History of High Mountain Forests of Polylepis Tarapacana at the Bolivian Central Andes

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Abstract

In this paper we have investigated the dendroclimatological history of *Polylepis tarapacana* (queñoa), a small tree growing in the Bolivian Altiplano and adjacent areas of Peru, Chile and Argentina (16-22°S) between 4000 and 5200 m elevation. Dendrochronological samples were collected on the slopes of the volcanoes: Sajama and Caquella. Presently, the chronologies range between 98 and 705 years in length, and represent the highest tree-ring records worldwide. In order to determine the climatic variables controlling *P. tarapacana* growth, interannual variations in tree growth were compared with regional records of precipitation and temperature. Correlation functions indicate that the radial growth of *P. tarapacana* is influenced by precipitation during the summer previous to the ring formation. In the sampling sites, precipitation explains around 50 % of the total variance in growth. Summer temperatures, which increase evapo-transpiration and reduce soil water supply, are negatively correlated with tree growth. These records offer the unique opportunity for reconstructing precipitation variations across the Altiplano during the past 5 - 7 centuries.

KEYWORDS: Mountain Forest, Bolivia, Central Andes, Dendroclimatological History

1. Introduction

The species of the genus *Polylepis* (*Rosaceae*) are widely distributed at the Andes from Venezuela to Argentina. They are little trees or bushes growing so much in dry atmospheres as humid at high mountain, where seasonal variations in precipitation and temperature could control the seasonal regulation of the growing cycles, and therefore the formation of annual growth rings. Because of that a considerable effort has been made to evaluate the dendrochronological potentiality of *Polylepis* species in Bolivia (Luckman and Boninsegna, 2002).

At the biogeographical Andean region in Bolivia, *Polylepis* is distributed in the sub region Yungueña and sub region Puneña above 3000 m and up to 5000 m. Nine species and 8 subspecies are distributed in the Bolivian Andes (Kessler, 1995).

In this study, we evaluate the dendrochronological potentiality of *Polylepis tarapacana Philippi*, that is widely distributed in the Cordillera Occidental of Bolivia. This study settled down the presence of growth rings in *P. tarapacana* and its annual feature. The similarity between annual variations in the width of the rings from tree of the same site has allowed us the development of two chronologies at the Bolivian Altiplano. Finally, to establish the climatic variations that control the radial growing, we proceed to determinate the relations between monthly climate variations and the growing of *Polylepis tarapacana* at the Bolivian Puna using correlation functions.

1.1. *Polylepis tarapacana* forests in Bolivia

Polylepis tarapacana appears as a little 1 to 3 m high tree or bush that grows between 4000 and 5200 m of elevation on the biogeographical floor of the Puna in Peru, Bolivia, Chile and Argentina (Kessler, 1995; Fjeldsa and Kessler, 1996; Braun 1997). This bioclimatic floor extends trough the Altiplano and is delimited for the Cordillera Oriental and Cordillera Occidental. The superior bound of distribution that reaches this species represents the maximum altitude in the world to an arborescent shape. This species grows in arid environments with a range of annual precipitation between 250 and 500 mm, where frost is common the whole year (Fjeldsa and Kessler, 1996).

P. tarapacana forests are located at the hillsides of extinguished volcanoes. They develop next to the common vegetation of the dry Puna. This forests contribute to the increasing of the soil water retention, decrease erosion by regulating the water runoffs and help to storage sediments and nutrients. Besides, they are the refuge and food source to many animal species, and facilitate the installation of numerous plants (Fjeldsa and Kessler, 1996). These forests have been an important resource to Altiplano population since they provide wood for houses constructions and firewood for peasants' works tames.

At present time, *Polylepis* forests are fragmented in small surfaces as a result of the degradation and alteration process product of many centuries of human intervention. In this way, these forests' animal and vegetation biodiversity are seriously threatened by the negative effects of human activity.

2. METHODS AND MATERIALS

2.1. Sites of study

The studied *Polylepis tarapacana* forests are located at the Western and South region of the Bolivian Altiplano (Table 1). The northernmost site is at 4750 m near to the Sajama Volcano (18°09'S, 69°00'W) and Caquella (21°30'S, 67°52'W) at 4560 m of altitude (Figure 1). These two sites are inactive volcanic complexes of Upper Miocene to Pleistocene age, consisting of lava flows and pyroclastic rocks. These volcanic mass have been affected by Upper Pleistocene glacier activity (Clapperton et al., 1997). Small *P. tarapacana* vegetation units develop on poor soils product of rocks physical weathering mainly cryogenic which forms talus debris where vegetation grows. In the same

Site	Lat.	Long.	Elevation	Exposition
Sajama	18° 06´	68° 53´	4450 m	S SW
Caquella	21° 15´	67° 35´	4560 m	SE

Table 1: Sites of Polylepis tarapacana dendrochronological material collection.

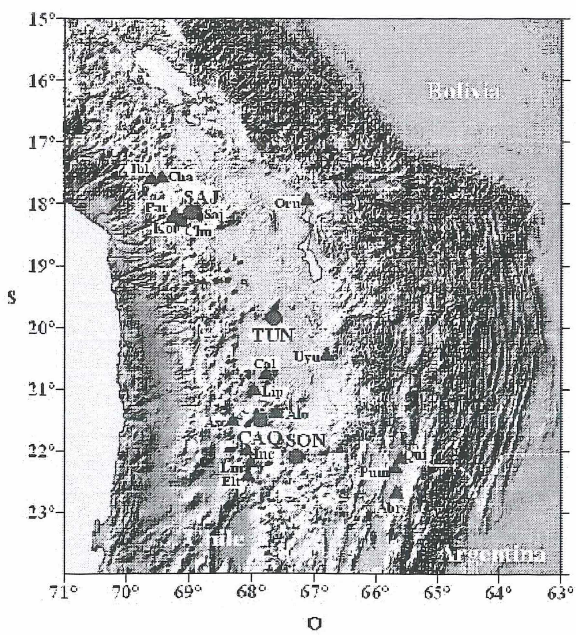

Figure 1: Location map of the sample sites and the meteorological stations used in this study.

way these trees develop on volcanic rock fracture, as much as on glacier deposits. These forests portions are established on slopes that vary from 20 to 40 grades sloping.

2.2. Taking samples

Samples were taken on October 2000 around Sajama Volcano, while Caquella was visited 3 times, October 2000, Jun 2001 and March 2002. All sites samples were taken with borers, achieving 5 mm diameter cylindrical sections with variable length according to each sample radius. Drill sampling was complemented with cross sections from living tree branches and death tree trunks. These sections were obtained with hand or mechanic saws.

2.3. Processing samples

Samples mounting and preparation were made at the laboratory in order to date them. These samples were allowed to get dry off at room temperature in the shade. Then they were polished with sandpapers of different ascendant progression texture (from 60 to 1000). Cross sections samples were polished with the same procedure.

Subsequently, growth rings were identified and dated using magnifying glass. The most recent ring was dated according to the Schulman convention (1956) for the South Hemisphere, which establishes that the outer ring corresponds to the year the ring began to get formed. Thus, for example the date for the last ring from the March 2002 samples was 2001, since this rings started to get formed in November-December 2001. Once the outer ring was dated, the dating continued until the inner ring of the sample.

The samples were visually co-dated using the thinner rings as a reference. One of the dendrochronology fundamentals establishes that trees growing in similar environmental conditions must show similar growing characteristics, that is to say similarity in the patron of thin and wide rings. The concept for co-date is based on this fundamental (Stokes and Smiley, 1968).

2.4. Establishment of chronologies

After the co-dating phase, the width of the rings was measured with 0.001 mm precision, generating temporal series for each tree. Measurement and co-date quality was controlled with the support of the program COFECHA (Holmes, 1983). This program uses correlation analysis to compare each series with a master series compound by the rest of the dated samples from a site.

In this way, it is possible to detect missing or false rings in a particular sample. After the dating control, the chronologies were constructed for each site using the program ARSTAN that eliminates the biologic growing trends, and minimizes the uncommon growing variations (Cook and Holmes, 1986). The biologic trends in the width of ring series were modeled using linear regressions or negative exponential graphs. These standardized series were finally averaged to obtain the media chronology for each site. Therefore, the chronologies constitute temporal series representing the radial growing annual variations of *Polylepis tarapacana* on each sampled sites.

2.5. Climate and radial growth relations

To determinate the strongest climatic variables related to the *Polylepis* growth on each study site, the interannual variations in width of rings where compared with climaticmental records (temperature and precipitation) from the Altiplano.

A simple comparison method between growth rings and climatic variations is the correlation function (Blasing et al., 1984). This method consists in correlating the interannual climatic fluctuations, taken month by month. The statistical relation between the width of the ring and the climatic variable are analyzed over a common period between the chronology and instrumental data. As the growth in a given year may be influenced by the previous year climatic conditions, the comparison period analyzed took 17 months since January from the previous growth season to May of the year when the rings were formed.

The total monthly precipitation and the media monthly temperature for the Altiplano stations were yielded for the SENAMHI, Meteorological Service in Argentina, Yann L`Hote (personal communication, IRD, France) and Mathias Vuille (personal communication, Climate System Research Center, University of Massachusetts, USA; Table 2). On the basis of their geographic and physiographic location, the meteorological stations with precipitation records were put in four groups. Group 1 with the stations on the Central section of the Altiplano, Group 2 with the stations to the North of the Cordillera Oriental, Group 3 with the stations to the South of the Cordillera Oriental, and Group 4 includes the stations on the South Altiplano, on Argentine territory (Table 2). The correlation functions were calculated comparing each chronology with the monthly average precipitation for each one of the four meteorological station groups.

Finally, for each chronology, a regional correlation function was established as a result of average the correlation functions of each chronology with the four precipitation groups. To do that, the value of each correlation coefficient resulting from the comparison between growth and precipitation (r) was divided for the value corresponding to the significant limit of 95 %, determined on the basis of the number of observations (ri). Higher values r/ri >1 (-1) corresponds to positive correlation coefficients (negative) statistically significant to a confidence level of 95 %. In this way, every station groups has the same weight to calculate the regional correlation function, independent of the record length.

The continuous and homogenous temperature records in the Altiplano are not as many as precipitation records. To establish the relations between radial growth of *P. tarapacana* and the temperature we used records from Oruro and La Quiaca. A regional correlation function between temperature and growth was calculated with the same procedure used for the regional correlation function for growth and precipitation.

	Site	Code	Latitude (°S)	Longitude (°W)	Elevation (m)	Record period	Source
Group 1	Oruro	Oru	17°57'	67°08'	3706	1944-2000	L'Hote
	Uyuni	Uyu	20°28'	66°48'	3660	1954-1997	SENAMHI
	Calcha	Cal	20°47'	67°47'	3700	1980-1996	Viulle
	Colcha de Lipez	Lip	21°01'	67°58'	3670	1983-1996	Viulle
Group 2	Isla Blanca	Ibl	17°36'	69°36'	4500	1969-1994	Viulle
	Charaña	Cha	17°35'	69°26'	4059	1948-1998	Viulle
	Parinacota	Par	18°14'	69°12'	4390	1952-1975	Viulle
	Kotakotani	Kot	18°11'	69°14'	4450	1962-1992	Viulle
	Sajama	Saj	18°06'	68°53'	4220	1975-1985	Viulle
	Chungara	Chu	18°17'	69°07'	4500	1962-1993	Viulle
Group 3	Alota	Alo	21°61'	69°37'	3609	1986-1997	Viulle
	Ascotan	Asc	21°32'	68°18'	4000	1975-1986	Viulle
	El Tatio	Elt	22°25'	68°04'	4320	1979-1992	Viulle
	Linzor	Lin	22°13'	68°01'	4096	1975-1992	Viulle
	Inacaliri	Inc	22°01'	68°05'	4100	1970-1993	Viulle
Group 4	La Quiaca	Qui	22°07'	65°36'	3442	1903-1993	Serv. Met. Arg.
	Pumahuasi	Pum	22°17'	65°41'	3560	1934-1990	Bianchi y Yañez (1992)
	Abra Pampa	Abr	22°42'	65°41'	3484	1934-1990	Bianchi y Yañez (1992)

Viulle: Mathias Vuille, Climate System Research Center, University of Massachusetts, USA.

SENAMHI: Servicio Nacional de Meteorologia e Hidrologia, Bolivia.

Ser. Met. Arg.: Servicio Meteorológico, Argentina.

L'Hote: Yann L´Hote, Instituto de Investigaciones para el Desarrollo (IRD), Francia.

Table 2: Metereological stations.

Site	No. Árboles	No. Radios	Período	Sensibilidad media	Des. Estándar	Auto-correlac.	Período común	No. series	Corr. entre árboles	Varianza en PC1
Sajama	19	25	1902-1999	0.1930	0.2324	0.4802	1948-1989	15	0.26	35.28 %
Caquella	25	32	1297-2000	0.2565	0.2820	0.3593	1794-1987	14	0.32	39.13 %

Table 3: Descriptive statistics for *Polylepis tarapacana* chronologies.

3. Results

3.1. Chronologies

The two chronologies developed from the *Polylepis tarapacana* extend between 98 and 705 years, being the Sajama and Caquella chronologies shorter and more extended, respectively (Table 3). The number of trees in each chronology varies between 19 and 25. Values of medium sensibility (a statistical used to evaluate the interannual variability in the rings width) are similar to those described to other subtropical species in South America (Villalba et al., 1987; 1992) and relatively greater than those of tempered and cold zones species (Bonisegna, 1992).

There is a clear common sign between both chronologies. A correlation's matrix between the two records for the common period 1902-1999, shows that all of them are correlated significantly.

3.2. Climate – radial growth relation

There exists a great similarity in correlation functions between the radial growth of *Polylepis tarapacana* and the interannual variations of precipitation and temperature in different studied sites of the Bolivian Altiplano (Argollo et al., 2004).

In Sajama, the growth of *P. tarapacana* is positively related with precipitation in the growth period before the growth ring formation (Figure 2). When the interannual growth variations are compared with the regional precipitation of the group 2 (the nearest one to the study place), we find that the December and January rain of the previous summer is correlated with the radial growth. Precipitation during the period of time of the ring formation is negatively correlated with the growth, principally in January. On the other hand, the growth is related negatively with temperatures during the previous summer (December and January) and positively with those from the common summer (January to March).

In Caquella, more consistent relations with the precipitation occurred in the last summer, being generally insignificant during the growth period in which the ring was formed (Figure 3). The January to February precipitations from previous summer, particularly those from the regional groups 2 and 3, are correlated with the growth, whereas the October to March temperatures during the same interval are inversely related with the radial growth of *P. tarapacana* in Caquella.

4. Discussion and conclusions

Dendrochronologic records of South America come principally from template and cold regions of Argentina and Chile (Boninsegna and Villalba, 1996; Villalba, 2000).

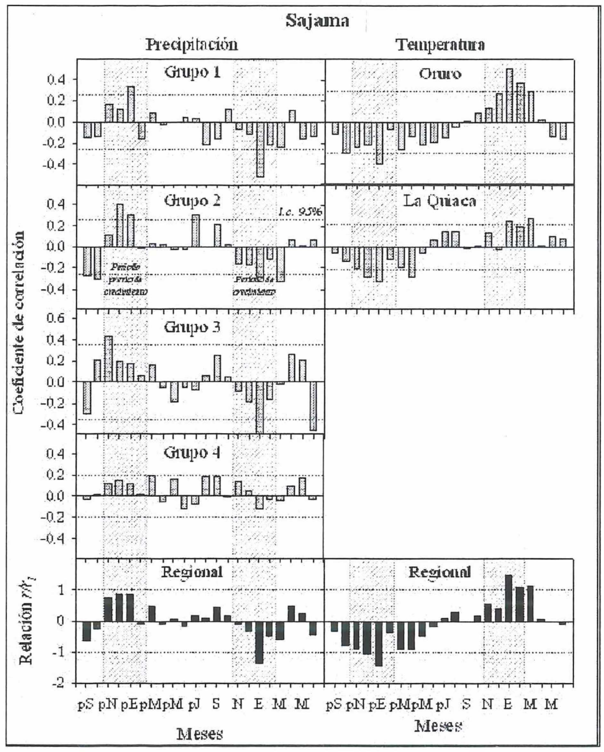

Figure 2: Correlation functions between precipitation, temperature and interannual variations in *Polylepis tarapacana* growth around Sajama Volcano.

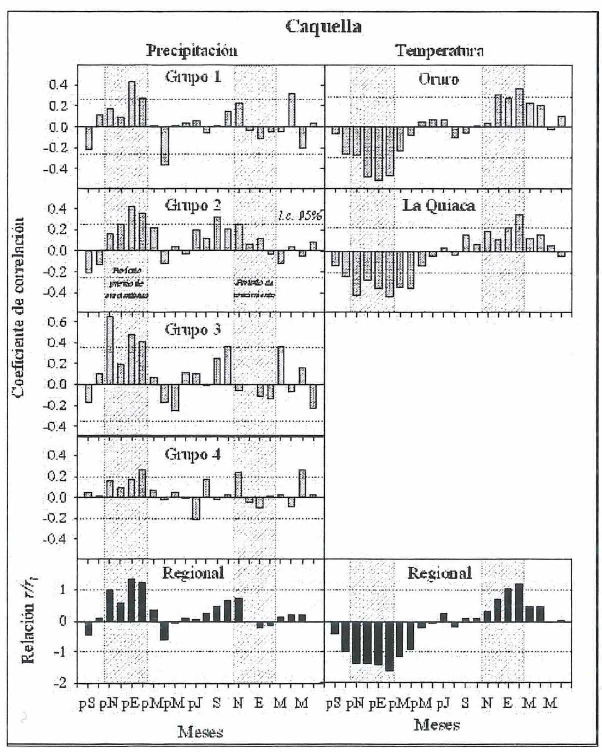

Figure 3: Correlation functions between precipitation, temperature and interannual variations in *Polylepis tarapacana* growth around Caquella Volcano.

Sub tropical records are fewer. In northeast of Argentina, chronologies were developed from forest species between 22 and 28°S (Villalba et al., 1992; 1998). In contrast with the high latitudes records, sub tropical chronologies are shorter, rarely overcoming 300 years of extension. *Polylepis tarapacana*, a characteristic species from the Bolivian Altiplano, give us new regional perspectives in the tropical dendrochronology field work. Our researches show that some trees can reach more than 500 years and that it's possible to co-date death wood, it's been allowed until now to elaborate chronologies of more than 7 centuries of extension. *P. tarapacana* grows in altitudes higher than 4000 m, in some areas it can reach 5200 m. For this reason, chronologies developed from this species represent the more elevated dendrochronological records of the world. The statistics used traditionally to measure the quality of the dendrochronologic series (Table 3) show that *P. tarapacana* chronologies are adequate to reconstruct the past climatic and environmental variations. Because of the similitude in the growth standard between chronologies along the Altiplano, these records can be also used as reference chronologies for the dating of archeological material.

P. tarapacana presents marked growth rings. However, it's very important to consider attributes like quality of polishing, illumination and perpendicularity of the woody plan in relation with the examined area to achieve a better growth rings definition. The coincidence in the chronologic sequence of wide and tight rings between woods of the same place and between places along the Altiplano show us that the *P. tarapacana* rings are bounded to an annual growing seasonal cycle. Another confirmation of the annual nature of the rings in *P. tarapacana* is the relation of themselves with the annual climate variations. The yearly precipitations in Altiplano show an extensive wintry period, where there is little rain or there isn't any. This dry period coincide to the period of lower temperatures in the year and the period of more daily thermal amplitude.

Correlation functions show that growth of *P. tarapacana* is strongly regulated by Altiplano interannual climate variations. In general, radial growth is influenced by the last summer climatic conditions. *P. tarapacana* growth is favored by abundant precipitations in the summer before the growth rings development. Negative correlations compared with temperatures during the same season, would be reflecting the indirect effect that the temperature has over the hydric availability. High temperatures increase the forests evapotranspiration process and the soil direct evaporation, reducing the available quantity of water for growth. On the other hand, there is a strong negative relation between precipitation and the summer temperature at the Altiplano: Dry summers are principally warm. For instance, in Oruro, summer precipitation and temperature are significantly related inversely ($r = -0.69$, $n = 38$, $p < 0.001$). This combination between climatic variables could make stronger negative relations showed between growth and temperature during the previous summer.

In general, in resulting functions the number of months significantly correlated with rings width is bigger for temperature than for precipitation, even when we should wait more influence from precipitation than from temperature in the *P. tarapacana* growth considering the arid conditions.

Correlation functions show that *P. tarapacana* growth is controlled by the hydric availability during the previous summer. Temperatures in this period are correlated negatively with the growth in answer to the negative effect of high temperatures (increase of evapotranspiration) on the accumulated water on soils. Correlation functions also show that growth is correlated with temperature during common summer, but this relation is positive in spite of what happened the previous summer. Based in these result, the *P. tarapacana* radial growth would be

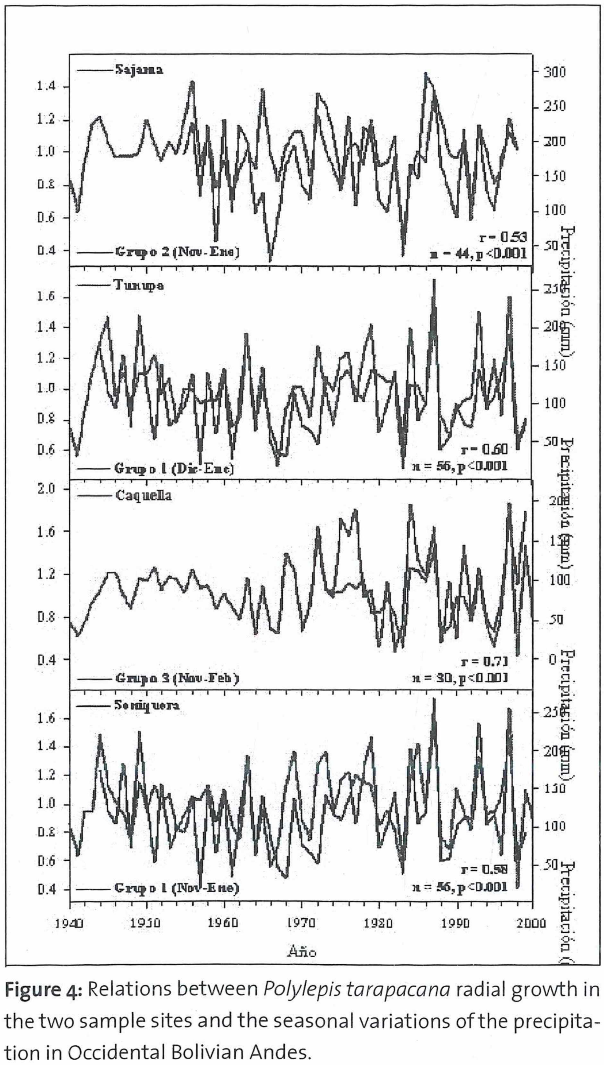

Figure 4: Relations between *Polylepis tarapacana* radial growth in the two sample sites and the seasonal variations of the precipitation in Occidental Bolivian Andes.

favored by temperatures below the average value during a summer and temperatures above the average value of the next summer (or conversely). It's difficult to explain from the physiologic point of view this contradict aspect of the response of *P. tarapacana* to the climate.

In the Figure 4, interannual variations of summer precipitation and growth indices for each sample places have been represented. It's possible to see that *P. tarapacana* growth in the Altiplano is strongly controlled by variability of summer rains. Centennial dendrochronologic records, with strong climatic indication offer the opportunity to use themselves to rebuild the past variations of precipitation in the Bolivian Altiplano during the last 500 – 700 years.

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