Dendroclimatology of high-elevation *Nothofagus pumilio* forests at their northern distribution limit in the central Andes of Chile

Antonio Lara, Juan Carlos Aravena, Ricardo Villalba, Alexia Wolodarsky-Franke, Brian Luckman, and Rob Wilson

Abstract: *Nothofagus pumilio* (Poepp et Endl.) Krasser, is a deciduous tree species that grows in Chile and adjacent Argentina between 36 and 56°S, often forming the Andean tree line. This paper presents the first eight tree-ring chronologies from *N. pumilio* at its northern range limit in the central Andes of Chile (36–39°S) and the first precipitation reconstruction for this region. Samples were taken from upper tree-line stands (1500–1700 m elevation) in three study areas: Vilches, Laguna del Laja, and Conguillío. Results indicate that, at the northern sites (Vilches and Laguna del Laja), the tree-ring growth of *N. pumilio* is positively correlated with late-spring and early summer precipitation and that higher temperatures reduce radial growth, probably because of an increase in evapotranspiration and decrease in water availability. At the southern Conguillío study area, radial growth was negatively correlated with late-spring and early summer precipitation. The presence of volcanic activity in this latter study area, which might have masked the climate signal, did not seem to have a significant influence on radial growth. A reconstruction of November–December (summer) precipitation for the period 1837–1996 from *N. pumilio* tree-ring chronologies accounted for 37% of instrumentally recorded precipitation variance. This is the first precipitation reconstruction from *N. pumilio* chronologies. Only temperature and snow cover have previously been reconstructed using this species. The reconstruction indicates that the driest and wettest 25-year periods within the past 160 years are 1890–1914 and 1917–1941, respectively.

Résumé : *Nothofagus pumilio* (Poepp et Endl.) Krasser est une espèce arborescente décidue qui croît au Chili et en Argentine entre 36 et 56°S et se retrouve souvent la limite des arbres dans les Andes. Cet article présente les huit premières séries dendrochronologiques de *N. pumilio* à la limite nord de son aire de répartition dans la partie centrale des Andes au Chili (36–39°S) ainsi que la première reconstruction de la précipitation pour cette région. Des échantillons ont été prélevés à trois endroits dans des peuplements situés à la limite supérieure des arbres (1500–1700 m d'altitude) : Vilches, Laguna del Laja, et Conguillío. Les résultats indiquent que dans les sites situés au nord (Vilches et Laguna del Laja), la croissance de *N. pumilio* est corrélée positivement avec la précipitation à la fin du printemps et au début de l'été et que les températures élevées réduisent la croissance radiale, probablement à cause d'une augmentation de l'évapotranspiration et d'une diminution de la disponibilité en eau. Dans la zone d'étude de Conguillío située au sud, la croissance radiale est corrélée négativement avec la précipitation à la fin du printemps et au début de l'été. Dans cette zone d'étude, la présence d'activité volcanique, qui pourrait avoir masqué l'influence du climat, ne semble pas avoir eu d'effet significatif sur la croissance radiale. Une reconstruction de la précipitation des mois de novembre et décembre (été) pour la période de 1837 à 1996 à partir de séries chronologiques basées sur les cernes annuels de *N. pumilio* explique 37% de la variation dans la précipitation enregistrée par les instruments. Il s'agit de la première reconstruction de la précipitation à partir de séries dendrochronologiques de *N. pumilio*. Seules la température et la couverture de neige ont précédemment été reconstruites en utilisant cette espèce. Cette reconstruction montre qu'au cours des 160 dernières années la période de 25 ans la plus sèche est survenue de 1890 à 1914 et la plus humide de 1917 à 1941.

[Traduit par la Rédaction]

Introduction

The study of historical climate change using tree-ring records provides important information for understanding the nature of climatic variability and its implications for the management of natural resources. Research on climate variation at these time scales is also essential for discriminating natural from human-induced climatic changes (Bradley 1990). High-elevation sites in mountain regions, although

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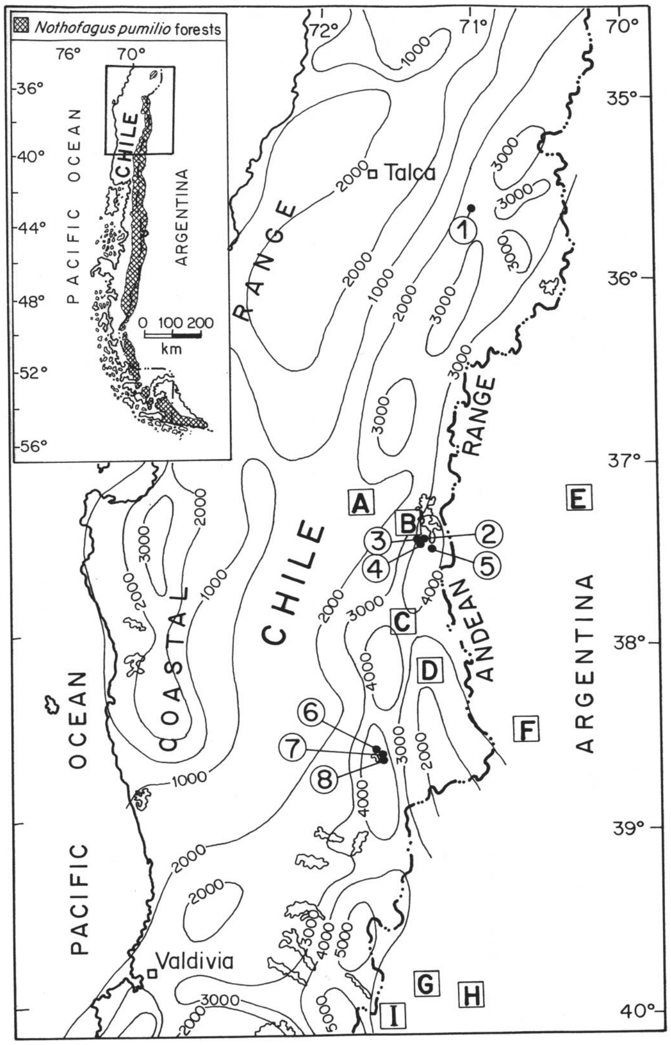
Fig. 1. Location of the sample sites and climatic stations. Distribution of *Nothofagus pumilio* forests is shown in an inset. (□) cities; (•) sampling sites: (1) Vilches, (2) Los Barros, (3) Las Cuevas, (4) Petronquines, (5) Lenga Larga, (6) Krummholz, (7) Lenga Media, and (8) Lenga Abajo, climatic stations: (A) Polcura, (B) Abanico, (C) Pangue, (D) Troyo, (E) Chos-Malal, (F) Las Lajas, (G) Collún-Co, (H) Chacayal, and (I) San Martín de los Andes. Precipitation isohyets are based on Almeyda and Sáez (1958).



often difficult of access, provide excellent opportunities for paleoenvironmental studies. Their diverse physical and biological systems are highly sensitive to climatic variations and may provide long proxy records across different spatial and temporal scales (Luckman 1990). In many cases these environments have been little affected by fire or human activities such as logging (Luckman 1990; Villalba et al. 1994) and, therefore, preserve old-growth forest stands that provide long dendrochronological records.

Few climate reconstructions based on tree rings are available for southern South America compared with the Northern Hemisphere. Nevertheless, these studies have shown high potential, and today over 200 tree-ring chronologies and several climate reconstructions have been developed in both Chile and Argentina (Boninsegna 1992; Lara and Villalba 1994; Boninsegna and Villalba 1996).

Nothofagus pumilio (Poepp. et Endl.) Krasser is a deciduous tree species that dominates upper tree-line stands in the Chilean Andes between 35°36′ and 55°31′S (Ormazábal and Benoit 1987; Donoso 1993). This wide latitudinal range presents an outstanding opportunity to develop proxy climate records from the same species over a long latitudinal transect (2200 km) and to examine the changing response of this species to a range of climatic regimes over the last 300–400 years. Previous work in Argentina has demonstrated that *N. pumilio* provides climate sensitive tree-ring records for the last 400 years. Climate reconstructions for summer temperature, generated using four *Nothofagus* chronologies from Tierra del Fuego (52–54°S), showed an increasing trend for the last decades (Boninsegna et al. 1989). Villalba et al. (1997) generated reconstructions for snow cover duration in late spring and mean annual temperature in northern Patagonia (41°S) for the period after AD 1750. Prior to the present project, only four *N. pumilio* chronologies had been developed in Chile between 45 and 53°S (Boninsegna and Villalba 1996). We believe there is an urgent need to develop tree-ring chronologies of *N. pumilio* throughout its latitudinal and elevation range in Chile to establish and exploit the dendroclimatic potential of this species.

In this paper we report the development of the first eight tree-ring chronologies for *N. pumilio* near the northern limit of its range in the central Andes of Chile (36–39°S). The potential for climate reconstruction from these chronologies was also examined. These are the first results from a project that is developing chronologies and climate reconstructions from *N. pumilio* at high elevation over its complete latitudinal range in Chile.[2]

We anticipate some differences in the response of *N. pumilio* to climate along this large latitudinal transect. Chronologies from wet and upper-elevation sites in Argentina (41 and 51–54°S) show clear relationships between radial growth and changes in seasonal or annual temperature and (or) late-spring snow cover (Boninsegna et al. 1989; Villalba et al. 1997). However, at drier sites in northern parts of the range of *N. pumilio*, we expect that radial growth is also influenced by moisture availability, which increases with latitude and elevation across our study area.

Study areas

Climate

The climate in the Andes of central Chile is of Mediterranean type. Rain and snow are concentrated in fall and winter, when over 75% of the annual precipitation occurs (Miller 1976). Two well-marked moisture gradients are observed in the study area. There is a strong north to south increase in precipitation, which is reflected by a decrease of the Mediterranean influence to the south. Total annual precipitation ranges from ca. 1000 mm in the north (35°S) to ca. 3000 mm in the south (39–40°S) (Fig. 1). This increase is due primarily to increased frequency of precipitation both in winter

[2] Lara, A., Aravena, J.C., Wolodarsky, A., Villalba, R., and Luckman, B.H. 1997. Climate variation from treeline *Nothofagus pumilio* tree-ring records in the Chilean Andes from 35°30′ – 55° southern latitudes. Unpublished manuscript. Chilean National Science Foundation, Santiago. Fondo Nacional de Ciencia y Tecnología. Project No. 1970812.

Table 1. Characteristics of the tree-ring chronology sites sampled.

Study area	Sampling site	Sample code	Latitude (S)	Longitude (W)	Altitude (m)	Aspect	Slope (%)
Vilches	Vilches	VIL	35°36′	71°02′	1530	N	5
Laguna del Laja	Los Barros	ARB	37°28′	71°19′	1500	SE	20
	Las Cuevas	AEC	37°28′	71°20′	1510	S	30
	Petronquines	ALP	37°29′	71°19′	1690	SE	20
	Lenga larga	ALL	37°34′	71°14′	1720	SE	25
Conguillío	Krummholz	CKZ	38°37′	71°36′	1650	NW	30
	Lenga media	CLM	38°37′	71°36′	1630	N	31
	Lenga abajo	CLA	38°38′	71°36′	1490	E	40

and summer towards the south (Miller 1976). In addition there is also an important west–east moisture gradient (Fig. 1). Precipitation increases with elevation, reaching a maximum at the Andean peaks. The precipitation on the mountain peaks is usually at least three to four times greater than the amount over the central Valley at the same latitude (Miller 1976). The rain shadow effect occurs mainly in Argentina, although locally it may also be present in Chile depending on the position of the highest peaks in the Andes and the Coastal Range (Fig. 1). Mean annual temperature decreases from north to south, from 14.8°C in Talca to 11.9°C in Valdivia (Almeyda and Sáez 1958, Fig. 1).

Interannual climate variability is driven by both low- and high-latitude climatic forcing. For example, extreme dry and wet years are related to El Niño – Southern Oscillation (ENSO) events. Warm ENSO events are associated with abundant precipitation in winter (Aceituno 1988). Above-average precipitation in the central Andes is also related to the presence of blocking highs over the Bellingshausen sea (70°S, 90°W; Rutlland and Fuenzalida 1991).

Sample sites

Nothofagus pumilio chronologies were developed from three areas: Vilches, Laguna del Laja, and Conguillío (Fig. 1, Table 1). In Vilches, samples were only collected from one site, a mixed *N. pumilio* – *Nothofagus obliqua* (Mirb.) Oerst. stand. Erect trees, ranging from 15 to 20 m in height, grow on a gentle slope along a saddle at 1580 m elevation on volcanic soils. This is the northernmost *N. pumilio* stand known and is located within a protected area (Reserva Nacional Altos de Vilches). Local tree line is formed by erect *N. obliqua* trees at 1870 m. elevation, with sparse patches of creeping *Nothofagus antarctica* (G. Forster) Oerst. shrubs (<1 m height) extending up to 2000 m.

At Laguna del Laja we sampled at four sites. Los Barros, Las Cuevas, and Lenga Larga are old-growth pure *N. pumilio* stands with erect trees reaching 18–22 m in height. Petronquines is a pure *N. pumilio* second-growth stand developed after fire but which included some old remnant trees. Both young and old trees were cored (Fig. 1, Table 1). These sites are located between 1500 and 1720 m in Laguna del Laja National Park, near the Antuco volcano, and are characterized by soils developed from coarse volcanic ash. The local tree line is formed by *N. pumilio* stands of erect trees at ca. 1700–1750 m elevation, with some shrubby patches of *N. antarctica* growing up to 1800 m.

In Conguillío, we sampled trees from three mixed *N. pumilio* – *Araucaria araucana* (Mol.) Koch stands along the Sierra Nevada range. The *N. pumilio* krummholz site is a dense old-growth stand, showing a distinct well-bounded zone with an abrupt transition to the alpine meadows. Creeping *N. pumilio* trees overtopped by some erect *Araucaria araucana* trees form the tree line, which is located at 1750 m. Tree cores from *Araucaria* were collected, but they could not be cross-dated because of the difficulties in distinguishing extremely narrow rings. The Lenga Abajo and Lenga Media sites are old-growth stands located downslope of the krummholz stand and have erect trees ranging from 22 to 26 m in height (Fig. 1, Table 1). Elevation ranges for these sites are between 1490 and 1650 m and all stands are located within Conguillío National Park, near Sierra Nevada and Llaima volcanoes. The Llaima volcano has erupted 45 times between 1640 and 1990 (Petit-Brehuil 1994), in some cases greatly affecting the vegetation and soils in the area. As a consequence, soils are dominated by coarse volcanic ash deposits.

Methods

Chronology development and quality assessment

Two cores were extracted from at least 40 trees at each sampling site, using increment borers. Cores were mounted, sanded using sandpaper of increasingly finer grain, and dated following the techniques outlined in Stokes and Smiley (1968). Tree-ring widths were measured under a microscope to the nearest 0.001 mm and stored in a microcomputer (Robinson and Evans 1980). The computer program COFECHA (Holmes 1983) was used to detect measurement and cross-dating errors. For dating purposes, we followed Schulman's convention (1956) for the Southern Hemisphere, which assigns to each tree ring the date of the year in which radial growth started.

Once the tree-ring series were dated, ring width data were standardized and averaged to produce a mean stand chronology for each site (Fritts 1976; Cook 1985). Standardization was performed using the program ARSTAN (Cook and Holmes 1984; Cook 1985), which generates mean chronologies by averaging standardized tree-ring series with biweight robust estimation. Standardization involves fitting the observed ring-width series with a theoretical curve and computing an index by subtracting the logarithms of the expected from the observed values. This reduces variance among cores, removes the tree's biological growth trend from ring-width series, and avoids potential biases in the tree-ring indexing procedure (Fritts 1976; Cook et al. 1992). We used negative exponential fits, linear regressions of negative slope, or horizontal lines as theoretical curves of standardization.

We used RBAR analysis (Briffa 1995) to assess the quality of the chronologies and temporal variability in the strength of the common variation, which we infer reflects common responses to climatic influences. This analysis was performed using program TURBO ARSTAN for MacIntosh. RBAR is the mean correlation coefficients for all possible pairings among tree-ring series from individual cores, computed for a specified common time interval (Briffa 1995). We used a 50-year window with an overlap of 10 years between adjacent windows. RBAR was computed only for time periods for which tree-ring data from at least five cores were available.

Climatic influences on radial growth

To identify associations between macroclimatic factors on *N. pumilio* radial growth, we computed correlations between standard chronologies (Cook 1985) and monthly mean temperature and

Table 2. Meteorological records used for comparing radial growth with climatic variations.

Station	Latitude (S)	Longitude (W)	Elevation (m)	Record period	Parameter[a]	Missing data (%)	Source[b]
Polcura	37°19′	71°32′	740	1959–1997	P	4	Endesa
Abanico	37°21′	71°30′	765	1944–1997	P	5.3	Endesa
Chos-Malal	37°23′	70°17′	862	1916–1960	T	20.8	Ser.Met.Nac.
Pangue	37°53′	71°36′	550	1960–1993	P	4	Endesa
Troyo	38°14′	71°18′	650	1968–1997	P	1.4	Endesa
Las Lajas	38°31′	70°20′	770	1916–1973	T	14.6	Ser.Met.Nac.
Collun-co	39°58′	71°12′	875	1912–1989	T, P	0	Ea. Collun-co
Chacayal	40°02′	70°57′	760	1929–1978	P	1.5	Hidronor
San Martín A.	40°10′	71°22′	650	1936–1975	P	0	Hidronor

[a]P, precipitation; T, temperature.
[b]Ser.Met.Nac., Servicio Meteorológico Nacional, Argentina; Hidronor, Nor-Patagonia, Argentina; Endesa, Empresa Nacional de Electricidad S.A., Chile.

total precipitation (Fritts 1976; Blasing et al. 1984). We selected the standard chronology to preserve low-frequency variance in radial growth, which is removed from the residual versions of the chronologies. The statistical association between ring indices and each climate variable was examined over the common period for the chronology and the instrumental climatic record (1912–1995). As radial growth is influenced by climatic conditions several months before ring formation (Fritts 1976), we included both the previous and current growing seasons in this analysis. Consequently, correlations between ring width and climate data were calculated for 21 months, starting in September of the previous growing season, and ending in May of the current growing season.

For calibration of the long-term relationships between climate and radial growth, we selected those climate stations with the longest available records in the central Andes of Chile and Argentina (Table 2). To give a similar weight to each of the stations in the regional mean, data were converted to standard deviations from the monthly temperature and precipitation means for each climate station and then averaged among stations. Precipitation data included the stations Chacayal, San Martín de los Andes, and Collun-co in Argentina and Abanico, Troyo, Pangue, and Polcura in Chile (Table 2). Because of the shortness of the available temperature records from stations within the Chilean Andes, three Argentinean stations from similar latitudes on the eastern slope of the Andes (Collun-co, Las Lajas, and Chos-Malal; Table 2) were used to develop a long regional temperature record for calibration purposes.

Potential effect of volcanism on radial growth

We assessed possible confounding effects of volcanic activity on radial growth at the Conguillio sites by superimposed epoch analysis (SEA) using the program EVENT (Holmes and Swetnam 1994). The dates for volcanic events were taken from the available eruption chronologies of Volcán Llaima (<5 km from the Conguillío sites; Brüggen 1950; Petit-Brehuil 1994; González-Ferrán 1995). A 5-year interval (1 year prior and 3 years after the volcanic event) was used as the time window. Values were averaged at each of these positions for all the volcanic events within the time period analyzed. Confidence intervals were provided by selecting a set of random dates in 1000 simulations. This analysis was performed for each tree-ring chronology (CKZ, CLM, CLA) with the relevant volcanic eruption chronology.

Climate reconstruction

To reconstruct past climate variations in the Chilean central Andes, we correlated the chronologies with annual and seasonal variations of temperature and precipitation. Many possible combinations of both the tree-ring and climate data sets were used to explore the feasibility of reconstructing a variety of temperature and (or) precipitation parameters.

We used multiple regression on principal components of the ring-width series (Cooley and Lohnes 1971) to predict climate as a function of tree-ring variations. This procedure generated a transfer function equation or model, which was then applied to the tree-ring data to develop the reconstruction (Fritts 1976). To maximize the climatic signal in the tree-ring chronology, we only used mean site chronologies that were significantly ($p < 0.05$) correlated with the 1912–1995 precipitation record. As radial growth in any specific year is influenced by the climate in both the current (t) and previous ($t - 1$) years, we modeled climate as a function of radial growth in both years t and $t - 1$. The stability of the multiple regression was evaluated using a cross-validation approach (Fritts 1976). Using this procedure, we split the climatic record into two subperiods of 42 years each: 1912–1953 and 1953–1995. We used one of these subperiods for calibration and the other one for verification, and vice versa. For each calibration–verification trial, we first obtained the transfer functions over the calibration period, and then we evaluated the goodness of fit over the verification period. Several possible combinations of the available climate data were used in calibration attempts; the results in this paper are the best ones we have obtained with the available climate data. We measured the quality of the two transfer functions using the Pearson's correlation coefficient (r), product mean test (t), and reduction of error statistic (RE).

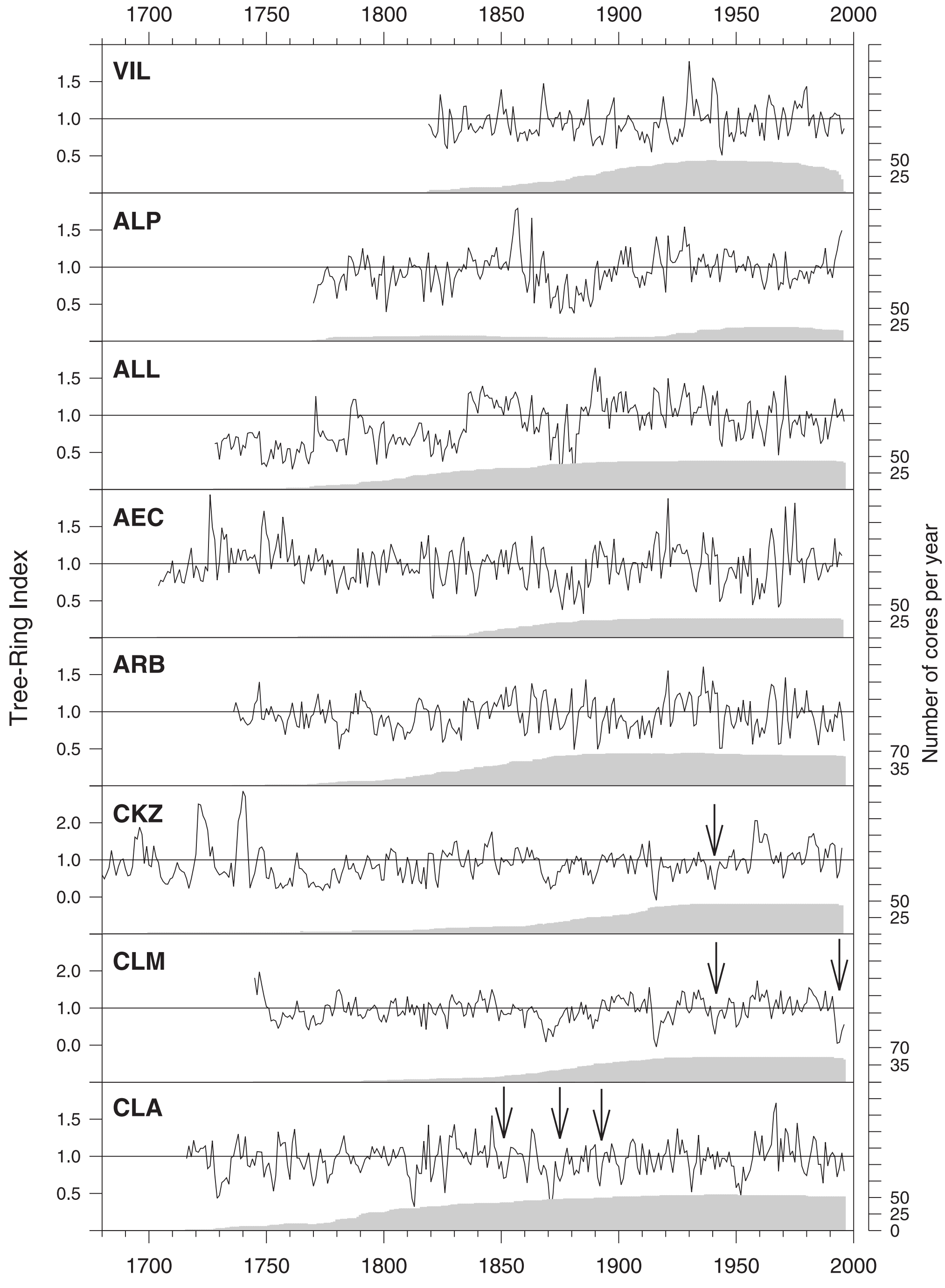
Results

Tree-ring chronologies

Two of the southernmost sites (CKZ and CLM) have the highest values of mean sensitivity, standard deviation, mean correlation between trees, and variance in the first eigenvector plus the lowest values for mean tree-ring width (Table 3). These two sites are the highest ones on the altitudinal transect in Conguillío and are located adjacent to each other. The trees in the CKZ stand have a krummholz growth form. This type of growth is quite common for *N. pumilio* stands at high-elevation tree-line environments, which are affected by snow accumulation and strong winds (Donoso 1993).

Mean sensitivity (Fritts 1976) and the standard deviation are measures of the total variability in a chronology; mean sensitivity characterizes the year-to-year variability in tree-ring records (Fritts 1991). The high standard deviations (0.447, 0.291) and mean sensitivity (0.263, 0.251) values for the CKZ and CLM sites, respectively, indicate more interannual variation compared with the chronologies at the northern study sites. These results are similar to those presented by Villalba et al. (1997), which show higher values of mean sensitivity and standard deviation for trees growing in more stressed sites because of a longer snow cover duration. The chronologies at the northern sites have a weaker com-

Fig. 2. Standard tree-ring chronologies for *N. pumilio* at sites in central Chile at the northern distribution of its range. Tree-ring indices provide nondimensional values that show changes in radial growth over time. Sample size is shown as a shaded area at the bottom of each chronology, representing the total number of cores per year. The arrows indicate the years in which documented eruptions since 1822 coincide with narrow tree rings (≤1 SD) in the same year for the sites CLA, CLM, and CKZ located in the Conguillío area. Site codes are given in Table 1.

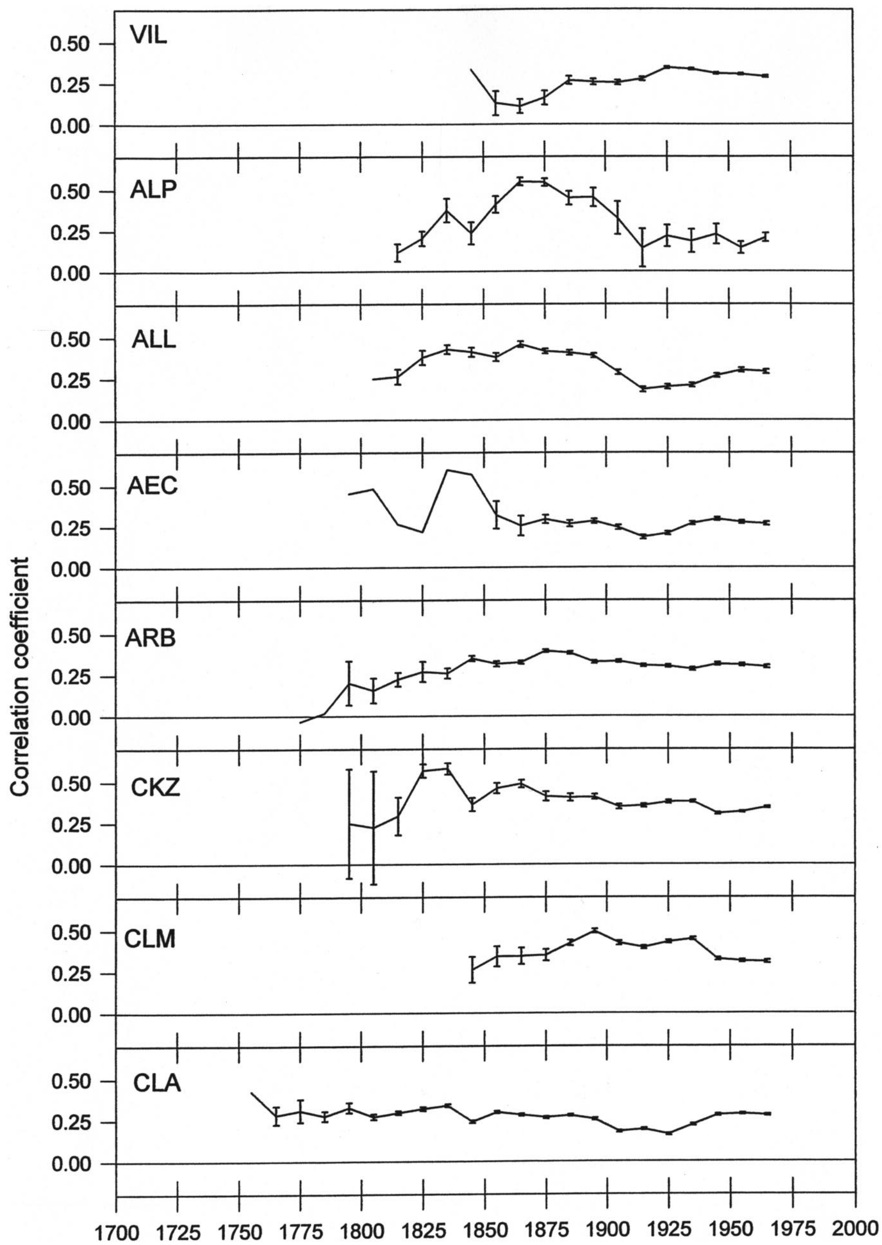


mon signal that is reflected in lower values for these statistics (Table 3).

Tree-ring growth patterns vary significantly between the different study areas (Fig. 2). However, in the Laguna del Laja, chronologies (sites ALP, ALL, AEC; Fig. 2) show a period of below-average growth between 1870 and 1890. Some chronologies present particular features, such as ALL, which shows a clear increase in radial growth starting around 1830 (Fig. 2), suggesting a local disturbance phenomenon.

Figure 3 shows the changes in the RBAR corresponding to the mean correlation among tree-ring series over time. The CKZ and CLM chronologies show persistent relatively high correlations among series for most of the intervals. VIL and ARB show relatively low values of RBAR in the initial portion of the chronologies. The ALP chronology had the

Fig. 3. Mean tree-ring series correlation for each chronology calculated using the RBAR routine in the TURBO ARSTAN program. The moving window used for computing RBAR statistics is 50 years with an overlap of 10 years between adjacent windows. The vertical bars represent the 2 SE limits for the RBAR values. Site codes are given in Table 1.



greatest variation in RBAR, with low values for the initial and final periods (Fig. 3) and had the lowest overall mean correlation between trees (Table 3), indicating that this is the poorest chronology.

The common variance among trees is one of the most useful parameters for evaluating the quality of a chronology for climate reconstructions (Fritts 1976). Higher common variance among trees indicates a stronger macroenvironmental influence on radial growth. The common variance among trees for each chronology was evaluated using principal components analysis (PCA) (Cooley and Lohnes 1971). In a PCA, the first component retains the largest percentage of the common variance among trees (Peters et al. 1981). In our study, the variance accounted for by the first principal component (PC) at each site ranges from 23% at ALL to 42% at CLM (Table 3).

The intercorrelation among the eight chronologies was examined using PCA. The first three PCs account for 35.2, 26.6, and 12.8%, respectively (cumulatively 75%), of the total variance in tree-ring chronologies during the common interval (1837–1995). Chronologies are grouped into three major clusters, reflecting the differences between the Conguillio (CKZ, CLM, CLA), Laguna del Laja (ALP, ALL, ARB, AEC), and Vilches (VIL) areas (Fig. 4). The Conguillío chronologies, located at southern latitudes, tend to have relatively lower loadings on the first PC axis and higher loadings on the second axis. In contrast, the Laguna del Laja chronologies show the opposite pattern. Within each study

Table 3. Descriptive statistics for eight standard tree-ring chronologies for *Nothofagus pumilio* in central Chile.

	Complete period							Common interval (1912–1995)			
Chronology code	Period	No. of trees	No. of radii	Mean tree-ring width (mm)	Mean sensitivity[a]	SD	First-order autocorrelation[b]	No. of trees	No. of radii	Mean correlation between trees	Variance in first eigenvector (%)[c]
CKZ	1680–1995	30	47	0.82	0.263	0.447	0.722	23	33	0.318	36.18
CLM	1800–1996	28	29	0.81	0.251	0.291	0.506	24	25	0.387	42.97
CLA	1716–1996	30	55	1.09	0.189	0.228	0.471	27	49	0.203	25.45
ARB	1736–1996	32	32	1.05	0.188	0.224	0.412	30	30	0.221	27.54
ALL	1728–1996	24	25	1.07	0.196	0.316	0.742	23	23	0.189	23.76
AEC	1704–1995	20	29	1.12	0.207	0.261	0.418	19	26	0.215	27.55
ALP	1770–1995	19	24	1.95	0.172	0.233	0.519	10[d]	11	0.129	29.73
VIL	1819–1996	31	49	1.44	0.172	0.215	0.444	10	15	0.211	30.26

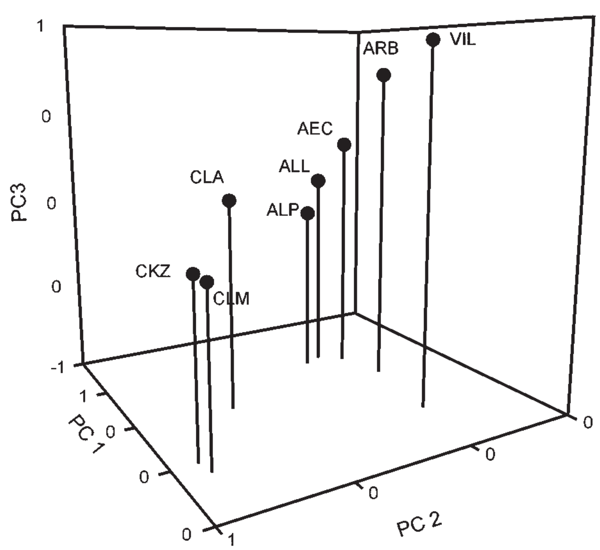
Note: Site codes are listed in Table 1.
[a]Mean sensitivity is the measure of the relative changes in ring width variations from year to year (Fritts 1976).
[b]Autocorrelation is the serial correlation coefficient for the chronology at a lag of 1 year.
[c]Variance in the first eigenvector is the percentage of common variance among tree-ring series explained by the first principal component.
[d]To increase the number of trees and radii in the analysis, the period for ALP was changed to 1926–1982.

Table 4. Correlation matrix for the eight standard *Nothofagus pumilio* chronologies for the period 1819–1995.

Chronology	AEC	ALL	ALP	CLA	CKZ	CLM	VIL
ARB	0.63**	0.52**	0.34**	0.23	–0.25	–0.12	0.46**
AEC	1.00	0.55**	0.46**	0.31**	–0.13	–0.04	0.21
ALL		1.00	0.59**	0.28	–0.11	0.06	0.17
ALP			1.00	0.26	0.07	0.08	0.04
CLA				1.00	0.33**	0.45**	–0.01
CKZ					1.00	0.67**	–0.14
CLM						1.00	–0.10
VIL							1.00

Note: **, $p < 0.01$.

Fig. 4. Principal component scores of the *Nothofagus pumilio* chronologies. The relative positions of the eight standard chronologies are shown in relation to their loading on the first three rotated principal components of the analysis described in the text. Site codes are listed in Table 1.



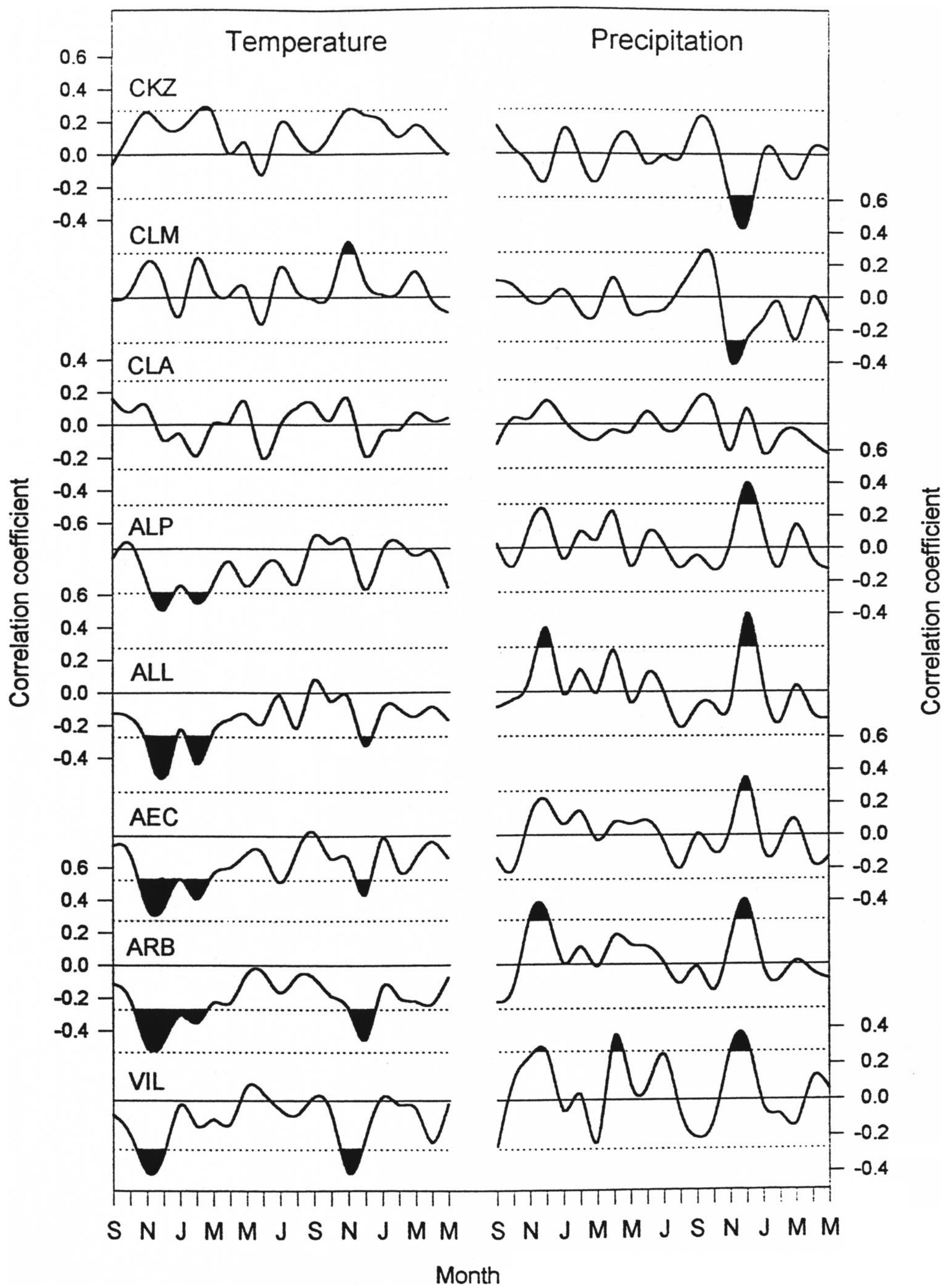
area, sites are arranged along PC3 following an order inversely proportional to elevation (Fig. 4).

A correlation matrix between the eight chronologies shows a clear clustering according to the geographical study areas (Conguillío, Laguna del Laja, or Vilches). In both the Conguillío and Laguna del Laja areas the highest correlations are between pairs of chronologies with similar site conditions and proximity (CKZ–CLM, r = 0.67; AEC–ARB, r = 0.63; AEC–ALL, r = 0.55; ALL–ALP, r = 0.59; ALL–ARB, r = 0.52; Table 4). Strong correlations among site chronologies likely reflect common responses to macroclimatic influences. However, these correlations can be diminished by differences in local disturbance history and environmental conditions such as soil, altitude, and slope–aspect.

Radial growth – climate associations

Figure 5 shows the correlations between monthly temperature and precipitation data and the eight indexed ring-width chronologies. The chronologies are presented in an approximately south (top) to north sequence that clearly demonstrates a changing response of radial growth to temperature and precipitation. Tree-ring indices at the northern and relatively dry sites in Vilches and Laguna del Laja (sites VIL, ARB, AEC, ALL, and ALP) show a positive significant correlation with November (spring) precipitation of the current growing season (Fig. 5). Sites VIL, ARB, and ALL also have a positive significant correlation with November pre-

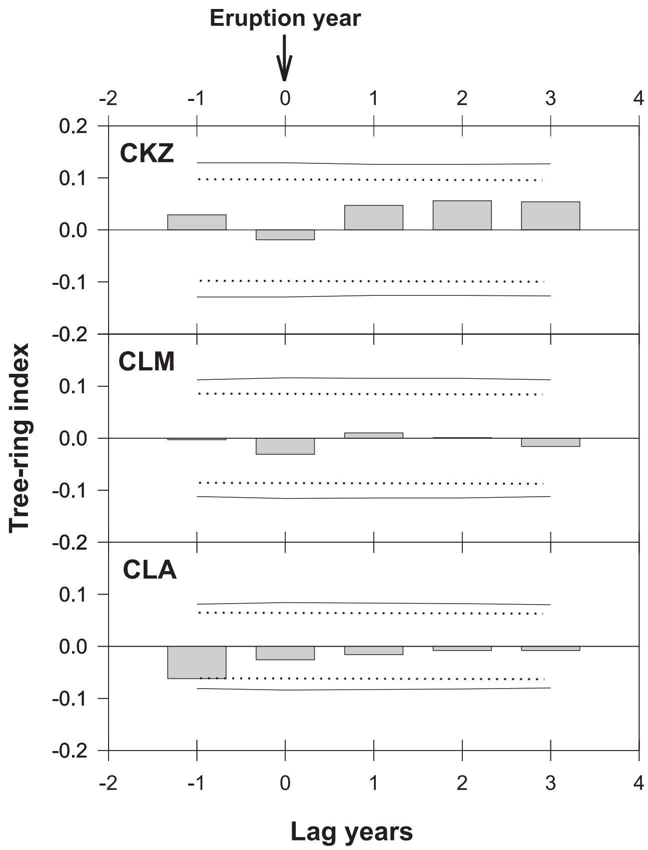
Fig. 5. Correlation functions for eight *Nothofagus pumilio* chronologies in the central Andes of Chile. The correlation coefficients compare tree-ring indices from the standard chronologies with regional mean monthly temperatures and composite records of total regional monthly precipitation over the period 1912–1995. Positive correlation indicates that above-average radial growth is associated with above-average values of the climate variable. Dark sections of the plot indicate significant correlations ($p < 0.05$; $r > 0.21$, or < -0.21). Site codes are given in Table 1.



cipitation of the previous growing season (Fig. 5). For most of these northern sites (VIL, ARB, AEC, ALL), radial growth has a significant inverse correlation with November temperature of both the previous and current growing seasons (Fig. 5). In contrast to this pattern, the southernmost and high-elevation chronologies from Conguillío (CKZ and CLM) show a significant negative correlation with November precipitation during the current growing season (Fig. 5). These sites also show a significant positive correlation with October temperature of the current growing season (Fig. 5).

The results from the two high-elevation sites at Conguillo (CKZ and CLM) are similar to those previously obtained by Villalba et al. (1997) for *N. pumilio* sites at ca. 41°S in Argentina. It, therefore, appears that the pattern of positive correlation of radial growth with spring precipitation and negative correlation with spring or early summer tempera-

Fig. 6. Plots of superposed epoch analysis (Holmes and Swetnam 1994) comparing tree-ring index with eruption occurrence for the Conguillío study area. The *X* axis represents a set of 5 years, from 1 year before the volcanic event to 3 years following it. The horizontal lines are the confidence intervals (CI) estimated from a bootstrap simulation of 1000 trials of randomly selected sets of the same number of key dates. The dotted line is the 95% CI and the solid line is the 99% CI.



ture is more typical of sites in the area immediately south of the region studied in this paper. The contrary, positive correlation with spring precipitation and negative correlation with spring temperature seen in the more northerly sites has not previously been reported.

Potential effect of volcanism on radial growth

The analysis of the chronology of eruptions of Volcán Llaima from various sources, indicates that 27.9% (12 of 43) of the dated eruptions of Volcán Llaima since 1822 coincide with narrow rings (≤1 SD) in one or more of the Conguillío chronologies (Fig. 2). In this analysis a match was conservatively identified as a narrow ring in the year of the eruption or up to 2 years after. However, when we checked for the statistical significance of these matches using the SEA between the eruption dates of Volcán Llaima and the Conguillío tree-ring chronologies, we found that the deviation in tree-ring indices using a window of 5 years around the eruption dates does not surpass the $p < 0.05$ confidence interval for any chronology (Fig. 6).

Table 5. Factor loadings for the seven selected variables used in the precipitation reconstruction extracted from an unrotated principal component analysis.

Chronology	PC1	PC2	PC3
VIL	0.62	0.15	–0.61
VIL-1	0.67	0.42	–0.19
ARB	0.70	0.11	–0.23
ARB-1	0.70	0.26	0.48
ALL-1	0.40	0.17	0.76
CKZ	–0.45	0.80	–0.09
CLM	–0.42	0.81	0.02

Note: The first three components, PC1, PC2, and PC3, account for 34, 28, and 18%, respectively, with a cumulative 75% of the total variance in radial growth during 1837–1995.

Table 6. Calibration and verification statistics computed for the tree-ring based reconstruction of November–December precipitation.

Calibration		Verification			
Time period	r^2_{adj} [a]	Time period	r [b]	t [c]	RE [d]
1912–1953	0.28	1954–1995	0.72	2.37	0.47
1953–1995	0.51	1912–1952	0.54	2.05	0.22
1912–1995	0.37				

[a] The square of the multiple correlation coefficient adjusted for loss of degrees of freedom.
[b] Pearson's correlation coefficient.
[c] Product mean test.
[d] Reduction of error statistic (Fritts 1976).

Reconstruction of precipitation (1837–1996)

Correlations with temperature records were not strong enough to permit an adequate reconstruction of past temperature variations. For precipitation, we found that November–December rainfall is the seasonal combination most highly correlated with *N. pumilio* radial growth in the central Andes. We used multiple regression on PCs (Cooley and Lohnes 1971) to predict November–December precipitation as a function of tree-ring variations. Following this procedure, seven variables were selected: chronologies CKZ and CLM in year *t*, ALL in year $t – 1$, and both chronologies ARB and VIL in years *t* and $t – 1$. The ALP, AEC, and CLA chronologies were excluded from this analysis, because they were not significantly ($p < 0.05$) correlated with the 1912–1995 precipitation record. Moreover, ALP is the lowest quality chronology (Table 3, Fig. 3). The first three significant components (accounting for 75% of the total variance), derived from an unrotated PCA of these seven selected variables, were used as predictors of November–December precipitation. Only the first PC was selected in the regression procedure. The factor loadings indicate that each of the selected chronologies contribute to the first PC (Table 5). CKZ and CLM have a negative sign, whereas all the other sites are positive, which indicates that their contribution to PC1 is inverse.

Significant statistics of calibration and verification indicated some predictive skill in the regression models (Table 6). However, the verification statistics are stronger for the most recent period (1953–1995). The early portion (1912–1944) of the regional precipitation record used for the

Fig. 7. Comparison of observed and predicted November–December standardized precipitation departures (z values) for the central Andes of Chile (35–39°S) between 1912 and 1995.

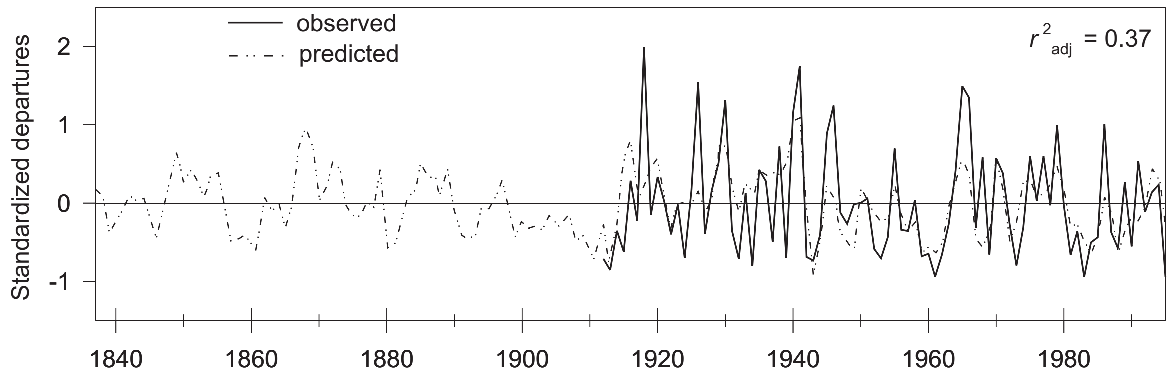
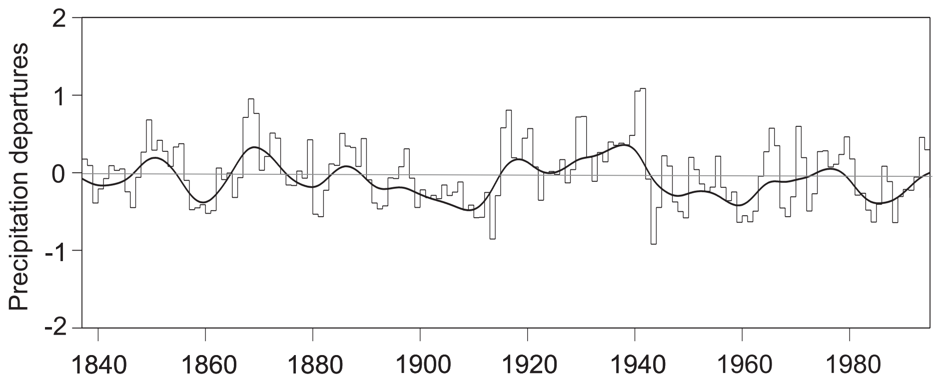


Fig. 8. Reconstructed variations in November–December precipitation for the central Andes of Chile (35–39°S) from 1837 to 1995. To emphasize low-frequency variations, the reconstruction is also shown in a smoothed version (bold line) based on smoothing the annual values with a cubic spline (Cook and Peters 1981) designed to reduce 50% of the variance in a sine wave with a periodicity of 15 years.



reconstruction is based exclusively on Argentinean weather records, and the Argentinean and Chilean stations are only equally represented after ca. 1960. Consequently, the weaker calibration–verification statistics observed for the early period may reflect this imbalance in the structure of the regional precipitation record. We used the whole 1912–1995 period to develop the final regression equation for reconstructing November–December precipitation. In general, the predicted precipitation reconstruction captures both high- and low-frequency variations in the observed instrument al record. However, dry seasonal conditions are better estimated than wet seasons (Fig. 7).

Using this regression model, we produced a precipitation reconstruction back to 1837, the earliest year when all the predictor chronologies used in the reconstruction had at least five series (Fig. 8). Using this precipitation reconstruction, we identified the wettest and driest November to December events and compared them with similar events reconstructed by Villalba et al. (1998) for Argentinean northern Patagonia (Table 7). Our reconstruction indicates that the driest and most extended dry seasonal interval since 1837 was from 1890 through 1914, and the years with the driest November–December season are 1943, 1913, and 1988 (Fig. 8, Table 7).

Discussion

In this paper we present the first chronologies from *N. pumilio* at the northern limit of its distribution (35–38°S) in the central Andes of Chile, thereby greatly expanding the geographical range of available chronologies for this species. We sampled along a latitudinal gradient to identify the total range of climatic influences on the growth of the subalpine *N. pumilio* forests (Table 1). The statistics used to characterize these chronologies (mean sensitivity, standard deviation and autocorrelation; Table 3) indicate that most of these chronologies are of similar quality to the *N. pumilio* chronologies developed from sites on the eastern side of the Andes (Villalba et al. 1997). In general, similar trends in radial growth occur within each of our three study areas (i.e., Vilches, Laguna del Laja, and Conguillío). Differences in growth patterns among study areas appear to reflect the influence of distinct climatic factors on *N. pumilio* radial growth. Correlation functions between climate and radial growth for the drier, northern sites (Vilches and Laguna del Laja) show an opposite relationship with precipitation compared with the wetter and cooler, southern sites in Chile (Conguillío; Fig. 5).

Differences in radial growth patterns may reflect the north–south differences in tree responses to temperature and precipitation variations. At the northern, and relatively dry, sites (Vilches and Laguna del Laja areas), the growth of the subalpine *N. pumilio* is favored by late-spring and early summer precipitation (Fig. 5). High temperatures in spring and summer, which enhance evapotranspiration and decrease water availability, appear to reduce radial growth. In contrast, at the southernmost, high elevation, and relatively wet sites in

Table 7. List of the five wettest and driest November to December precipitation events in Argentinean northern Patagonia reconstructed from *Austrocedrus chilensis* tree rings (Villalba et al. 1998) and central Andes of Chile reconstructed from *Nothofagus pumilio* tree rings (this paper) since 1837.

	Wettest		Driest	
	Year	SD	Year	SD
Northern Argentinean Patagonia				
Individual years	1945	1.203	1943	–1.649
	1868	1.195	1962	–1.490
	1941	1.111	1845	–1.445
	1920	0.95	1877	–1.340
	1928	0.947	1893	–1.307
Moving average	1925–1949	0.378	1893–1917	–0.111
	1868–1892	0.298	1947–1971	0.066
Central Andes of Chile				
Individual years	1941	1.104	1943	–0.902
	1940	1.069	1913	–0.836
	1868	0.97	1988	–0.624
	1916	0.824	1959	–0.622
	1869	0.781	1984	–0.618
Moving average	1917–1941	0.306	1890–1914	–0.265
	1866–1890	0.181	1943–1967	–0.184

Note: Precipitation departures from the long-term (1837–1995) mean are listed for individual years and for non-overlapping moving average of 25 years.

Conguillío (CKZ, CLM), radial growth is negatively correlated with late-spring and early summer precipitation. This negative correlation with precipitation reflects the cooling effect of clouds and the occasional damage to the foliage by late-season wet snowstorms (Alberdi et al. 1985). Interestingly, radial growth responses to climate at Conguillío (38°37′S) are similar to those recorded for the high-elevation, wetter sites at Tronador (41°S) in Argentina (Villalba et al. 1997). This may reflect similar environmental constraints at relatively wet and cool, high-elevation sites in the Andes.

The possible effects of volcanic eruptions on the tree-ring width chronologies were examined for the Conguillio site. Only 12 of the 43 dated eruption years (27.9%) since 1822 at Llaima volcano were matched with narrow rings in one or more of the Conguillío chronologies. However, none of these eruptive events produced narrow rings in all three chronologies, and only three eruption years may be associated with narrow rings in two of the three chronologies. Moreover, the lack of statistically significant correlation between radial growth and volcanic events at Conguillío indicates that most narrow rings in the chronologies are not related to volcanic eruptions (Fig. 6). These results indicate that the effects of these disturbances on radial growth are not important in the Conguillío area and are local in scale. We, therefore, concluded that the volcanic effects on the Conguillío chronologies did not have significant effects on climate reconstructions based on PCs derived from a regional chronology data base.

The dendroclimatic reconstruction of November–December precipitation based on *N. pumilio* chronologies developed for the central Andes of Chile accounts for 37% of the instrumentally recorded precipitation variance (Table 6). Since the factor loadings of PC1 used in the reconstruction have negative values for the southern chronologies (CKZ and CLM) and positive values for the ones located towards the north, this reconstruction provides a signal that integrates the regional climate variability (Table 5). This would not have been achieved using a single set of chronologies with a similar pattern of response.

From this reconstruction, it is apparent that the 20th century has the most extreme intervals of both drought and wetness since 1837 (Fig. 8). For the past 160 years, the reconstruction shows that the driest and wettest 25-year periods are 1890–1914 and 1917–1941, respectively (Table 7). These results demonstrate the usefulness of tree rings in developing proxy climate data that extend limited instrumental climate records, thereby improving the analysis and understanding of long-term climate variation.

Recently, Villalba et al. (1998) have developed a set of long-term precipitation reconstructions from *Austrocedrus chilensis* for the dry forest – steppe ecotone in northern Argentinean Patagonia. The November–December precipitation reconstruction from *Austrocedrus* shares several common features with our reconstruction. For example, both reconstructions indicate that 1943 is the driest year since the 1830s, and the years 1868 and 1941 are among the five wettest years since 1837 in both reconstructions. Remarkable coincidences are also observed for the low-frequency variations in the reconstructions. For the *Austrocedrus*-based reconstruction, the driest and wettest 25-year intervals are 1893–1917 and 1925–1949, respectively, almost exactly coinciding with the 1890–1914 and 1917–1941 intervals identified in the *Nothofagus* reconstruction (Table 7).

Although subalpine tree-ring records are generally considered to be more sensitive to temperature variation than precipitation, our results show that *N. pumilio* radial growth on dry sites near its northern distribution limit is mainly controlled by precipitation. In addition, radial growth at these sites also shows a negative relationship to spring and summer temperatures, reflecting the combined effect of temperature and precipitation on soil moisture availability. Our results also indicate that climate during the previous growing season is equally or more important than climatic conditions during the present growing season in controlling *N. pumilio* radial growth. As previous studies using *N. pumilio* only reconstructed temperature or snow cover (Boninsegna et al. 1989; Villalba et al. 1997), this is the first precipitation reconstruction based on *N. pumilio* ring-width chronologies. In addition, the important climatic influence of prior growing season conditions on ring width has not previously been noted from the subalpine forests in South America.

Ongoing and future research will be focused on the completion of a network of tree-ring chronologies for *N. pumilio* subalpine forests along latitudinal, longitudinal, and elevation gradients in southern South America. This network should provide a comprehensive understanding of differences in radial growth responses along environmental gradients and a better understanding of climate variations in these remote areas of the Southern Hemisphere.

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