

Austrocedrus chilensis growth decline in relation to drought events in northern Patagonia, Argentina

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Abstract The significant mortality of the *Austrocedrus chilensis* (D. Don) Pic. Serm. et Bizarri forests, locally known as “Mal del Ciprés”, has been reported since 1945 for most sites across its distribution in Argentina. However, the cause of this decline is still a topic of discussion. In this study, radial growth patterns from symptomatic and asymptomatic *A. chilensis* trees were analyzed to determine the influence of drought events on tree growth. Fifty pairs of symptomatic and asymptomatic trees with similar DBH, competition, and microsite conditions were

cored at five pure *A. chilensis* stands near El Bolsón, Río Negro, Argentina. A reference chronology from non-affected trees was used to cross-date all cores and to determine the relationship between *A. chilensis* radial growth and climate. The growth of *A. chilensis* is favored by above average precipitation in late spring–early summer (November and December). A strong relationship was also observed between radial growth patterns and the Palmer drought severity index, a measure of the regional water deficit. Significant differences in growth patterns were recorded between symptomatic and asymptomatic trees. Following extreme drought events, the growth of symptomatic trees is consistently lower than in asymptomatic trees. Based on the larger number of droughts recorded during the past decades and on future climatic predictions suggesting increasing trends in the frequency and intensity of drought events in northern Patagonia, a gradual increase in the number of trees affected by “Mal del Ciprés” along the twenty-first century is likely expected.

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Introduction

Growth rates, a measure of tree vigor, reflect the integrated response of individuals to current and past environmental stresses (Kozłowski et al. 1991; Pedersen 1998). Stem growth has relatively low priority for resource allocation within trees, and consequently, is a good indicator of environmental stress (Waring and Pitman 1985). In consequence, interannual variations in ring widths provide an indirect record of temporal changes in tree stress (Pedersen

1998). The integration of multiple stresses over time leads, in most cases, to a decline in growth, the onset of tree weakening, and a larger sensitivity to subsequent stress (Monserud 1976; Pedersen 1998). Manion's dieback model predicts that previous droughts or insect attacks lead to decline, which in turn make trees more susceptible to death from other environmental factors such as recurrent droughts (Manion 1981).

The *Austrocedrus chilensis* (D. Don) Pic. Serm. et Bizzarri decline and significant mortality, locally called “Mal del Ciprés” (sensu Filip and Rosso 1999), are characterized by progressive withering, yellowing of the crowns and the gradual defoliation of trees (Havrylenko et al. 1989; Filip and Rosso 1999). Trees of all size classes growing in forests with different structures are affected by “Mal del Ciprés” (Havrylenko et al. 1989; La Manna et al. 2006). Root rot and decay, and internal bark necrosis at the root, root collar and lower part of the stem, have also been observed in affected trees (Rajchenberg and Cwielong 1993; Greslebin et al. 2005).

The first massive mortality of *A. chilensis* stands was recorded in the year 1945 in the Nahuel Huapi National Park (Varsavsky et al. 1975). Presently, dispersed and aggregated mortality patterns are observed in most *A. chilensis* stands along their natural distribution in Argentina (Havrylenko et al. 1989; La Manna and Rajchenberg 2004). Although several etiological models have been proposed to explain this mortality, including biotic, abiotic or a combination of both factors, the causes of “Mal del Ciprés” are still today a topic of discussion (El Mujtar and Andenmatten 2007).

The first attempt to compare radial growth patterns from symptomatic and asymptomatic *A. chilensis* trees was conducted by Calí (1996) in an area of the Nahuel Huapi National Park, near Bariloche, Argentina. According to Calí (1996), the “Mal del Ciprés” was associated with a decrease in radial growth, that in most cases, started several years before external crown dieback was evident.

Drought events in northern Patagonia influence the structure of *A. chilensis*–*Nothofagus dombeyi* forests by affecting tree demography (Villalba and Veblen 1997a, 1998; Suarez et al. 2004). Episodes of mortality of *A. chilensis* over the past ca. 100 years were related to exceptionally dry spring–summer events during the 1910s, in 1943–1944 and in the 1950s (Villalba and Veblen 1997a, 1997b, 1998; Villalba et al. 1998). Calí (1996) proposed warm and dry climatic conditions as triggers of the “Mal del Ciprés” mortality.

The main objectives of this study are: (1) to compare the radial growth patterns between pairs of trees with and without external symptoms of “Mal del Ciprés” and (2) to determine the influences of extreme drought events in *A. chilensis* growth decline near El Bolsón, Patagonia, Argentina.

Materials and methods

Study area

Five pure *A. chilensis* stands were sampled along the north–south oriented intermountain valley nearby the town

Fig. 1 Location of the sampling sites (triangles) along the El Bolsón intermountain valley. The interstate boundary between Río Negro and Chubut is indicated. Contour interval between isolines is 100 m

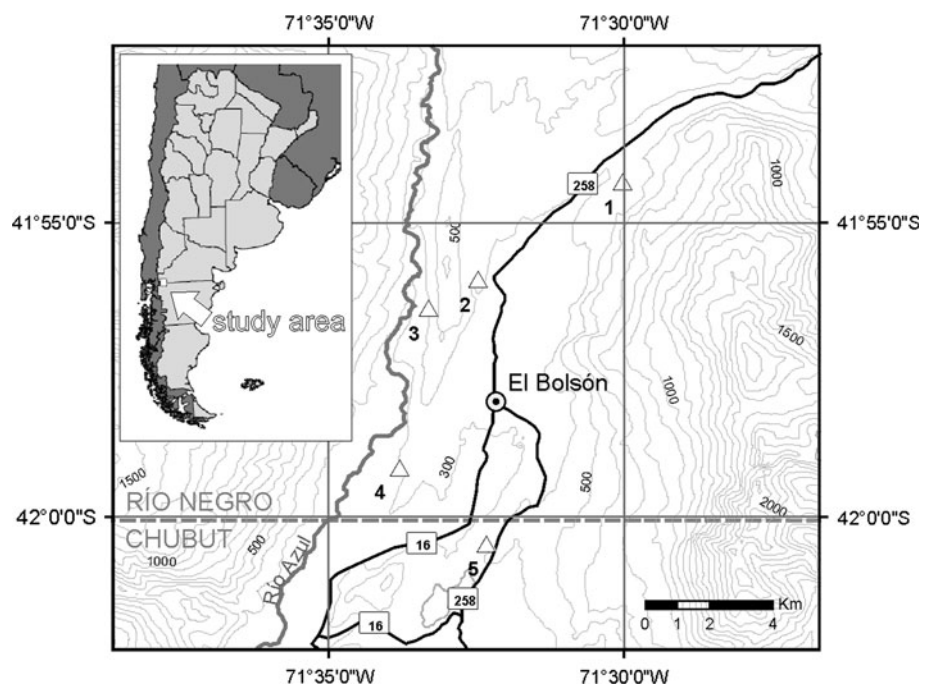


Table 1 Site characteristics of the *Austrocedrus chilensis* stands

Stand	Altitude (m a.s.l.)	Aspect	Slope (°)	BA (m ² /ha)	HD (m)
1	491	S (159°)	2	25	25
2	398	W (267°)	20	35	25
3	311	W (266°)	9	31	26
4	401	W (248°)	1	35	21
5	467	E (100°)	14	40	25

BA basal area, HD mean dominant height

of El Bolsón (41°57'01"S, 71°31'54"W), Río Negro province, Patagonia, Argentina (Fig. 1, Table 1). The study area covered 2,542 ha.

The area has a mean annual temperature of 9.3°C and total annual precipitation of 904 mm concentrated in winter (Servicio Meteorológico Nacional 1981). Summers are characterized by high irradiance and extreme air dryness (Cordon et al. 1993). The Thornwaite's water balance indicates a surplus of winter precipitation (445 mm) and a deficit (146 mm) during the spring–summer growing season (Goya et al. 1995). Soils are Udivitrand type developed from Holocene volcanic ashes showing good effective depth and drainage (Buamscha et al. 1998).

The monospecific forest consists of even aged stands of *A. chilensis* (Dezzotti and Sancholuz 1991). Due to extensive fire events late in the nineteenth and beginning of the twentieth centuries, individuals older than 100–120 years are rare (Willis 1914; Veblen et al. 1995).

Field sampling and laboratory analysis

In the summers of 2007 and 2008, 50 pairs of symptomatic and asymptomatic *A. chilensis* trees were cored. Symptomatic trees were considered those trees which had at least 25% of dead crown area with light-green to yellow needles. The sampling strategy corresponds to a matched-pair case-control study, which is widely used in epidemiology (Breslow and Day 1980; Woodward 1999; Bigler and Bugmann 2003). For each stand, ten pairs of living trees were identified. For each pair, the selected individuals were similar in DBH (>10 cm), height, crown-class position, competition status, and microsite conditions. The average distance between both trees of a pair was lower than 15 m. At least two cores were taken from each tree at ca. 1.1 m height.

Twenty healthy, dominant trees from an *A. chilensis* stand in the northern part of the study area were cored for developing a reference chronology. Past events of “Mal del Ciprés” have not been documented for this stand (Chauchard and Barnaba 1986). All cores from the five stands were cross-dated against this reference chronology.

Cores were mounted, sanded and visually cross-dated following Stokes and Smiley (1968). Following the Schulman's (1956) convention for the Southern Hemisphere, annual rings are assigned to the year in which the ring formation starts. Ring widths were measured to the nearest 0.001 mm, and the computer program COFECHA (Holmes 1983) was used to detect measurement and cross-dating errors.

Two different standardization methods were used for developing the chronologies. The tree-ring series used to develop the reference chronology were standardized using negative exponential functions. In contrast, the symptomatic and asymptomatic ring width series were adjusted to a horizontal line equal to the mean ring width of each series. This standardization method facilitates the detection of past disturbance events (such as insect outbreaks or fires), which are more difficult to identify when the individual series are standardized using polynomial or cubic spline functions (Veblen et al. 1991). The series standardization was conducted using the program ARSTAN (Cook 1985).

Standardized tree-ring series from symptomatic and asymptomatic trees were first averaged into individual mean series, then into symptomatic and asymptomatic local chronologies for each site, and finally in symptomatic and asymptomatic regional chronologies. In order to reduce the interannual variability in the tree-ring series, the local and regional chronologies from symptomatic and asymptomatic trees were filtered using a 5-year running mean.

Statistical analysis

The quality of the reference chronology was assessed on the basis of the following statistics: mean sensitivity (MS), the average correlation between all series (RBAR), the expressed population signal (EPS), and the first-order autocorrelation, a measure of the association between growth rings in two consecutive years.

The MS represents a measure of the interannual variability in tree-rings (Fritts 1976), whereas, the RBAR is a measure of the common variance between the single series in a chronology (Wigley et al. 1984). Running RBARs illustrate changes in the strength of common forcings of tree growth over time. The EPS measures how well the finite sample chronology compares with a theoretical population chronology based on an infinite number of trees (Wigley et al. 1984). It varies from 0.0 to 1.0. The cutoff point for accepting EPS suggested by Wigley et al. (1984) is 0.85. The RBAR and EPS values were computed using a 20-year moving window with a 10-year overlap.

Correlation functions (Blasing et al. 1984) were used to determine the influence of climatic factors on the growth of *A. chilensis*. Interannual variations in the reference chronology were compared with temperature and precipitation

records from the Bariloche meteorological station (Servicio Meteorológico Nacional: 41°09'S–71°09.6'W) and with the 2.5° × 2.5° gridded Palmer drought severity index from Dai et al. (2004) (central point: 41°15'S–71°15'W). The Palmer drought severity index (PDSI, Palmer 1965) takes into account precipitation, evapotranspiration and soil moisture conditions, all of which are determinants of hydrologic droughts. The PDSI is a standardized measure, ranging from about –10 (dry) to +10 (wet), of surface moisture conditions that allow comparisons across regions and time.

A correlation function between the reference tree-ring chronology and monthly values of temperature and precipitation was computed for the 16-month period from January of the previous growing season to April (i.e., at the end of the current growing season) of the growth year. Calculations were performed for the common periods of the chronology with the instrumental climatic record and PDSI series, including the periods 1915–2005 and 1901–2005, respectively.

A discriminant analysis (DA) was conducted on the interannual variations in radial growth to determine the correspondence between tree growth patterns and external manifestations of the “Mal del Ciprés”. The DA is a method used to model the extent to which an observation belongs to a group based on the values of several variables, so as to assess the adequacy of classification and then to determine the most likely group for a given observation knowing only the values of the variables for this observation (Anderson 1957; McLachlan 1992). Discriminant analysis (Monserud 1976; Crow and Hicks 1990) in addition to others methods (neural networks, classification and regression trees, logistic regressions) have been widely applied to model tree mortality (Bigler and Bugmann 2004). In dendrochronology, e.g. DA was used to detect the most discriminant years in tree-ring chronologies (Dutilleul and Till 1988) and to clarify the species-specific signal as it allowed to group individual trees according to their species (García-González et al. 1997). In our study, radial growth years and trees' condition (symptomatic and asymptomatic) were considered as the discriminant variables and categories, respectively, over a common period of time.

Crossing-curve events were assigned to years when the running means from the symptomatic and asymptomatic growth indexes intersect, representing the onset of the period with persistent differences between groups. Paired student's *t* tests were performed between symptomatic and asymptomatic mean annual indexes, and the mean annual index differences were calculated for each site.

Differences in the 10-year mean index before and after the crossing-curve events were analyzed using a two-way repeated measures ANOVA where the moment (before and after the events) was considered as a within-subject effect. Shapiro–Wilk tests were performed in order to evaluate the

normality in the series. Significant differences between pairs of means in ANOVA were analyzed using the Fisher LSD post test.

Running *t* tests of 5-year contiguous intervals were conducted for regional chronology index differences. The recorded *t* values were assigned to the last year of the first 5-year group in the comparison. A superposed epoch analysis (SEA, Swetnam 1993) was performed in order to test the departures of PDSI during the 15 years with the most negative extreme values in the running *t* tests. In SEA, each year in a list of event dates is taken as a key or zero-window year. Chronology values for 11-year windows (5 years before and 5 years after the events) are expressed as departures from the mean for the 11 year in each case. The departures for all the 11-year windows are superposed and averaged. A Monte Carlo simulation technique was used to assess statistical significance. Thus, 1,000 simulations were performed by random sampling with replacement (Mooney and Duval 1993) to determine the probability associated with the average departures for the key dates. SEA was conducted using program EVENT version 6.02P (<http://www.ltrr.arizona.edu/software.html>). In all analyses, significant differences were considered for $\alpha = 0.05$.

Results

Reference chronology

The reference tree-ring chronology has a mean ring width of 1.899 mm (SD 0.365) and covers the interval

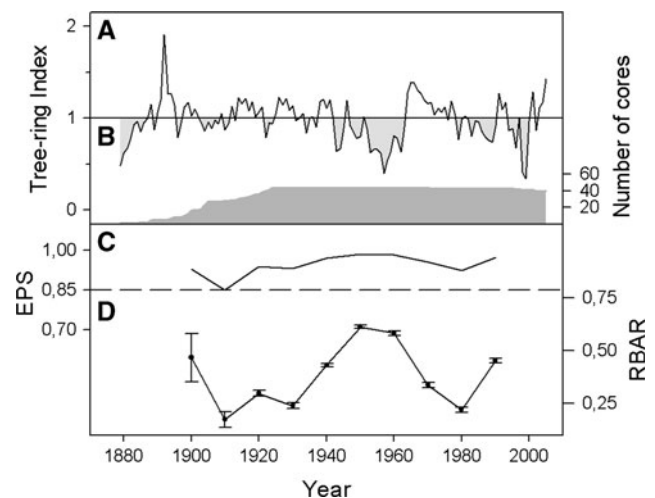


Fig. 2 Reference chronology of *Austrocedrus chilensis*. Tree-ring indices (a) and sample size (b) are shown for the interval 1879–2006. The expressed population signal (EPS, c) and the running mean correlations between series (RBAR, d) were estimated over 20-year windows with 10-year overlaps (with standard error bars). The cutoff point for accepting EPS is 0.85 (dashed line)

1879–2006 (127 years; Fig. 2). The chronology statistics (MS = 0.160, mean RBAR = 0.429, first-order autocorrelation = 0.602) are within the ranges of *A. chilensis* tree-ring records in the region (Villalba and Veblen. 1997b). Stable EPS values exceed the cutoff value of 0.85 during the twentieth century.

The correlation function analysis indicates that the radial growth of *A. chilensis* is positively associated with precipitation during most of the year (Fig. 3). Statistically significant correlations between rainfall and tree growth are observed in April, May and June (autumn), and in November and December (spring) during the current growing season. In contrast to precipitation, tree growth is negatively related to temperature during growing seasons, being highly significant for November and December during the current growing season. Positive and significant relationships between the PDSI and radial growth occur for most of the months, except for August and September with positive, but not significant correlations (Fig. 3).

Validation of tree classification

A total of 89 mean individual series covering the interval 1940–2005 were included in the discriminant analysis. Two asymptomatic trees from site 1 (13A and 37A) were incorrectly predicted as symptomatics. In contrast, 100% of the symptomatic trees were correctly classified. The overall

classification accuracy of the DA model is 97.7%, indicating a high degree of success for the classification of symptomatic and asymptomatic *A. chilensis* trees.

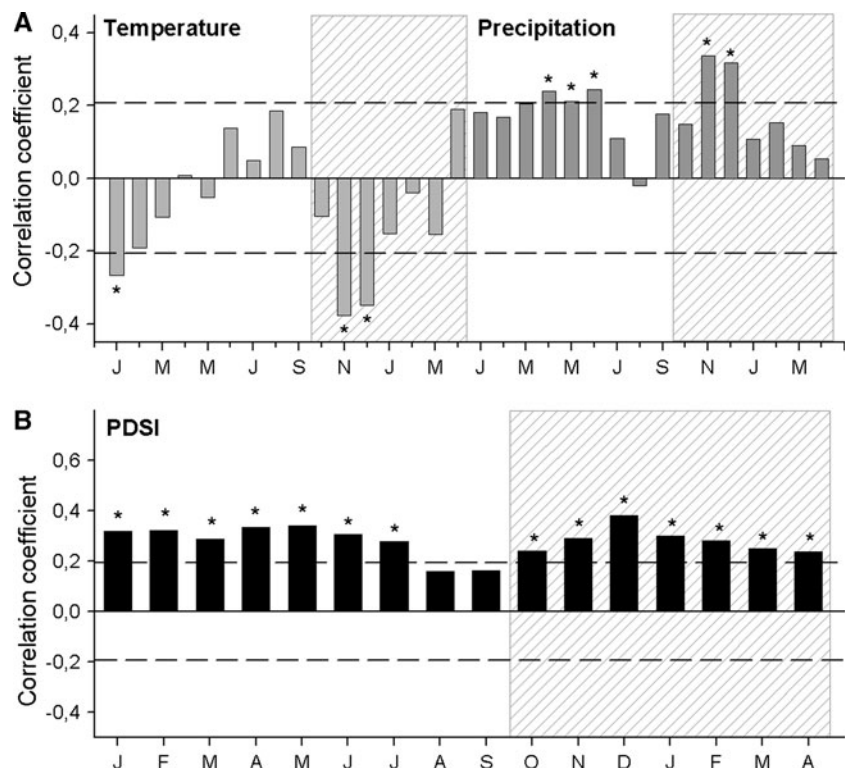
The most recent ring in five symptomatic trees does not match with the sampling date. For example, the last ring formed in a radius from tree 17S was dated to 1997, whereas, the other two radii from the same tree were dated to 2006. All trees were alive at the coring time in March 2007.

Growth patterns for symptomatic and asymptomatic trees

The development of tree-ring chronologies from both symptomatic and asymptomatic trees in each stand allows the identification of the years in which the radial growth from these groups starts to diverge (Fig. 4). Four divergence events were clearly detected: 1932, 1943, 1944 and 1963. Although the curves crossed over in the year 1932 at site 1, differences in tree growth between symptomatic and asymptomatic trees started to be consistently negative since 1943. Divergences in tree growth between symptomatic and asymptomatic trees started in 1944 and 1943 at stands 2 and 3, respectively, whereas in sites 4 and 5 persistent differences were recorded since 1963.

Differences between the chronologies from symptomatic and asymptomatic trees show a consistent pattern of

Fig. 3 Correlation functions for the reference chronology of *Austrocedrus chilensis*. **a** Correlation coefficients between ring width indices and monthly temperature and precipitation from Bariloche during the interval 1915–2005. **b** Correlation coefficients between ring width indices and monthly PDSI for the interval 1901–2005. In both graphs, the shaded areas represent the current growing season (October–April) and the dashed lines the 95% confidence limits



positive followed by negative values since the dates when the chronologies intercept. This observation indicates that symptomatic trees show larger tree growth than asymptomatic trees before chronologies intercept. The paired t tests showed significant differences in tree growth between symptomatic and asymptomatic trees before and after the chronologies interception dates.

The interval with significant negative differences in radial growth between symptomatic and asymptomatic trees varied between sites. These intervals range between 4 and 49 years in length for sites 4 and 3, respectively (Fig. 4). For all sites, however, significant differences were recorded in the most recent period of the records. Differences in radial growth between symptomatic and asymptomatic trees increased, particularly, after 1999.

Two-way repeated measures ANOVAs were used to statistically validate the differences in tree growth for 10-year periods before and after the curve intersection dates (Fig. 5). Decreases in radial growth were recorded for sites 1, 2 and 3. In the case of symptomatic trees, differences were statistically significant in those three sites. Individual mean series from sites 4 and 5 show increases in the 10-year mean growth after the intersection dates. However, symptomatic trees in sites 4 and 5 showed smaller increases in radial growth than asymptomatic trees.

Regional analysis

Symptomatic and asymptomatic trees from all sampling sites were grouped into regional chronologies. The 5-year running means for the regional chronologies intersected in the year 1944 (Fig. 4). Differences between the regional indices have been persistently negative since 1944 and significantly different since 1963. An increasing negative trend in the index differences has been recorded since 1999.

The 15 most negative t values, based on 5-year contiguous means, were identified in the regional differences between symptomatic and asymptomatic trees (Fig. 6). The most significant values lag 1 year from the extreme drought events identified in the October–March PDSI series. The years 1943, 1944 and 1963 are coincident with the intersection dates registered at the local stand level.

A superposed epoch analysis was conducted for the whole area to determine the temporal evolution of the October–March PDSI for years in which the running t test of the regional index difference reached the most negative values (1909, 1910, 1928, 1929, 1930, 1940, 1941, 1942, 1943, 1944, 1956, 1963, 1990, 1999 and 2000). The October–March PDSI record exhibits significantly negative (droughts) departures for 1 year before the occurrence of extreme negative regional differences between chronologies (Fig. 7).

Fig. 4 Symptomatic (grey) and asymptomatic (black) tree-ring chronologies (left) and their corresponding index differences (right) at stand and regional scale. To emphasize the long-term oscillations in the records, the chronologies are shown as 5-year running mean curves. Arrows indicate the intersection dates for the 5-year running mean curves. On the right plots, segments capped with asterisk correspond to intervals with index differences statistically different ($p < 0.05$) from the long-term mean based on paired t tests. The sample depth of each chronology is also shown at the bottom of each pair of chronologies. Sites are indicated on the upper-right corner of each plot

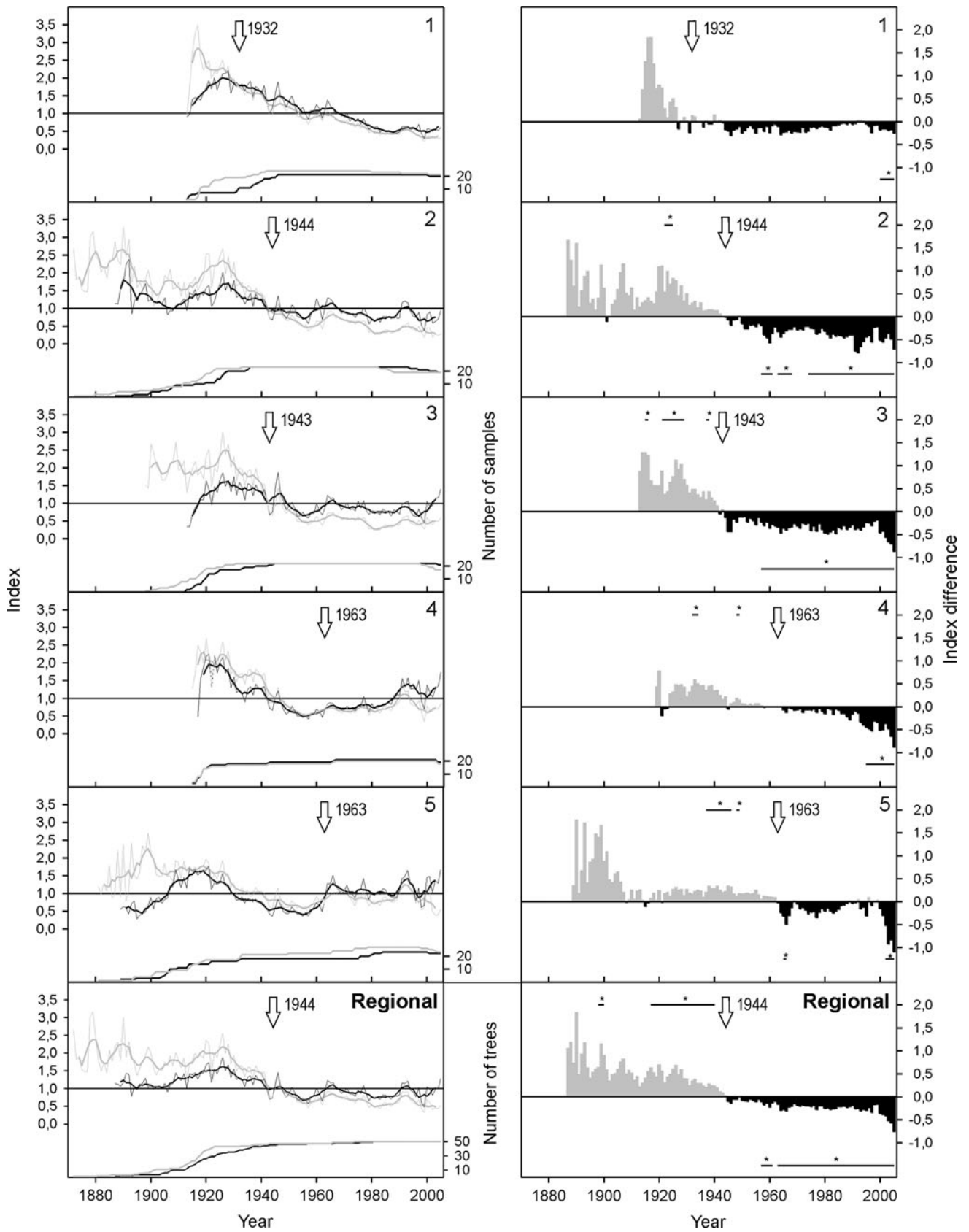
Discussion and conclusion

The reference chronology of *A. chilensis* provides a reliable context for dating tree-ring series from symptomatic and asymptomatic trees and for evaluating the climate–tree growth relationships. In this region, the radial growth of *A. chilensis* is favored by above-average precipitation in late spring–early summer (November and December). Temperatures above the long-term mean during late spring–early summer increase evapotranspiration, reduce water supply, and diminish tree growth. Our results are consistent with previous studies for several *A. chilensis* stands along its distribution in Argentina (Villalba and Veblen, 1997b). The positive relationship between radial growth and precipitation in the previous and current growing season indicates that the growth of *A. chilensis* is extremely dependent on water supply. This observation is consistent with positive relationships between radial growth and the PDSI (Fig. 3b).

The DA model results, based on the growth pattern of individual trees, show an excellent agreement between field classification and tree growth patterns for symptomatic vs. asymptomatic trees. Thus, tree-ring patterns from *A. chilensis* can be used in advance to assess future changes in tree health considering that symptomatic trees show a persistent decline in radial growth many years before the external symptoms (chlorosis and defoliation) are evident.

Cores with the outer-most ring dates prior to the sampling year indicate partial cambial mortality in sectors of the stem. Rajchenberg and Cwielong (1993), Calí (1996) and Amoroso (2009) have also reported partial cambial mortality in declining *A. chilensis*. In some individuals, almost 40 years of difference between radii were reported. Rajchenberg and Cwielong (1993) observed that the sectors in the trees showing partial cambial mortality were also affected by root and stem rots. However, according to these authors, partial cambial mortality was localized in the lower 0.6 m of the stem. Only 5 of the 100 sampled trees in our study showed partial cambial mortality. Since we sampled on average at 1.1 m height, many sectors with cambial mortality might have been missed.

Symptomatic and asymptomatic chronologies at local and regional scales show significant differences in tree



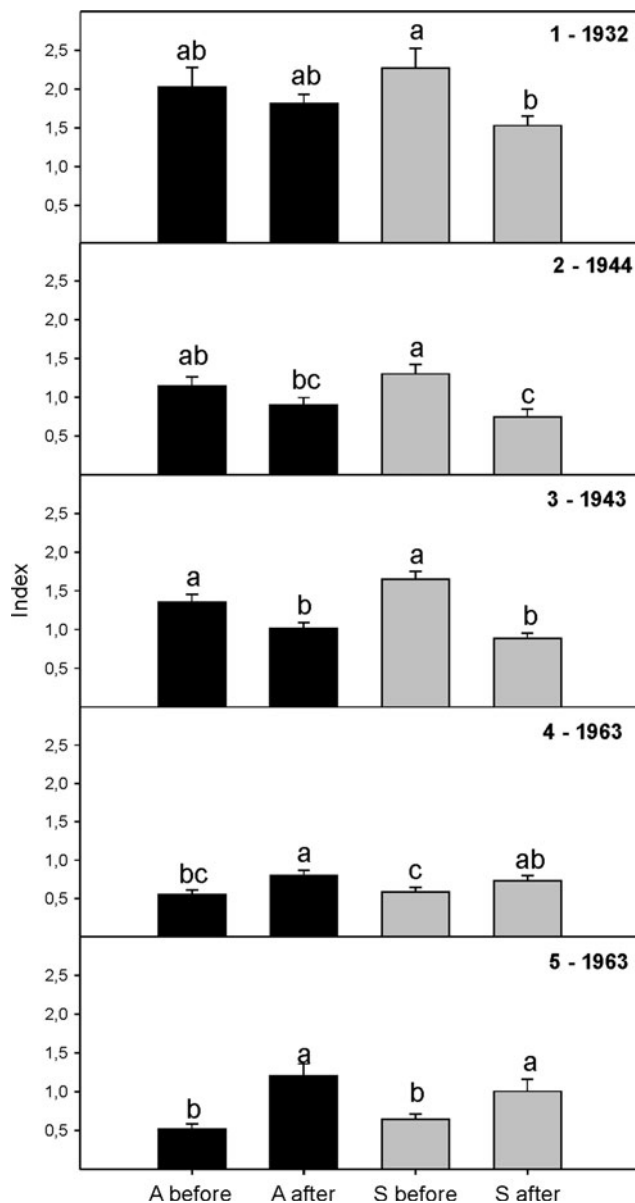


Fig. 5 Mean 10-year radial increments before and after the intersection dates for the asymptomatic (black bars) and symptomatic (grey bars) individual mean series for each sampling site. Site codes and intersection dates are indicated in the upper-right corner of each plot. Means with the same letter are not significantly different at $p < 0.05$ based on two-way repeated measures ANOVA and Fisher LSD post tests

growth patterns. Crossing-curve points, providing the dates when radial growth from symptomatic trees starts to be consistently lower than in asymptomatic trees, were identified at all sites and at the regional level. However, the intersection dates vary between sites (Fig. 4). Crossing points in sites 2 and 3 occurred in 1944 and 1943, respectively, in response to extreme droughts in 1942 and 1943. In addition, extensive fires were recorded in northern

Patagonia during 1943 (Tortorelli 1947; Kitzberger et al. 1997; Veblen et al. 1999). Although the symptomatic and asymptomatic chronologies for sites 4 and 5 did not show a decrease in the 10-year mean increments before and after the crossing-curve points, tree growth was consistently lower in symptomatic than in asymptomatic trees. The increases in the 10-year mean growth at these two sites after the crossing points in 1962 should be related to the onset of a long-term cool and wet period in 1963 (Villalba and Veblen, 1997a; 1998). Although the symptomatic trees responded to these cool and wet climatic conditions, the increase in radial growth was smaller in symptomatic than asymptomatic trees in both sites 4 and 5. Differences in radial growth between symptomatic and asymptomatic trees have increased in recent years. Indeed, the running t tests comparing the regional index differences reach the highest values since 1999.

Local and regional chronologies show larger radial growths of symptomatic than of asymptomatic trees during early decades (before the crossing-curve points). We speculate that symptomatic individuals were more vigorous and had a denser crown during early stages of growth. In consequence, these trees were more affected by the extreme droughts due to their larger evapotranspiration leaf areas. Water stress associated with droughts affects tree vigor by inhibiting physiological processes such as photosynthesis, the movement of gases, the flow of latex and oleoresins, and the absorption of water and ions (Kozłowski 1982). However, as the largest diameter trees at the sampling time may not always have been the largest trees and may not continue to be so, the comparison between their past and present increments introduces some bias in the results. Our sampling strategy, based on sampling dominant and co-dominant pair trees, may create a bias in the interpretation of larger growth rates in symptomatic trees during their early stages attributable to the influence of stand dynamics on each particular tree (Cherubini et al. 1998).

The 15 most extreme negative values identified by the running t test for the differences in regional chronology indices are significantly related to negative PDSI anomalies during the year prior to growth. Based on the mean annual PDSI (Dai et al. 2004), the number of severe droughts increased drastically during the last 50 years in the record. Indeed, 10 severe droughts were recorded in the last 20 years in comparison with 6 in the previous 80 years. The mean drought interval for the period 1909–1983 was 12 years, but it dropped to 2 years during the most recent interval (1983–2003). In addition, the model simulations, recently released by IPCC in its Fourth Assessment Report, predict drier conditions along the southern Andes during the twenty-first century (Christensen et al. 2007). Continental climate simulations by Labraga (1998) also predict a

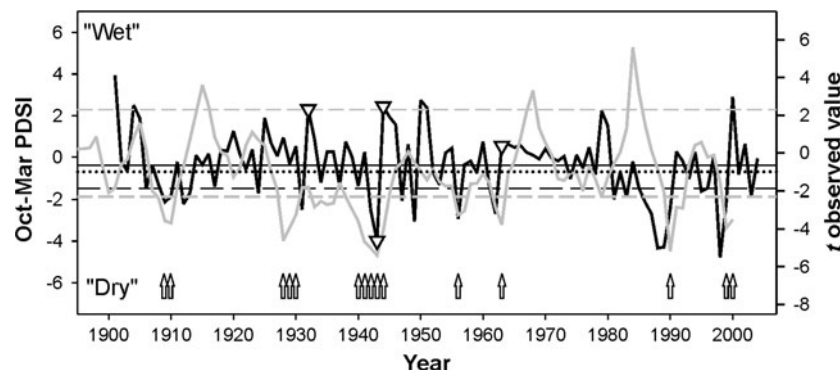


Fig. 6 Running t values for the regional index difference (grey curve) and October–March PDSI (black curve). Intersection dates from Fig. 4 are shown by triangles. Arrows at the bottom indicate the 15 most negative t values. The PDSI mean (black solid line),

moderate drought (PDSI < -1.0; black dotted line), and severe drought (PDSI < -1.5; black dashed line) are also shown. The grey short dashed lines represent the 95% confidence limits of the paired t tests

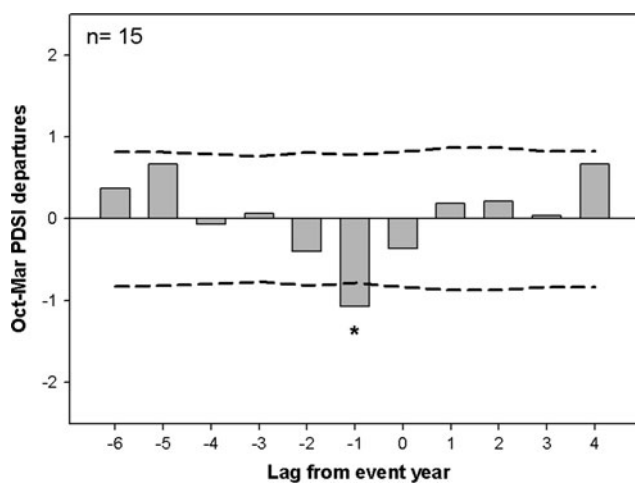


Fig. 7 October–March PDSI departures over the interval 1904–2003 for the 15 years with the most extreme negative running t values from the differences between indexes in the symptomatic and asymptomatic regional chronologies. A 10-year time-window, starting 6 years prior and ending 4 years after the events was used for the SEA estimation. The October–March PDSI during 1 year prior to the events is statistically different ($p < 0.05$) from the mean based on 1000 Monte Carlo simulations (Mooney and Duval 1993). Dashed lines represent the 95% confidence limits

decrease in summer precipitation (between 2 and 42% of present mean values) by 2070 for northwestern Patagonia. Taking into account these climate predictions and the drought sensitivity of *A. chilensis*, we expect that the number of *A. chilensis* stands affected by “Mal del Ciprés” will increase in the next decades.

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