 2001, 2002; Peri *et al.*, 2002, 2013). However, in forests managed for silvopastoral purposes, the pastures allowance must be also monitored. This variable can be estimated using the tree crown cover as a proxy (Peri *et al.*, 2006a,b). Here we tested the use of hemispherical photographs for monitoring crown and radiation variables using simple models and available software (*e.g.* Martínez Pastur *et al.*, 2011). This methodology allowed to measured variation in these variables through the years, which greatly influenced on several ecological processes related to productivity in agroforestry systems (*e.g.* moisture availability, nutrient cycles, decomposition, regeneration) (Soler, 2012; Bahamonde *et al.*, 2013, 2015; Martínez Pastur *et al.*, 2013; Peri *et al.*, 2016a). Finally, these monitoring also allowed us to detect changes in the control treatment (*e.g.* increasing crown cover), which can be related to the natural development of the stand (*e.g.* Ivancich *et al.*, 2011, 2014) or climate change effects (Kreps *et al.*, 2012) which occurring in the last decades in Tierra del Fuego (Ivancich *et al.*, 2012).

In summary, intensive thinning in *Nothofagus antarctica* secondary forests increased individual tree growth rates and doubling the radiation levels at the understory level, achieving the main objectives of the silvopastoral management. These forests exhibit a desirable resilience to forestry interventions and natural disturbances (*e.g.* heavy defoliator attack), with a quickly reaction in the canopy cover growth. Monitoring of thinning for silvopastoral purposes must include easy and cheap measuring variables, *e.g.* diameter growth as a proxy for timber production objectives and hemispherical photos (crown cover and radiation) as a proxy for pasture production. Long-term monitoring allowed identifying reliable indicators, which can be used to develop new sustainable management alternatives.

Acknowledgements

To Benjamin Roberts and Juan Apollinaire of San Pablo Ranch (Tierra del Fuego) for their valuable collaboration in the establishment and monitoring of the long term plots in their land.

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