Chapter 15
Tree-Growth Variations of *Nothofagus antarctica* Related to Climate and Land Use Changes in Southern Patagonia, Argentina

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Abstract Isolated forest patches of *Nothofagus antarctica* (ñire) are frequent in the Patagonian forest-steppe ecotone. These remnants, also called *relicts* (R), are separate from the *continuous* forests (C). Over the past century, these ecotonal forests have been impacted by anthropogenic activities, including fires, logging, and cattle ranching. In order to identify in *N. antarctica* ring-width records the variations in tree growth associated with documented changes in land use, five sites were selected in Santa Cruz, Argentina. In each site, increment cores from R and C were collected. We developed individual chronologies, and the relationships between regional climate variations and *N. antarctica* growth were established for each forest type and site. The similarities/differences between site-paired chronologies (R-C) were estimated by calculating moving correlation coefficients lagged by 1 year. *N. antarctica*

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regional growth was directly related to precipitation during the current growing season (November–December; $r = 0.34$, $n = 62$, $p < 0.01$), and inversely related to temperature (December–March; $r = -0.58$, $n = 62$, $p < 0.001$). Since the middle of the twentieth century, a progressive decrease has been recorded in regional radial growth, consistent with an increase in summer temperature and a decrease in spring precipitation. In the context of this regional response of *N. antarctica* to climate, differences in growth patterns between R and C were associated with past changes in land use. Overall, the largest differences between R and C chronologies were concurrent with the settlement of cattle ranches and the associated use of forests. Conversely, similarities between R and C records increased after the establishment of protected areas and during the implementation of similar management practices in both forest types. Our research provides the first dendrochronological records from *Nothofagus antarctica* for the Argentinean Patagonia and represents one of the first efforts to identify in tree-rings past changes in livestock practices in southern South America.

Keywords Forest-steppe ecotone · Relict and continuous forest · Dendrochronology · Climate-tree growth relationship · Historical and cultural use of the land · Dendroclimatology

15.1   Introduction

The genus *Nothofagus* is widely distributed in the continental and insular sectors bordering the South Pacific Ocean, particularly in the mid-latitudes of Australasia and South America (Veblen et al. 1996). *Nothofagus antarctica* (G. Forster) Oerster (ñire or ñirre) and *Nothofagus pumilio* (Poepp. and Endl.) Krasser (lenga) have the most extensive geographic distributions of the genus in South America, covering 2200 km along the Andes from 35° 36' S in Central Chile to 55° S in Tierra del Fuego (Donoso 1993; Lara et al. 2001). The altitudinal range of these species extends from sea level to the upper tree line (Veblen et al. 1996; Roig 1999).

It is known that the Andes induce a marked precipitation gradient across Patagonia (Paruelo et al. 1998). The *Nothofagus* forests are located in the western, most humid areas of this gradient (Moore 1983; Donoso 1993). Along the west-east precipitation gradient in southern Patagonia, *N. antarctica* forests develop within a precipitation range that varies between 3000 mm to less than 800 mm over a west-to-east distance of only 50 km (Veblen et al. 1996; Paruelo et al. 1998). In response to its high phenotypic plasticity, *N. antarctica* presents a large ecological amplitude (Ramírez et al. 1985) growing from wet meadows (mallines) to dry areas in the forest-steppe ecotone. Furthermore, *N. antarctica* grows at flat-low valley sites as well as on steep slopes with strong and persistent winds (Veblen et al. 1996; Donoso et al. 2006; Kreps et al. 2012). In addition, *N. antarctica* tolerates winter frosts up

to −22 °C (Alberdi 1995). In consequence, *N. antarctica* shows a great adaptive environmental capacity and multiple phenotypic responses. Under suitable site conditions (moderate temperature, adequate humidity, well-drained and fertile soils), *N. antarctica* is an erect tree of up to 20 m in height (Marazana et al. 1984; Ramírez et al. 1985; Veblen et al. 1996). By contrast, under extreme soil moisture conditions or at the upper treeline, it becomes a small tree or shrub of approximately 2–3 m height. Shrubby individuals (krumholz) are common in upper tree lines due to abundant snow deposition in winter (Pérez Moreau 1959; Veblen et al. 1996; Donoso et al. 2006). In the forest-steppe ecotone, it is common to observe trees up to 10 m coexisting with individuals less than 3 m in height (Marazana et al. 1984; Ramírez et al. 1985).

In the forest-steppe ecotone, *N. antarctica* usually forms the eastern boundary of the arboreal vegetation. In this ecotone, trees group into a mosaic of small monospecific patches of forests that alternate with the steppe in elevated areas and with meadows or mallines in depressions (Roig 1999; Peri and Ormaechea 2013). These remaining patches, called *relicts* (R), are marginal forest communities spatially disconnected with the *continuous forests* (C) located towards the west over the Andes mountain range (Fig. 15.1).

The ecotones are considered very dynamic habitats where the initial impacts of environmental changes become more evident (di Castri et al. 1988; Neilson 1991). In this sense, several authors (Iverson et al. 2004; Hampe and Petit 2005) claim that the populations of tree species located on their distribution margins are very sensitive to environmental variations. Due to the high perimeter/surface ratio, trees at the

Fig. 15.1 Photograph showing sectors of the relict (*black arrow*) and continuous (*grey arrow*) forests of *N. antarctica* in Estancia Cancha Carrera (site 3). The relict forests are represented by isolated patches bordered by steppe vegetation, while the most developed continuous forest extends all along the foothills of the Andes

ecotonal patches are exposed to more severe stress and higher rates of change than trees in continuous forests (Murcia 1995).

Ecotones have often been heavily impacted by human activities, particularly at the low elevation forest-grassland transitions. Changes in cultural land use have greatly influenced their dynamics (Kitzberger 2012). In southern Patagonia, the *N. antarctica* relicts have been subjected to different cultural uses, and only 14% of these are included in protected areas. The European immigration in the late-nineteenth and early-twentieth centuries caused the demise of the native Aonikenk hunter-gatherer population and the rapid establishment of livestock farming (Bandieri 2005). The new socio-economic system gradually modified the forests in the region (Barbería 1994, 1995; Schweitzer 2011). The *N. antarctica* forests were intensely used during the European colonization inducing a substantial reduction in the total area of the ecotonal forests. Among the various anthropogenic causes related to the decrease in *N. antarctica* forest extension were the opening of new roads, unplanned settlements, intensive grazing, forest fires, and logging (Montaña 1982; Manacorda and Bonvissuto 2001). Livestock causes the browsing of arboreal species and limits the natural regeneration of the forest. Livestock also facilitates the introduction of exotic plants that compete with native species (Christensen and Emborg 1996; SAyDS 2005). There have also been registered increments of certain understory taxa resistant to browsing, such as the *Berberis* sp. (Rajchenberg et al. 2014). As a consequence, the overconsumption and unsustainable use of natural resources led to the accelerated transformation of the environment (Schweitzer 2011). Concurrent with these vegetation changes, a general warming trend at the extreme south of South America (45–55° S) has become evident during the last century (Rosenblüth et al. 1997; Villalba et al. 2003; SAyDS 2005) concurrent with a decrease in precipitation (Aravena and Luckman 2009). These climatic changes, in combination with other local anthropic factors, may have also contribute to the fragmentation of native forests along the region.

It is well known that tree rings can record information about changes in the environmental factors affecting tree growth. However, few studies have been conducted in South America to determine variations in tree rings associated with past changes in land use related to livestock (but see Morales et al. 2005; Morales and Villalba 2006; Mundo et al. 2017). The objectives of this study were to use ring-width chronologies from *N. antarctica* to identify the species response to climatic variations and determine the influence of different land use practices between relict and continuous forests in Santa Cruz, Argentina. To reach these goals, we first established the relationships between *N. antarctica* tree growth and the regional climate. Based on these relationships, we postulated that historical changes in stocking density and harvesting intensity have led to important differences in the radial growth of *N. antarctica* at isolated and continuous forests in the eastern limit of its natural distribution. Changes in cultural land use may provide clues to understand the differences observed in tree growth between nearby stands. Although more than 300 tree-ring chronologies have been developed from different species in Argentina (Villalba et al. 1997; Villalba et al. 2003; Roig and Villalba 2008; Boninsegna et al. 2009), to the best of our knowledge, there are no

dendrochronological records from *N. antarctica* trees. In consequence, the present study provides the first chronologies for *N. antarctica* in the Argentinean Patagonia.

15.2   Methods

15.2.1   Study Area

Located in southern South America, Patagonia presents a cold climate. In Santa Cruz, there are two main geo-climatic units: the Andes dominated by ice and forests with relatively abundant rainfalls to the west, and the Patagonian steppe dominated by grasslands with dry climate to the east (Díaz 2005). The difficulty of analyzing climatic variability in the region lies in the lack of weather stations, or the short extension of available records (Paruelo et al. 1998; Díaz 2005; Garreaud et al. 2013; Soto-Rogel and Aravena 2017). In the study area, the mean annual temperature is 6 °C, with a mean maximum of 17 °C in January and a mean minimum of −5 °C in July (Kreps et al. 2012). The reported absolute minimum temperature for the region is −20 °C (Paruelo et al. 1998). Total annual rainfalls at the study sites is estimated around 400 mm ± 150 mm. In this region, strong westerly winds prevail throughout the year but intensify during the spring and summer (Coronato and Del Valle 1993; González and Vera 2010).

   We selected pairs of *relict* (R) and *continuous forests* (C) of *N. antarctica* in five sites in southwestern Santa Cruz province, Argentina. These forests are distributed in a latitudinal range of 467 km, between 47° 04´ W and 51° 05´ S in southern Patagonia (Fig. 15.2). Table 15.1 summarizes the most relevant climate data and the location of each study site.

15.2.2   Tree-Ring Data and Chronology Development

Dendrochronological samplings were conducted during the interval 2012–2016 in *relict* (R) and *continuous* (C) forests at five study areas (Fig. 15.1). In each site, 20 dominant individuals were selected, and 2 cores were obtained by tree using increment borers. Even though individuals with the best health status were chosen, in many cases only one sample could be recovered per tree. *N. antarctica* commonly presents tortuous stems of poor sanitary status with rotten centers. For the most part, samples were taken close to the root collar of the trees. However, when sampling at the collar was impeded by logistical problems, cores were extracted at the lowest possible height on the stem.

   The samples were processed according to conventional techniques used in dendrochronology (Stokes and Smiley 1968). Tree rings were dated under a binocular magnifier, and the ring widths were measured with an accuracy of 0.001 mm using
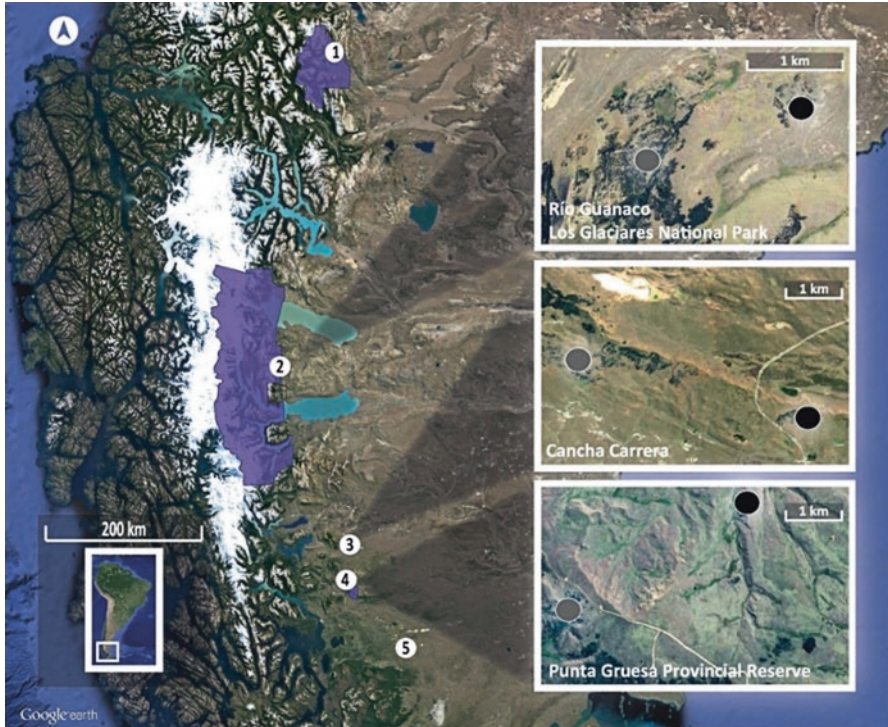
Fig. 15.2 Geographical distribution of the study sites are indicated by *white dots*: (**1**) Perito Moreno National Park, (**2**) Río Guanaco – Los Glaciares National Park, (**3**) Estancia Cancha Carrera, (**4**) Punta Gruesa Natural Reserve and (**5**) Estancia Rincón de los Morros. Protected areas (shown in *shaded blue*). Satellite images (framed *in white*) for the three study sites in which good-quality chronologies were developed are also included. Relict and continuous forests in these three images are indicated by *black* and *grey dots*, respectively

a Velmex machine (Fig. 15.3). After that, the quality of the measurements was examined using the COFECHA software (Holmes 1983). Finally, the ARSTAN program (Cook 1985) was used to develop raw, standard and residual chronologies from each pair of *N. antarctica* stands (R and C) at the five study sites. In addition, all series were combined to develop three additional chronologies: two independent chronologies for relict (R) and continuous (C) forests, and a regional chronology including all series from the five study areas. This set of chronologies was developed to validate different hypotheses. Thus, to identify differences in tree growth between relicts and continuous forests due to changes in land use, we developed chronologies in both forest types at each study area. Regional scale chronologies were elaborated to determine the existence of a common growth signal among all sampled trees and to establish differences between relicts and continuous forests.

Table 15.1 Site characteristics of tree-ring collections

Study sites	Site code	Forest type	Mean annual temperature (°C) [a]	Total annual precipitation (mm) [a]	Longitude	Latitude	Altitude (m.a.s.l.)
Perito Moreno national park	**1**	**R**	4.9	252	72° 8′47.82″W	47°43′40.91″S	971
	1	**C**	5.0	252	72° 9′16.07″W	47°43′39.86″S	886
Río Guanaco, Los Glaciares National Park	**2**	**R**	5.5	516	72°49′10.42″W	49°55′22.79″S	708
	2	**C**	5.5	528	72°50′32.42″W	49°55′37.01″S	692
Estancia Cancha Carrera	**3**	**R**	5.3	228	72° 6′56.25″W	51°12′38.15″S	431
	3	**C**	6.0	223	72°13′41.88″W	51°11′49.47″S	312
Punta Gruesa natural reserve	**4**	**R**	4.5	304	72° 8′49.84″W	51°29′28.07″S	534
	4	**C**	4.1	324	72° 9′10.55″W	51°31′6.65″S	577
Estancia Rincón de los Morros	**5**	**R**	6.3	220	71°30′27.68″W	51°55′10.15″S	139
	5	**C**	9.4	300	71°32′57.92″W	51°54′40.11″S	119

The name and codes of the study sites together with the forest types, the mean annual temperature, the total annual precipitation and the geographical locations are indicated

R relict forest, *C* continuous forest

[a] www.worldclim.org; Hijmans et al. (2005)
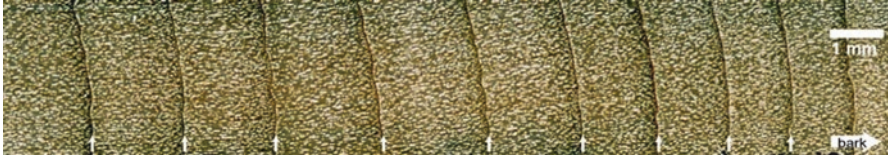
Fig. 15.3 An incremental core of *N. antarctica* showing the annual bands (*white arrows*), clearly discernible in the wood of this species. Although this is a diffuse porous species, a common feature of most *Nothofagus* species, the vessels at the beginning of the growing season are larger and their cell walls thinner than those formed later in the growing season. Fibers are abundant at the end of the growing season and show thick cell walls

15.2.3   Climate-Tree Growth Relationship

To determine the climate influences on the *N. antarctica* radial growth, the residual ring-width chronologies from the three well-replicated sites (sites 2, 3 and 4; Fig. 15.2) were compared with the instrumental temperature and precipitation records available for the region. The correlation function is a simple method for comparing the interannual variations in tree-ring chronologies with monthly inter-annual fluctuations in climate (Blasing et al. 1984). The statistical relationship between ring-width and climate variable was examined over the common 1952–2014 period (62 years) between the chronologies and the instrumental data. In addition, since the growth in a given year may be influenced by the climatic conditions during the previous years (Fritts 1976), the comparison period analyzed comprised 20 months, starting in September of the previous year until April of the year in which the rings were formed. Based on the results of the correlation function comparing variations between the regional chronology and the regional climate, we proceeded to group the monthly temperature and precipitation records into seasonal means including the months most strongly related to growth. To carry out these calculations, the Microsoft Excel spreadsheet (2013) was used.

15.2.4   Cultural Land Use Changes

Land uses changes in the forest-steppe ecotone in Santa Cruz were compiled from several historical documents, including the Memories from the National Park Administration, scientific publications on regional anthropological and archaeological studies, management plans of protected areas, technical reports and documents from the Santa Cruz Cadastral Department. Bibliography and files deposited at the Provincial Historical Archive in Río Gallegos were also consulted. Open interviews were also conducted among the residents and cattle ranch administrators.

Finally, the standard version of the tree-ring width chronologies from *N. antarctica*, obtained for R and C forests at each site, were compared by calculating

the correlation coefficient in segments of 20 years lagged by 1-year between consecutive segments. To carry out these calculations, the Microsoft Excel spreadsheet (2013) was used. Finally, we analyzed the consistency between historical changes in land use and in growth patterns.

15.3 Results

15.3.1 Chronology Development

Eleven chronologies from *N. antarctica* were developed in Santa Cruz, one from each site and forest type (R2, C2, R3, C3, R4, C4, R5, and C5), with the exception of site 1 (Perito Moreno National Park), where samples were not cross-dated. Two other chronologies were developed using all the cross-dated series of each forest type (*relicts* and *continuous* respectively) and, finally, a *regional* chronology with all cross-dated series in southwestern Santa Cruz (Fig. 15.4).

The longest chronology, extended for 206 years, is from the Cancha Carrera relict forest (R3). On the other hand, the shortest chronology is from Rincón de los Morros continuous forest (C5), and it extended for 42 years. The mean length of all chronologies per site was 122 ± 54 years long (Table 15.2).
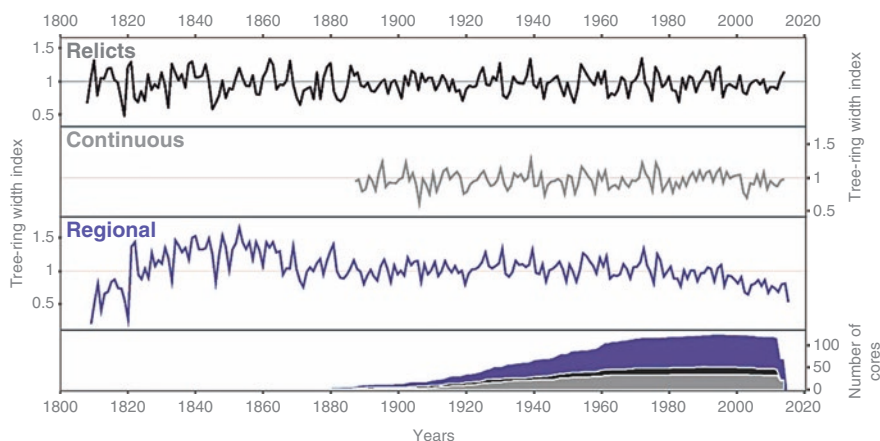
Fig. 15.4 Composite *N. antarctica* width chronologies in their standard versions. The left and right axes represent the tree-ring width index (dimensionless) and the number of series per year (replication), respectively; in *black* is represented the regional relict forest (R); in *light grey* the regional continuous forest (C) and in *blue* the regional chronology. Forest type and site codes are listed in Table 15.1

Table 15.2 Statistics for the 11 *N. antarctica* chronologies developed in Santa Cruz, Argentina

Forest type and site codes	Number of trees bored	Total series number	% Correlated series	Inter-correlation coefficient[a]	Period (years)	EPS[b]	R bar[b]
R2	86	56	36	0.510	1819–2013	0.936	0.370
C2	72	42	44	0.557	1914–2013	0.941	0.389
R3	61	40	48	0.608	1807–2013	0.945	0.439
C3	77	46	32	0.567	1888–2013	0.934	0.398
R4	30	23	53	0.578	1909–2011	0.897	0.397
C4	25	24	48	0.595	1886–2011	0.899	0.489
R5	32	24	50	0.645	1945–2011	0.935	0.510
C5	21	20	29	0.585	1971–2011	ND	ND
Relicts	**172**	**56**	**33**	**0.509**	**1807–2013**	**0.958**	**0.328**
Continuous	**154**	**37**	**24**	**0.506**	**1886–2013**	**0.920**	**0.256**
Regional	**326**	**137**	**41**	**0.4783**	**1807–2014**	**0.970**	**0.224**

Forest type and site codes are shown in Table 15.1
ND no data
[a]From COFECHA
[b]From ARSTAN

The composite R chronology was considerably longer than the composite C chronology (206 and 125 years, respectively). The regional chronology began in 1807 with 1 sample, reached 10 samples in 1888, a maximum of 133 samples between 1992 and 1995, and ended with 73 samples in 2014 (Fig. 15.5).

15.3.2 Climate-Tree Growth Relationship

The patterns of temperature variability are relatively uniform across our study area. Thus, the most extensive local temperature record in Torre Glacier (from 2002 to the present) is near the town of El Chaltén. This is significantly correlated with gridded data from ERA-Interin across most southern Patagonia (Fig. 15.S1). The extensive field of spatial correlation includes the Argentinean weather stations of Esquel and Río Gallegos and Punta Arenas in Chile (Fig. 15.S1). Located to the north, east and south of the study sites, respectively, these weather stations provide the most extensive and homogeneous records in southern Patagonia. Therefore, the mean from the monthly temperature deviations from these three stations were composed in a single regional record, and it was used to compare with tree-ring variations. All temperature series were normalized over the 1952–2014 common period. The use of normalized deviations to develop the regional temperature record implies that each meteorological station has similar contribution in the regional mean temperature.
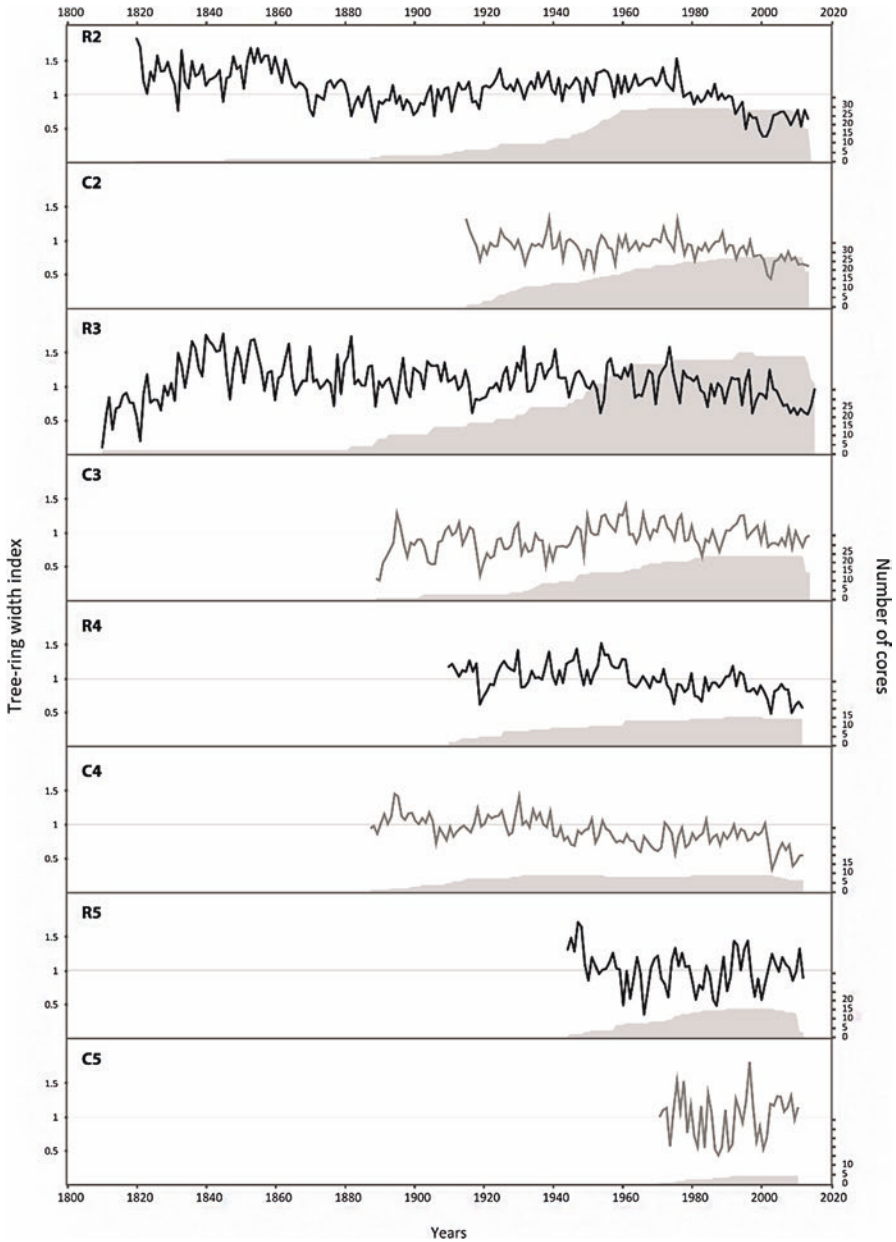
Fig. 15.5 *N. antarctica* tree-ring width chronologies in their standard version. The left axis represents the tree-ring width index (dimensionless); the right axis represents the number of series per year (replication); in *black* are represented the relict forests (R), and in *light grey* are represented the continuous forests (C). Forest type and site codes are listed in Table 15.1

Unlike the extended spatial correlation pattern of temperature for Torre Glacier, the spatial pattern of precipitation is much more limited. The abundant precipitation on the western and eastern slopes of the Andes sharply contrasts with the reduced rains on the Patagonian plateau. Thus, the local precipitations measured at Los Huemules station, also nearby to El Chaltén town (from 2006 to the present), have a much more spatially reduced representability pattern than temperature (Fig. 15. S2). Because there are no long (>20 years) and homogeneous precipitation records in the forest-steppe ecotone in Santa Cruz province, the monthly precipitation from Punta Arenas were compared with the *N. antarctica* chronologies here developed. Precipitation variations in Punta Arenas from December to August are significantly related to ERA-Interin precipitation over the study sites (Fig. 15.S3).

The correlation functions between climate and regional tree-ring records were estimated over the 1952–2014 common period (62 years). In all these cases, it is observed that *N. antarctica* growth responds to both temperature and precipitation levels. The previous growing season temperatures are directly associated to the tree-ring growth, while the current growing season temperatures are inversely related to the tree-ring growth.

Conversely, it is observed that *N. antarctica* growth is inversely related to previous precipitation levels and directly related to current growing season precipitation levels. There is even a negative trend in *N. antarctica* growth due to rain during the winter (July). Besides, the R responses, compared to the C responses, are most closely associated to the regional pattern (Fig. 15.6).

Regional temperatures during the growing season (December to March) are significantly inverse related to tree growth ($r = -0.58$, $n = 62$, $p < 0.001$). Above-average temperatures increase evapotranspiration, reducing the water available for tree growth. In contrast, the accumulated precipitation during November and December was positively correlated with *N. antarctica* growth ($r = 0.34$, $n = 62$, $p < 0.01$). Thus, abundant rainfalls at the beginning of the growing season favor tree-ring growth. Since the 1950s to the present, a negative trend has been recorded in the *N. antarctica* radial growth. These pattern is consistent with a regional increase in the mean annual temperature and, consequently, with a regional water deficit (Fig. 15.7).

15.3.3   Cultural Land Use Changes

The local historical documents for each site showed substantial changes in land use over time (Table 15.3). These land use changes were used to interpret the differences in radial growth variations between the pairs of R and C chronologies at each site (2–5).

At each sampling site, we registered several periods with opposite trends in radial growth between the R and C chronologies (Fig. 15.8). In general, the largest differences between the growth patterns from R and C occurred in periods concurrent with the settlement of the estancias, i.e. large rural establishments for the
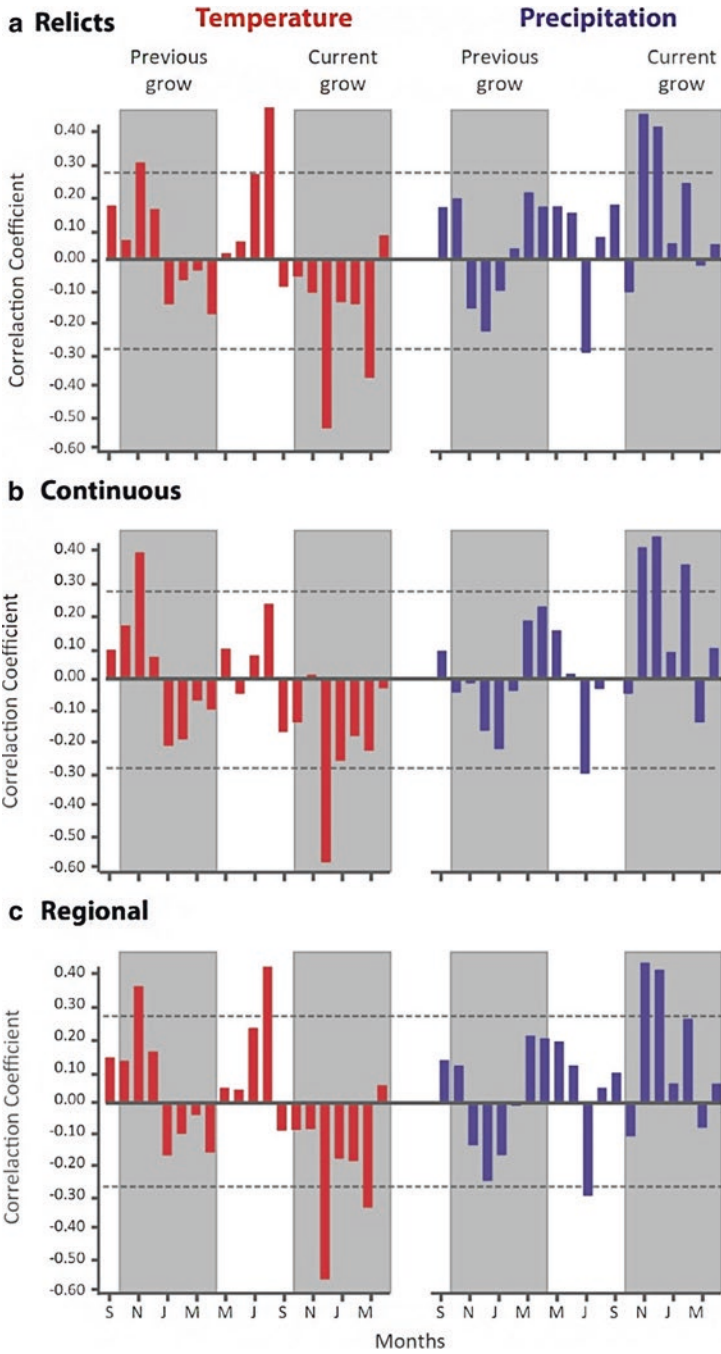
Fig. 15.6 Correlation functions between *N. antarctica* tree growth and regional climate. The red bars represent the relationship with temperature, and the blue bars represent the relationship with precipitation. (**a**) Relict forests. (**b**) Continuous forests. (**c**) Forests in the entire study area (*regional*). Dotted lines indicate 95% confidence levels
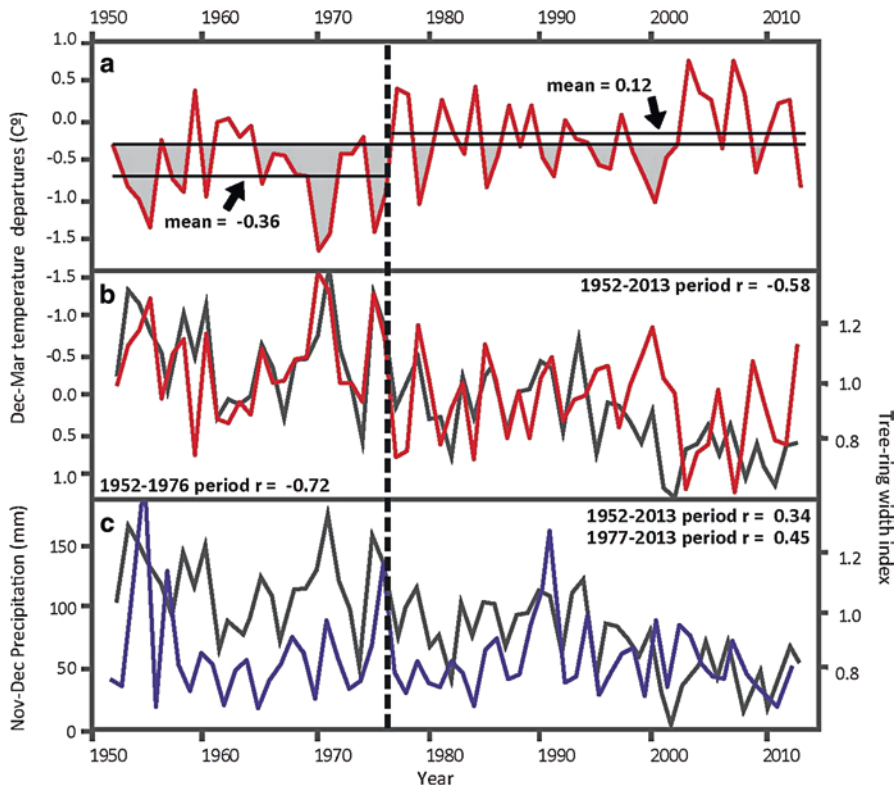
Fig. 15.7 Comparison between variations in *N. antarctica* regional tree growth and climate during the 1952–2013 period. (**a**) Variations in summer temperature (December to March; *red line*) in southern Patagonia showing the abrupt increase close to 0.5 °C around 1976/77. The temperature means for the periods before and after the 1976/77 climatic jump are indicated. (**b**) Regional temperature deviations from December to March (*red line*) and *N. antarctica* tree-ring width variations (*grey line*). (c) Punta Arenas accumulated precipitation for November and December (*blue line*) and *N. antarctica* tree-ring width variations (*grey line*). To facilitate visual comparison, the temperature axis has been inverted in (**b**). The correlation coefficients between climate and tree-ring variations are shown for the 1952–2013 period in (**b**) and (**c**), and the periods before and after the 1976/77 temperature jump in (**b**) and (**c**), respectively

extensive breeding of cattle or sheep. This extensive settlement process was associated with the intensification of the use of forests. For example, in Estancia Cancha Carrera (site 3), we observed very low correlation values between R and C chronologies from the first two decades of the twentieth century. These low correlations were concurrent with the settlement of Cancha Carrera affecting the C forests. Around 1945 similar breeding practices were applied in both stands (R and C), and after that period, correlation values increased sharply (Fig. 15.8b). Conversely, records were similar since the establishment of governmental protected areas, or during periods when the intensity of land use was similar in R and C. For example, towards 1980 in Punta Gruesa Natural Reserve (site 4) the anthropic activity

**Table 15.3** Historical changes in cultural land use in each study site

Study site	Code site	Historical events
Perito Moreno national park	1	Between 1910 and 1937, the settlers based their economy on the intensive extraction of firewood for sale and on cattle ranching. R and C were strongly intervened. In 1937, Perito Moreno National Park was created. In 1975, the extraction of firewood was interrupted. In 1982, the cattle were removed.
Río Guanaco, Los Glaciares National Park	2	In 1926, Estancia La Irene was built with sawmills and livestock activity in R and C. In 1937, Los Glaciares National Park was created; the woody industry was forbidden and precarious occupation and pasture permissions for cattle were assigned to the owners. Livestock use intensified between 1965 and 1985. In 2010, the cattle were definitively retired.
Estancia Cancha Carrera	3	In 1895, sawmills were established, and livestock activity began in C. R remained without human intervention. In 1945, in C the stocking density increased, and in R the intervention began. Since 2000, in C there were no changes of use. In R, the use intensified by the installation of a precarious cabin and the National Route 40 was paved, with the consequent increase in cattle ranching and wood extraction.
Punta Gruesa natural reserve	4	Between 1880 and 1890, the Sociedad Explotadora de Tierra del Fuego was established. Its economy was based on sheep farming and forest wood extraction in association with small sawmills. In 1940, the Yacimientos Carboníferos Fiscales (National Coal Company) was established. The use of wood increased due to road building, steam engines use, urban population rise, house heating and house building. In 1980, a cattle ranch was established in the area close to R. In 2002, Santa Cruz province created the Punta Gruesa Natural Reserve. R and C cattle use were reduced. In C, there is now a tourist camping area, but there is no access road to the R.
Estancia Rincón de los Morros	5	Since European immigration, the local population based its economy on extensive livestock (cows and sheep) and the intensive extraction of firewood in order to build and heat their homes.

R relict forest, *C* continuous forest

decreased. Since then, there has been a drastic increase in the correlation between the R and C chronologies, which continues after the creation of the Punta Gruesa Natural Reserve in 2002 (Fig. 15.8c).

15.4 Discussion

In this study, we developed the first dendrochronological records for *N. antarctica* in Argentina. The new chronologies contribute to the expansion of the dendrochronological network and provide new knowledge of ecological processes and climatic
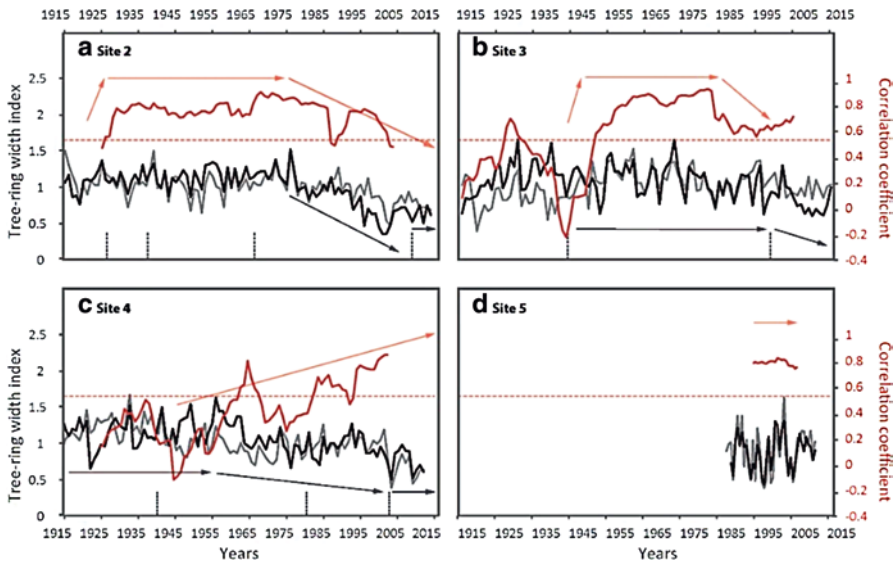
Fig. 15.8 Comparisons between R and C tree-ring width chronologies obtained at each site: (**a**) Río Guanaco – Los Glaciares National Park, (**b**) Estancia Cancha Carrera, (**c**) Punta Gruesa Provincial Natural Reserve and (**d**) Estancia Rincón de los Morros. Growth patterns (relict forests; *black lines*, continuous forests; *grey lines*) and the history of land uses (historical events mentioned in Table 15.3; *grey dotted lines* on the X-axis). Variations in the correlation coefficient between chronologies evaluated in 20 years lagged between them by 1 year (*red lines*). Correlation patterns (*red arrows*). Changes in growth patterns (g*rey arrows*). Dotted red lines indicate 99% confidence levels

variability across southern Patagonia (Villalba et al. 2009). The maximum reported age of 259 years for *N. antarctica* in Tierra del Fuego (Ivancich 2013) is a bit longer than those found in our study for Santa Cruz (206 years). This suggests that the maximum ages reached by *N. antarctica* in the southern extreme of South America would be around 200–300 years old. Furthermore, the intercorrelation between the series that integrate the regional chronology is similar to those reported for *N. pumilio* in the same region (Aravena et al. 2002b; Villalba et al. 2003; Suarez 2010).

The collection of samples for providing well-replicated dendrochronological records *of N. antarctica* is problematic. The difficulties are in part due to the stem architecture, which commonly has a sympodial growth, with trunks branched from the base. Minor fires used for opening the forest canopy and browsing at early stages of growth cause morphological changes in *N. antarctica* trees, including branching from the base (Veblen and Lorenz 1987; Aravena et al. 2002a). In addition, browsing affects tree-growth rates by reducing the tree photosynthetic biomass (Veblen et al. 1992; Relva and Veblen 1998; Martínez-Pastur et al. 1999; Pulido et al. 2000; Srur et al. 2013). In addition, these forests usually present deficient phytosanitary conditions (Fig. 15.9). *N. antarctica* trees frequently have hollow trunk centers and abundant rotting wood. There are reports about several species of fungi that cause

Fig. 15.9   The *N. antarctica* relict forest in Punta Gruesa Natural Reserve, Santa Cruz (site 4). The phytosanitary status of the individuals is regular to poor with numerous dead trees and branches

chestnut and white rot in the xylem of several *Nothofagus* species (Rajchenberg et al. 2014). One of the most conspicuous fungus genus is *Cyttaria*, which develops obligatory parasitism with *Nothofagus*. *Cyttaria* hyphae alter the morphology of *N. antarctica*'s vascular system and generate extrusions that totally or partially surround the stem (Ipinza et al. 1989). Another very frequent interaction occurs between *Nothofagus* trees and *Misodendrum* species. Although *Misodendron* presence is not always a direct indication of tree decline (Rodríguez-Catón and Villalba 2018), these hemiparasitic plants may affect the *Nothofagus* radial-growth rates (Velásquez et al. 2012).

The well-defined tree rings in *N. antarctica* make this species suitable for developing good chronological records. However, the sampling effort was high at most sites with only 41% of the collected radii cross-dated and used for the chronology development. In addition to the poor health, the endogenous dynamics of the *N. antarctica* related to site and competition factors rather than climate reduce the interannual common signal in tree growth (Wigley et al. 1984). Some local factors, such as anthropogenic fires, gap canopy dynamics, local defoliation episodes, and differences in the browsing intensity between nearby forest sectors may contribute to the lack of a common signal between trees. In spite of the mentioned limitations, the radial growth of *N. antarctica* is sensitive to regional climatic variability. This characteristic offers the opportunity to use the *N. antarctica* ring-width variations to estimate past changes in environmental fluctuations.

The *N. antarctica* radial growth is positively correlated with spring precipitation. Radial growth is favored by abundant precipitations at the beginning of the growing season (November and December). On the other hand, tree-ring widths are narrower when the temperature during the growing season (December–March) is above average (Fig. 15.6). Our results are consistent with those reported by Lara et al. (2005), Suarez (2010) and Jara (2011) for other *Nothofagus* species in dry Patagonian environments.

The stronger relationship between tree growth and temperature ($r = -0.58$) in comparison with precipitation ($r = 0.34$) is related to the lower spatial representativeness of the Punta Arenas precipitation record in relation to the regional temperature pattern (Figs. 15.S1 and 15.S3). It is known that precipitation is more spatially and temporally variable than temperature (Aravena and Luckman 2009). Therefore, we can assume that precipitation records in the proximity of the sampling sites would provide stronger relationships between rainfall and *N. antarctica* growth.

The regional chronology showed a progressive decrease in the radial growth of *N. antarctica* from the 1950s to present, which is consistent with the increase in summer temperatures since 1977 and the negative trend in precipitation starting in the 1990 across the region (Fig. 15.7). The increase in water deficit, exacerbated by higher summer temperatures and scarce precipitation, reduces tree growth. Similar negative trends in radial growth have been documented in several studies for other *Nothofagus* species in the Patagonian Andes (Villalba et al. 2003; Jara 2011; Villalba et al. 2012; Soto-Rogel and Aravena 2017). Interestingly, the relationships between tree growth and temperature were much stronger prior to the documented climatic jump of 1976/77 (Villalba et al. 2003). As a consequence of the shift from the negative to positive phase of the Pacific Decadal Oscillation in 1976/77, an abrupt increase in temperature was recorded all along the coast of South America, including Patagonia (Villalba et al. 2003; Vuille et al. 2015). Based on the regional temperature variations, this 1976/77 jump was associated with an approximate 0.5 °C increase in summer temperatures (Dec-Mar) throughout our study area (Fig. 15.7). Comparatively to the long-term 1952–2013 relationship between tree growth and climate ($r = -0.58$), it was much stronger during the colder interval from 1952 to 1976 ($r = -0.72$). In contrast, the relationship between tree growth and precipitation becomes stronger during the more recent, relatively warmer interval starting in 1977 ($r = 0.34$ and $r = 0.45$ for the long-term 1952–2013 and 1977–2013 intervals, respectively). These results suggest changes in the intensity of the relationships between climate and *N. antarctica* tree growth modulated by recent climate changes.

The comparative analysis between the R and C chronologies reveals periods of poor relationships between the chronologies, consistent with different forest stand histories (Fig. 15.8; Table 15.3). The most remarkable differences in the *N. antarctica* growth patterns are associated with the local history of cultural land use. For Perito Moreno National Park (site 1), it was not feasible to cross-date the samples. This reflects the impacts of persistent anthropogenic changes since the beginning of the twentieth century when the first cattle ranches were established in the region. At that time, the economy of Estancia El Rincón was based on livestock production and firewood sale. For the intensive extraction of wood from the *N. antarctica* for-

est, a network of trails was built in the area. During our surveys, abundant tree stumps were observed in the steppe matrix located between R and C, which evidences the recent anthropic fragmentation of these forests. In 1937, the area was declared a Natural Reserve and in 1945 this area became part of the Perito Moreno National Park. However, it was not until 1975 that the cattle were effectively removed from the area, and in 1982 firewood extraction was finally interrupted.

At the Sectional Río Guanaco in Los Glaciares National Park (site 2; Fig. 15.8a), we observed an abrupt increase in the correlation between the R and C chronologies which started in the 1920s. Around 1926 the main facilities for the cattle ranch La Irene were built, and livestock and forest practices were unified in R and C forests. Although Los Glaciares National Park was created in 1937, cattle were not removed from the Rio Guanaco's area. In contrast, in the 1960s the owners increased six times the stocking. This reduced *N. antarctica* growth, affecting R to a greater extent than C forest. In 2010, the cattle were definitively removed, which is consistent with a period of stabilization in tree growth.

In Estancia Cancha Carrera (site 3; Fig. 15.8b), the cattle ranch was established at the end of the nineteenth century. The livestock and forestry activities focused on C, and R remained without human intervention until 1945. Coinciding with this first period, higher growth rates occurred in R than in C. Results showed a significant increase in the correlation after 1945, probably due to the establishment of four paddocks with different use intensities. This subdivision caused an increase in the livestock numbers in C and the first introduction of cattle in R. In 2000, a little ranch was installed in R at the time that the National Route 40 was been paved. All these changes provoked and intensified the use of firewood for heating. The proximity of the forest to the new route facilitates the extraction of firewood from R. These events, coupled with the regional increase in temperature, induced the extremely low growth in R observed during the last decade.

The first records of permanent use in Punta Gruesa Natural Reserve (site 4; Fig. 15.8c) date back to the end of the nineteenth century. At that time, the Sociedad Explotadora de Tierra del Fuego, the most important cattle company in the history of Chilean-Argentinean Patagonia, started working in the area. Historically, C has been more intensively intervened than the R. While R is isolated in a sector without any access trail and with a high slope (>30°), C has been intensely used for the extraction of firewood. Moreover, C was exposed to roads that were previously used to transport livestock to Chile. The relationships between chronologies were poor until the 1940s, when they became more similar to each other. It was precisely in 1940 that the exploitation of the area by Yacimientos Carboníferos Fiscales (National Coal Company) began. As a consequence, logging for trail building started as well as the construction of urban and rural infrastructure. The use of wood for house heating and steam engines also increased. In 1980, a farm breeding livestock was established in the area with a limited number of animals and remains until today. Results showed an increase in the correlation between chronologies since 1945, following the establishment of Yacimientos Carboníferos Fiscales, and the persistent decrease in radial growth, reaching a minimum growth at C in 2003. In 2002, the

Punta Gruesa Natural Reserve was created and logging prohibited in the area. In recent years, the growth rate tends to stabilize.

Finally, the Estancia Rincón de Los Morros (site 5; Fig. 15.8d) represents an area with a permanent history of intense anthropogenic uses and changes. Since the arrival of the Europeans, the economy was based on extensive livestock production and the extraction of wood by selective logging. As a result, the trees present in the area are young (<69 years), so that the chronologies obtained were short and strongly correlated. This led to the assumption that the intensive anthropogenic uses in Estancia Rincón de Los Morros have a lasting impact on the *N. antarctica* longevity and growth pattern.

The presence of livestock in the forest causes persistent browsing, soil erosion in overgrazed sites and damages in the root systems, leading to a decrease in primary forest productivity (Teague and Smit 1992; Quinteros 2018). Browsing also generates changes in the composition, structure and functional diversity of the understory plant community. In particular, it induces the occurrence of a shrub stratum and the increase of browsing resistant invasive species (Relva et al. 2009; Arias-Sepúlveda and Chillo 2017). Other authors have reported dominance of herbs and annual grasses in overgrazed sites (Gowda et al. 2012; Peri et al. 2016). As a consequence of the understory plant community changes, the decomposition rate (Vázquez 2002; Arias-Sepúlveda and Chillo 2017) the nutrient cycling (Relva and Núñez 2014), and the net primary productivity can be altered (Lencinas et al. 2011). In addition, the livestock production includes practices to increase the forage availability by opening the forest canopy with small fires, thinning and dead tree removal (Somlo et al. 1997; Peri et al. 2016; Amoroso et al. 2018). As a result of the increase in livestock density at *N. antarctica* stands, the intensification of human practices in neighboring forests is inevitable. These induces in turn, important changes in the growth patterns not related to climatic variability.

In conclusion, our work reports on the first tree-ring chronologies from *N. antarctica* developed for the Argentinean sector in southern Patagonia. Given the common tortuous form of *N. antarctica* trees in the forest-steppe ecotone and the poor health conditions of these forests, the development of tree-ring chronologies requires a sampling strategy including a large number of trees. Only 41% of the collected samples were cross-dated and included in the chronologies. At the forest-steppe ecotone, the interannual variations in *N. antarctica* radial growth are particularly sensitive to water availability during the growing season. The *N. antarctica* growth increased with the increase in the water supply. However, these relationships between climate and tree growth seem to be unstable and vary according to the prevailing climatic conditions (cold versus warm periods). In the recent warmer decades following the 1976/77 climatic shift in the Pacific Decadal Oscillation (PDO) (Mantua and Hare 2002), the radial growth seems to be more closely related to spring rainfall variations. Finally, the interactions between land use changes and climate variability considered in this study provide a valid approach to interpret past variations in *N. antarctica* tree-ring in the forest-steppe ecotone in the Patagonian Andes foothills.

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