Chapter 14
Dendroecology Applied to Silvicultural Management in the Southern Patagonian Forests: A Case Study from an Experimental Forest in Tierra del Fuego, Argentina

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Abstract Most of radial growth studies of *Nothofagus pumilio* (locally known as 'lenga') in Tierra del Fuego have focused on mature forests and climate relations, but little is known about growth dynamics after harvesting and even less after applying intermediate treatments. The objective of this chapter is to analyze the effect of thinning and pruning on radial growth of *N. pumilio* in Tierra del Fuego (Argentina) in the Aguas Blancas experimental long-term forest, which was harvested in 1967 and had different combinations of interventions in 1984–1985 and 1999. Three treatments were analyzed: (i) one thinning (1 T, thinned in 1984–85), (ii) two thinnings (2 T, thinned in 1984 and 1999), and (iii) two thinnings with pruning of 2/3 of the living crown (2 T + P, thinned in 1984 and 1999 with pruning). Using standard dendrochronological methods, ring widths were cross-dated, measured and the mean ring width (RW), basal area increment (BAI) and the corresponding

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percentages of change in growth (PGC) in 5-year windows were calculated. The three treatments showed significant increments in PGC in both RW (129%) and BAI (419%) after the 1984–1985 thinning. However, from 1999 there were significant differences in periodic growth between the three treatments with the highest RW and BAI in the thinned with pruning treatment. In these forests, dendrochronology emerges as a complementary method to quantify and to reconstruct the individual response of trees affected by silvicultural treatments.

14.1   Introduction

Forest management, whatever its objectives and modalities, substantially modifies the original forest structure. Silvicultural interventions produce changes in micro-climatic conditions, such as increased solar radiation input, variations in the redistribution of the intercepted rainfall (Caldentey et al. 1998; Otero et al. 1998; Martínez-Pastur et al. 2011), changes in temperature, nutrient cycling (Thibodeau et al. 2000), moisture availability (Fayle 1983) and air humidity (Barg and Edmonds 1999). These changes, according to their intensity and the spatial distribution of the silvicultural interventions, influence and stimulate the growth of the remaining or residual trees (Thorpe et al. 2007; Vincent et al. 2009; Peri et al. 2013; Venturoli et al. 2015; Pamerleau-Couture et al. 2015). In this way, improved radial growth of residual trees generally leads to higher financial returns at the stand level despite the reduced tree density (Liu et al. 2007).

Dendroecology (Fritts and Swetnam 1989) is a useful tool to evaluate different processes of forest dynamics, e.g. regeneration, establishment, maturity or senescence of trees. In addition, it is used to date and quantify the effect of past disturbances in the tree canopy which can be translated into periods of suppression or releases of tree rings (Schweingruber 1996). Such information is required to build growth and yield models useful when predicting forest responses after the application of silvicultural treatments based on its past responses. In this way, radial growth releases due to thinning interventions and detected by dendrochronological methods were reported for several species in different parts of the world (Misson et al. 2003; Pérez-de-Lis et al. 2011; Ruano et al. 2013). In particular for Tierra del Fuego (Argentina), Franco (2015) analyzed the response to different combination of thinnings from below in an experimental *Nothofagus betuloides* secondary forest at Estancia Moat, located close to Beagle channel. She found that different thinning intensities produced differential effects on radial growth, where heavy thinning

treatments resulted in higher individual radial growth rates than the control treatments.

Nothofagus pumilio (Poepp. et Endl.) Krasser (locally known as 'lenga') is the most important native tree forest species in economic terms of the sub-Antarctic forests of Argentina and Chile. On the Isla Grande de Tierra del Fuego (Argentina), the silvicultural systems have varied in the last decades, from high grading (Mutarelli and Orfila 1973), shelterwood cuts (Martínez-Pastur et al. 2000), and recently, variable retention harvesting (Martínez-Pastur et al. 2009). However, there are few examples of intermediate treatments that improve and lead the second growth forests (Martínez-Pastur et al. 2001; Peri et al. 2002, 2013), because forests are generally abandoned after the first cuts. Recently, the Dirección General de Bosques de Tierra del Fuego, within the framework of National Law No. 26,331, has promoted the large-scale implementation of these intermediate treatments in secondary forests of Tierra del Fuego (e.g. Martínez-Pastur et al. 2013). In the Argentinean forests of Tierra del Fuego, *N. pumilio* has been used in dendroclimatic studies because of its radial growth sensitivity to annual climate variability (Boninsegna et al. 1989; Gutiérrez 1992; Mundo et al. 2007; Massaccesi et al. 2008). However, dendrochronological methods have not been used until now for silvicultural management.

Intermediate treatments are performed to ensure the composition, stem quality, spacing and desirable characteristics within a stand (Daniel et al. 1982; Smith et al. 1998). The positive effects of thinning are to increase net productivity and the stand quality as well as to favor the growth of the remaining trees, i.e. those with the best characteristics for the management objective. However, so far, the effects of thinning, and even pruning, on radial growth to sustain their inclusion in silvicultural systems in the *N. pumilio* forests of Tierra del Fuego have not been quantified through tree-ring methods yet. In consequence, the objective of this study was to analyze the effect of thinning and pruning on *N. pumilio* radial growth through dendrochronological techniques in a long-term experimental stand.

14.2 Materials and Methods

14.2.1 Study Site

This study was based on samples from plots located in the Aguas Blancas long-term experimental forest (Fig. 14.1, 54°36′35″ S; 67°15′43″ W; 215 m a.s.l.) in the department of Ushuaia (Tierra del Fuego province, Argentina), 14 km from the town of Tolhuin. These plots are part of the PEBANPA network (Peri et al. 2016). The forest type corresponds to *N. pumilio* pure-type based on the classification of Uriarte and Grosse (1991) and to site classes II and III according to the classification proposed by Martínez-Pastur et al. (1997), where dominant heights fluctuate between 22 and 26 m.
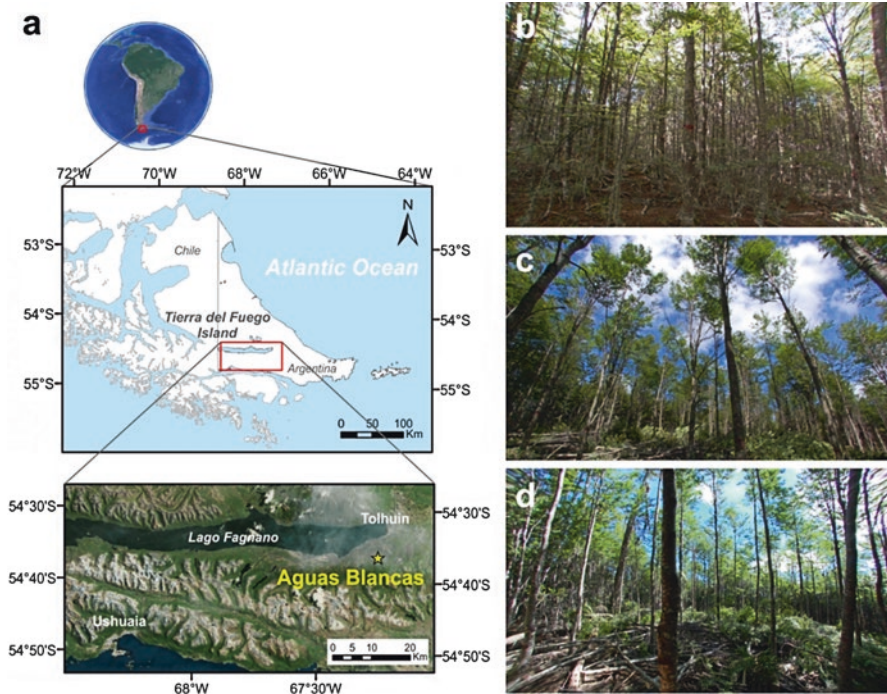
Fig. 14.1 (**a**) Map showing the location of study site in Tierra del Fuego, Argentina. On the right, photos (taken in 2010) of the different treatments analyzed in this study: (**b**) one high-intense thinning (1 T, only thinned in 1984–1985), (**c**) two thinnings (2 T, thinned in 1984–1985 and 1999) and (**d**) two thinnings with pruning (2 T + P, thinned in 1984–1985 and 1999 plus pruning)

Between 1965 and 1967, the National Forestry Administration and the University of Buenos Aires installed a 16-hectare trial in the Aguas Blancas experimental forest where single-tree selective cutting was carried out previously. At that moment, strip clearcuts were performed on alternate strips of 30–40 m wide and 400 m long. Natural regeneration was installed homogeneously and abundantly in all the strips. In the 1984–1985 season, the former National Forest Institute (IFONA) performed different pre-commercial low thinning systems on the regeneration (saplings of approximately 2 m height, 2.5 cm at DBH and 80,000–100,000 ind.ha^{-1}). In 1999, the Centro Austral de Investigaciones Científicas (CONICET) and the Provincial Forest Administration (Dirección de Bosques) of Tierra del Fuego evaluated the first trial on a 2350 m^2 area where 5% of the original basal area (BA) had been left. Subsequently, new treatments were installed on this thinned forest and unmanaged sector within the same strip. A second low-intense thinning was performed leaving 68–75% of the BA left by the thinning carried out in 1984–1985. In addition, the same low-intensity thinning with pruning up to 4–5 m in height (2/3 of the living crown) was applied on another sector of the same strip. In consequence, in this study, the following treatments were analyzed: (i) one high-intense thinning (1 T,

only thinned in 1984–1985), (ii) two thinnings (2 T, thinned in 1984–1985 and 1999), and (iii) two thinnings with pruning (2 T + P, thinned in 1984–1985 and 1999 plus pruning). In each of these treatments, ring width patterns of 20 individuals were analyzed by means of transverse sections taken at breast height (1.30 m) during an intervention in 2011 (not analyzed in this study). The mean DBH (SE) of the 20 sampled in each treatment was 9.7 cm (0.5) for 1 T, 10.8 cm (0.3) for 2 T and 11.6 cm (0.5) for 2 T + P.

14.2.2   Dendrochronological Methods

The processing of cross-sections followed standard dendrochronological procedures (Stokes and Smiley 1968). Samples were air-dried and sanded to create polished surfaces to facilitate the identification of the annual rings under a stereomicroscope (10x–50x). Two perpendicular radii were analyzed on each sample and the growth rings were identified and visually cross-dated. According to Schulman's (1956) convention for the Southern Hemisphere, calendar years of annual rings were assigned to the year in which ring formation begun. The ring widths (RW) were measured using a Velmex UniSlide tablet connected to a Metronics Quick-Check QC-1000 digital counter with an accuracy of 0.01 mm. COFECHA software (Holmes 1983) was used to statistically verify the dating quality of the series and to calculate the correlation between series and mean sensitivity. Basal area increment (BAI) was calculated from RW series assuming circular cross sections after averaging the two radii for each tree. BAI is usually preferred over the RW series since this variable provides a more precise quantification of wood production due to the ever increasing diameter of a living tree (Visser 1995; Pedersen 1998). Then, individual records of both variables were combined to obtain a mean chronology per treatment. In addition, the methodology developed by Nowacki and Abrams (1997) was used to detect growth releases. This method calculates the percentage of growth change (PGC) year by year over the series, in this case individual and average per treatment, using the following equation: [(M2-M1)/M1] x 100 where M1 is the average ring width of the previous 5 years including the calculated year, and M2 is the average of the following 5 years following Fang et al. (2018). A PGC that exceeded 50% and was sustained for at least 3 consecutive years was considered a release.

   To compare growth before and after interventions, we calculated 5-year means (periodic annual increments, PAI$_5$) and statistically analyzed the differences between them for the 2 years of interventions. The mean differences in PAI of pre- and post-intervention periods (ΔPAI$_5$) for each treatment were calculated in the context of pretest-posttest analyses (Dimitrov and Rumrill Jr 2003) and then compared with one-way ANOVAs and HSD Tukey post-hoc tests. Before performing this procedure, the series were checked for normality using the Shapiro-Wilk test. Residuals normality and homoscedasticity were also checked through Kolmogorov-Smirnov and Bartlett tests, respectively. Since the ΔPAI in BAI for the 1984 did not fulfilled

this assumption, the non-parametric Kruskal-Wallis test was used to detect differences between means.

To estimate the effect of the second intervention in relation to what was expected with an unaffected control situation, the radial growth pattern of 1 T treatment was used as a reference pattern. Thus, the percentage differences of 2 T and 2 T + P treatments in relation to 1 T were calculated. In addition, paired student's *t* tests were performed between 1 T, 2 T and 2 T + P mean annual increments.

All statistical analyses were conducted on R version 3.5.3(R Development Core Team 2019).

14.3 Results

14.3.1 *Radial Growth Patterns*

To analyze the effect of thinning and pruning on radial growth in the experimental long-term stand at Aguas Blancas, ring widths were measured for each radii to create individual RW and BAI series and then combined into treatment mean series (Table 14.1 and Fig. 14.2). Firstly, all mean series had almost the same starting year, which corroborated the existence of a post-harvesting cohort in the three treatments.

The first thinning in 1984, which was very intense since it reduced the occupation level to 6% of the initial density, generated an increase in the average annual increment for the three treatments. This was reflected by large peaks in the radial growth patterns associated to this event, both in ring width and basal area increment in all three treatments. The second intervention of 1999, which left 56% of the density of individuals in 2 T and 2 T + P treatments, could only be seen as a peak, smaller than that of 1984, in the RW and BAI series of 2 T + P treatment (Fig. 14.2e, f), but with almost no changes in 2 T (Fig. 14.2c, d).

In terms of common variability between individual series per treatment, the average inter-correlation per individual series before the first intervention was relatively low ($r = 0.274 \pm 0.031$) and it increased to 0.719 ± 0.023 between-interventions period (1985–1999). Then, after the second intervention, the 2 T and 2 T + P treat-

Table 14.1 Structural characteristics (density), radial growth (ring width) and inter-annual variation in growth (mean sensitivity) for the three treatments during the three periods defined by the two interventions (1984 and 1999)

Treat.	Pre-first cut (pre-1984)			Between cuts (1985–1999)			Post-second cut (2000–2009)		
	Density (ind/ha)	Mean RW (mm)	MS	Density (ind/ha)	Mean RW (mm)	MS	Density (ind/ha)	Mean RW (mm)	MS
1 T	80,000	1.25 ± 0.02	0.23	4426	1.79 ± 0.04	0.37	4426	0.89 ± 0.02	0.38
2 T	80,000	1.26 ± 0.02	0.26	4426	1.66 ± 0.04	0.33	2478	1.15 ± 0.03	0.36
2 T + P	80,000	1.22 ± 0.03	0.26	4426	1.91 ± 0.05	0.34	2478	1.39 ± 0.04	0.30

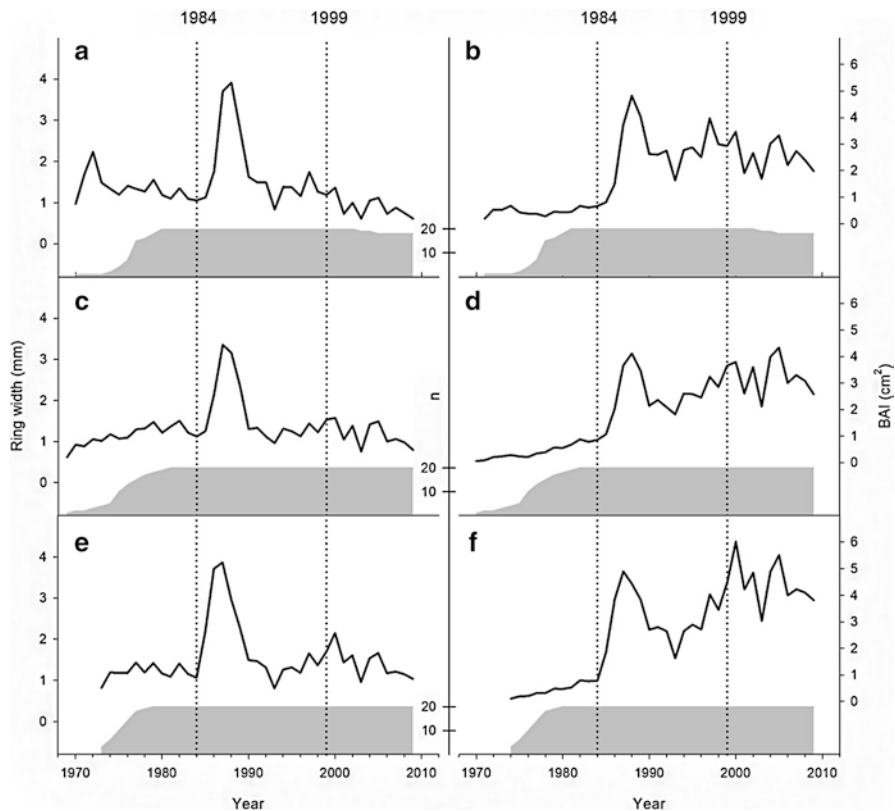*Treat* treatment, *RW* ring width, *MS* mean sensitivity

Fig. 14.2 Average ring width (RW, left panels) and basal area increment (BAI, right panels) for one thinning (1 T; **a** and **b**), two thinnings (2 T; **c** and **d**) and two thinnings with pruning (2 T + P; **e** and **f**) treatments. The central axis indicates the number of trees (n). The vertical dotted lines indicate the years of the two interventions (1984 and 1999). The grey shaded areas at the bottom of each panel represent the sample size (average series per tree) per year

ments showed a greater increase, reaching *r* values of 0.733 and 0.749 respectively. The 1 T treatment, which had no intervention in 1999, showed a slight decrease in the mean inter-correlation from 0.764 to 0.722. On the other hand, the mean sensitivity, as a measure of the degree of inter-annual variation, also showed an increase associated with the application of the intermediate treatment.

To evaluate the annual variation in each treatment and to quantify growth releases, the annual percentages of growth change (PGC) in RW and BAI series were calculated (Fig. 14.3). For the 1984 intervention, the average PGC between treatments was 129% (SE = 20%), and it was recorded as individual releases on 57% of the trees in each treatment. However, the PGC for BAI increased to 419% (SE = 39%) at same year. Neither RW nor BAI showed a PGC greater than 50% nor individual release associated with the interventions carried out in 1999 were detected. Only a light growth release was found in 1996 for the three treatments.
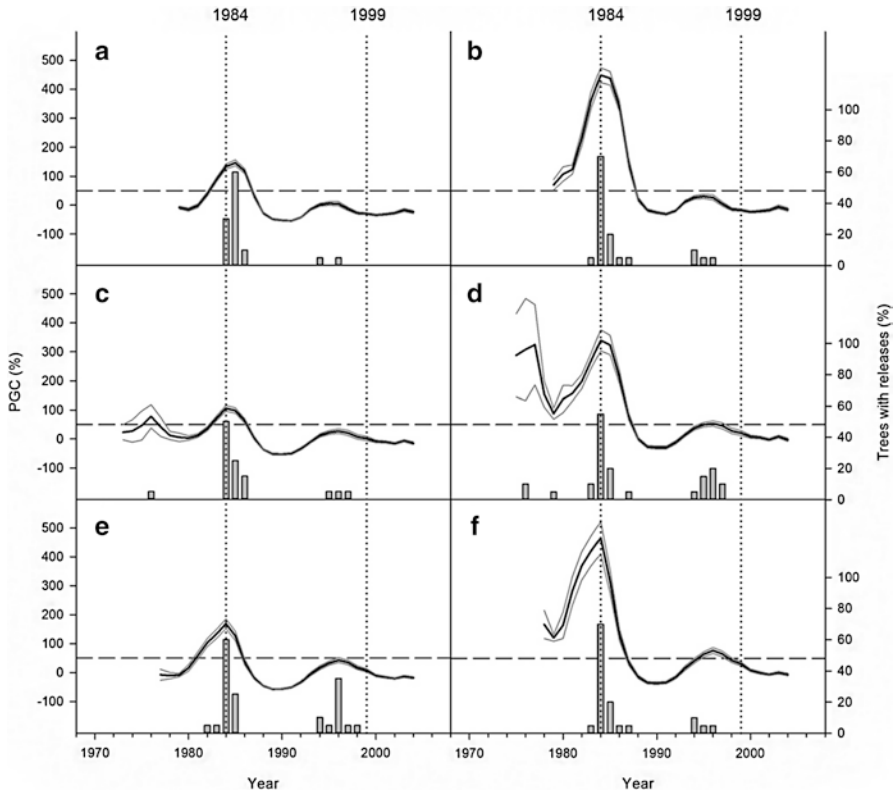
Fig. 14.3 Percentages of growth change (PGC) in mean ring width (RW, left panels: **a**, **c** and **e**) and basal area increment (BAI, right panels: **b**, **d** and **f**) (black lines) with their respective standard errors (grey lines) for the three treatments: 1 T, one thinning (**a**, **b**); 2 T, two thinnings (**c**, **d**) and 2 T + P, two thinnings with pruning (**e**, **f**). Cut lines indicate 50% PGC threshold for release detection. The bars show the individual trees released (PGC >50%) in each treatment. The vertical dotted lines indicate the two interventions (years 1984 and 1999)

14.3.2   *Differences in Periodic Growth Due to the Interventions*

Growth changes associated with the two interventions were analyzed by calculating 5-year periodic annual differences (ΔPAI_5) and by comparing them between treatments (Fig. 14.4). In the case of the 1984 strong thinning, significant differences were found in RW ($F = 7.994$, $p < 0.001$), but not for BAI ($H = 5.318$, $p = 0.07$). The paired comparison of means indicated that 1 T treatment was not different from 2 T + P and 2 T, respectively, with the highest and lowest growth which were significantly different from each other. In opposition, the 1999 intervention generated significant differences in both RW ($F = 14.008$, $p < 0.001$) and BAI ($F = 16.729$, $p < 0.001$). In this last intervention, 1 T presented negative differences and differed
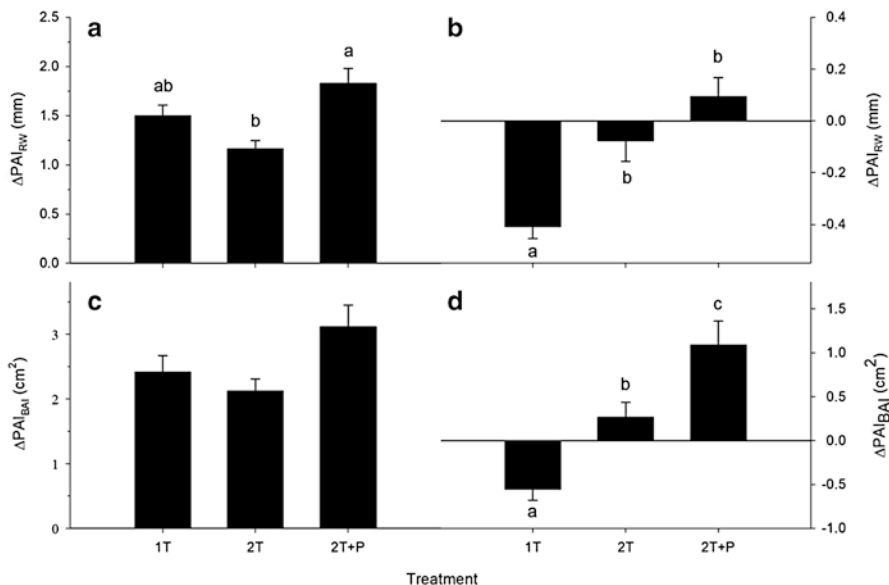
Fig. 14.4 Differences in periodic annual increment (ΔPAI) for 5 years before and after the 1984 (left panels: **a** and **c**) and 1999 (right panels: **b** and **d**) interventions in ring width (RW, upper panels: **a** and **b**) and basal area increment (BAI, lower panels: **c** and **d**) for each treatment (1 T, one thinning; 2 T, two thinnings and 2 T + P, two thinnings with pruning). Bars represent mean difference with standard error bars. Means with the same letter are not significantly different at $p < 0.05$ based on ANOVA and HSD Tukey post-hoc tests. Kruskal-Wallis test was used to detect differences between medians in panel c ($H = 5.318$, $p = 0.07$)

from 2 T and 2 T + P in both RW and BAI. The treatments 2 T and 2 T + P had positive values in $ΔPAI_5$, but differed significantly from each other with a greater increase in 2 T + P treatment.

In order to evaluate the effect of the second intervention compared to what was expected without any type of treatment, the percentage differences in the annual growth of the 2 T and 2 T + P treatments in relation to the 1 T treatment were analyzed (Fig. 14.5). No percentage changes lower than −25% or greater than 15% were found for 2 T and 2 T + P during the years prior to the 1999 intervention (Fig. 14.5a, b). After the intervention, positive differences were found with peaks in 2001 with greatest percentage difference of 96% and 121% in RW and BAI, respectively. The difference corresponding to 2 T + P was found to be greater than 2 T in all situations. Paired t tests evidenced that these differences were of lesser magnitude and limited to 2 years for 2 T treatment (Fig. 14.5c, d) while in 2 T + P the increase in growth lasted until 10 years after the last intervention (Fig. 14.5e, f).
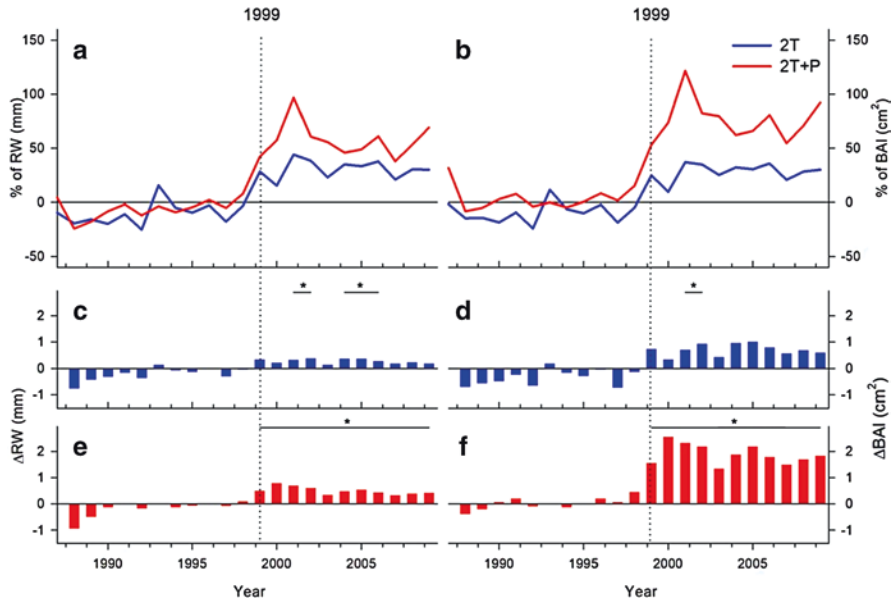
Fig. 14.5 Annual average differences of the two-thinning (2 T, blue lines and blue bars) and two-thinning plus pruning (2 T + P, red lines and red bars) treatments with respect to the one thinning treatment (1 T) for ring width (RW, left panels) and basal area increment (BAI, right panels) analyzed for 10 years before and after the second intervention. Differences are expressed as a percentage of the 1 T treatment (**a**, **b**) or in the same units (**c–f**). The vertical dotted lines indicate the date of the second intervention (1999). On the lower plots (c, d, e and f), segments capped with an asterisk correspond to intervals with index differences statistically different ($p < 0.05$) from the long-term mean based on paired t tests

14.4 Discussion

This long-term case study showed that the dendrochronological techniques widely and mainly used to detect growth releases due to disturbances can be applied to quantify and to reconstruct the effect of intermediate treatments in *N. pumilio* forests. In addition, as it was expected, higher growth rates were found as a consequence of highly intensive thinning interventions. On the other hand and using dendrochoronological methods for the first time in this species under silvicultural management, a significant increase in radial growth was detected as a response to the combined effect of thinning and pruning. Moreover, BAI appears to be a more sensible parameter than RW to detect the effect of intermediate treatments.

The effect of the intermediate treatments performed in 1984 and 1999 were verified both visually through peaks in their growth patterns and increases in the PGC for the three treatments. In the three treatments analyzed, in terms of trends, considerable increases in RW and BAI were observed as a consequence of the heavy thinning that these plots had in 1984 (Fig. 14.2) These radial growth releases are due to the fact that thinning, as an intermediate type of silvicultural treatments, produces

the release of resources (Smith et al. 1998) and, consequently, has a positive effect on the growth of the remaining trees. In relation to the 1999 intervention, the plot that received thinning and pruning (2 T + P) showed a higher growth, in relation to the 1 T treatment, 2 years after the intervention (2001). The treatment that only received thinning on 1999 (2 T) also showed an increase in the percentage difference with respect to treatment without intervention. However, this increase did not reach the magnitude detected in 2 T + P. This could be due to the fact that the elimination of basal branches coincided with those less efficient in terms of photosynthetic balance and, consequently, leaving remnant branches with greater photosynthetic capacity that use more efficiently the higher amount of light irradiance resulting from the simultaneous thinning of individuals.

In relation to the second intervention that took place in 1999, in the 2 T treatment, which only had a low intense thinning, no changes were observed in RW growth, though there was a slight increase in BAI. On the contrary, treatment with thinning and pruning (2 T + P) showed an increase in both variables. Therefore, the repetition of thinnings 15 years apart did not translate into significant changes in radial growth. However, the addition of pruning produced the increase of radial growth, both measured in RW and BAI, for 10 years after the intervention in comparison to the control situation. This fact would be explained by a greater accumulation of biomass in the stem, possibly due to a greater efficiency in the capture of resources by the remaining individuals who suffered a rejuvenation of the crown. Other authors also detected an increase in radial growth due to the application of pruning in other species from the northern hemisphere (Stein 1955; Staebler 1963). Recently, Giantomasi et al. (2015) also observed that *Prosopis flexuosa* trees increased radial growth after pruning in the Monte region of western-central Argentina.

The growth rate recorded before the first intervention in the three treatments is similar to that observed by Barrera et al. (2000) in self-thinning young forests located in Valle de Andorra, Tierra del Fuego. The percentage of growth change quantified in this study (with maximum values of 155% in RW and 449% in BAI) was parallel to those reported by Franco (2015) (360% in RW and 431% in BAI) for thinned *N. betuloides* trees in Tierra del Fuego, and even surpassed the value (80% in BAI) reported by Pérez-de-Lis et al. (2011) for thinned *Pinus canariensis* trees. However, these values are similar to those reported in other thinning studies on *N. pumilio* conducted in Southern Patagonia (Peri et al. 2002, 2013).

On another subject, after the first intervention, the mean inter-correlation values, as an expression of the degree of agreement and common signal between ring width series, in comparison to those values reported by Mundo et al. (2007) and Massaccesi et al. (2008) were very high. This would indicate that the application of thinning and pruning treatments had a very homogeneous effect on the remaining trees, they were not damaged and they responded very homogeneously. In addition, the increase in average sensitivity after the first intervention in the three treatments would indicate that these trees had a quite constant radial growth before the opening of the canopy and that once competition had been reduced due to the thinning; the remaining individuals began to show radial patterns with greater inter-annual vari-

ability more linked to climatic annual variability than to the competition for resources.

Finally, this research could be used as reference for future studies to quantify the intensity of past interventions using these same dendrochronological methods presented in this chapter in complementation with reports of exploitation or measurements of forest structure. In this way, by calibrating different thinning intensities with releases in RW and BAI, it would be possible to estimate past thinning and pruning intensities on stands where this type of information is unknown. In addition, it would be very useful to carry out anatomical studies on the samples analyzed in this study or in other sites with known intermediate treatments to better understand the response of *N. pumilio* in terms of xylem transportation and ecophysiology linked to silvicultural management.

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