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# Vegetation, climate and fire regime changes in the Andean region of southern Chile (38°S) covaried with centennial-scale climate anomalies in the tropical Pacific over the last 1500 years

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ABSTRACT

Pollen and charcoal analysis from Laguna San Pedro (38°26′S, 71°19′W), a small closed-basin lake located within the present-day distribution of *Araucaria-Nothofagus* forest in the Temperate-Mediterranean Transition zone in the Andes of Chile (35.5–39.5°S), reveal centennial-scale changes in vegetation, climate and fire regime since 1500 cal yr BP. We interpret periods of relatively low growing season (summer) moisture and increased fire activity between 1500–1300 and 1000–725 cal yr BP, the latter period is also characterised by remarkably rapid bulk sediment accumulation and we infer prolonged annual sedimentation resulting from a decrease in the duration of lake freezing under a warmer climate. Relatively moist conditions during summer and low fire activity occurred between 1300–1000 and 725–121 cal yr BP, with slow bulk sediment accumulation through the latter phase in particular implying a cool and wet climate. Our results suggest that the Medieval Climate Anomaly chronozone was relatively warm and dry, followed by a cool-wet climate during the Little Ice Age chronozone, before a substantial modification of the vegetation landscape by Europeans occurred in the mid 1800's. The timing and direction of changes in the Laguna San Pedro record bear a striking resemblance to multiple independent tropical Pacific precipitation reconstructions, areas where precipitation is governed by the El Niño-Southern Oscillation (ENSO), and with the modern influence of ENSO over the climate in the region. We conclude that ENSO was the main driver of changes in growing season moisture in this part of the Temperate-Mediterranean Transition in south-central Chile over the last 1500 years.



## 1. Introduction

It is of vital importance that we understand the nature, timing, impacts and regional expression of past periods of abrupt climate change if we are to place current and future climate trends in to a meaningful historical context. A significant body of evidence now documents widespread evidence for decadal to centennial-scale climate intervals over the last 1500 years, most notably manifest in the so called Little Ice Age (LIA), Medieval Climate Anomaly (MCA) and the Dark Ages Cold Period (DACP) (Seager et al., 2007; Solomon et al., 2007; Mann et al., 2009; Graham et al., 2010). To date, there is a heavy bias towards northern hemisphere records and comparatively little empirical evidence for concurrent climate intervals from southern hemisphere landmasses. Available studies from the southern hemisphere indicate evidence of both regional-scale trends over the last 1500 years (e.g. Seager et al., 2007; Mann et al., 2009; Graham et al., 2010; Neukom et al., 2010a, 2010b) and a high degree of spatial heterogeneity in the nature, direction and timing of climate trends (Masiokas et al., 2009).

South America is the only landmass that virtually transects the entire meridional gradient from the tropics to the sub-Antarctic latitudes and is, thus, an important location for the discourse over global climate dynamics. Southern South America spans the entire zone influenced by the sub-tropical and extra-tropical climate domains and, as such, is well situated to track changes in two globally important components of the climate system: the sub-tropical South Pacific Ocean high pressure system and the extra-tropical southern westerly winds (SWW), as well as their leading inter-annual modes (the El Niño-Southern Oscillation (ENSO) and Southern Annular Mode (SAM), respectively). Moreover, the Andes Cordillera, a lofty and glaciated mountain range that runs in a north-south direction along the entire western sea-board of southern South America, intercepts the Earth's zonal tropospheric

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flow (Garreaud et al., 2009), resulting in sharp environmental gradients that make this region well suited for tracking the effects of past climate change on terrestrial environments. Despite this critical geographical setting, the plethora of fast sediment-accumulating lakes and long-lived climatically sensitive tree species, there are remarkably few continuous palaeoclimatic reconstructions of sufficient resolution to allow an adequate appraisal of change over the last 1500 years (e.g. Stine, 1994; Villalba, 1994; Jenny et al., 2002; Ariztegui et al., 2007; Boës and Fagel, 2008; Moy et al., 2009; von Gunten et al., 2009; Neukom et al., 2010b; Jara and Moreno, 2012).

Available evidence from sub- and extra-tropical southern South America suggests that the broadly defined LIA chronozone (ca 600-100 calendar years before present [cal yr BP]) was characterised by: (i) an expansion of virtually all studied Andean glaciers (Luckman and Villalba, 2001; Masiokas et al., 2009) and (ii) relatively low temperatures between 20 and 55°S (Villalba, 1994; Villalba et al., 2003; Neukom et al., 2010b). Despite these broad-scale trends, there is a substantial degree of spatial heterogeneity in the timing and nature of environmental responses to climate change through the LIA chronozone, with, for example, substantial differences in the timing of maximum 'LIA' glacier expansion across southern South America (Luckman and Villalba, 2001; Masiokas et al., 2009). Likewise, the MCA (ca 1050–600 cal yr BP) broadly encompasses a period of climatic change in southern South America that is variously manifested in both temperature and precipitation changes (Jenny et al., 2002; Bertrand et al., 2005; Mann et al., 2009; Moreno et al., 2009; Moy et al., 2009; Graham et al., 2010; Neukom et al., 2010a, 2010b; e.g. Villalba, 1994; von Gunten et al., 2009).

Here we present detailed pollen, charcoal and sedimentary data from a lake sediment core retrieved from Laguna San Pedro, south-central Chile, that span the last 1500 years. Laguna San Pedro is a small closed-basin lake located close to the precipitation dependent forest-steppe ecotone in the transitional zone between the sub-tropical and temperate regions of southern South America, the Temperate-Mediterranean Transition (TMT). The site, which was the focus of a previous palynological study of sediments extracted from a profile in an adjacent wetland (Rondanelli-Reyes, 2000), is located in Valle Lonquimay (Fig. 1), near several explosive stratovolcanoes. Precipitation in the TMT is derived entirely from the SWW and the main driver of inter-annual variability in the modern climate is ENSO (Montecinos and Aceituno, 2003; Garreaud, 2007; Garreaud et al., 2009). The Laguna San Pedro data allows assessment of the following questions: (1) what was the nature of environmental change in this region over the last 1500 years?; (2) are there discernible biological/climatic anomalies during the LIA, MCA and DACP chronozones?; and (3) what were the main driver(s) of environmental change in this region over the last 1500 years?

## 2. Study region

### 2.1. Physical setting

This study is centred on the mountainous Región de la Araucanía (36–39.5°S) in south-central Chile. The study area lies in the core of the Andes Cordillera which in this sector attains average elevation of ca 3000 m a.s.l., hosting several glaciers and active volcanoes. Here we sampled and analysed sediment cores from Laguna San Pedro (913 m a.s.l.; 38°26′S, 71°19′W; Fig. 1), a small closed-basin lake that lies within the formerly glaciated Valle Lonquimay that is situated 3 km east of the town of Lonquimay. The valley is a relatively flat southwest-northeast trending glaciofluvial plain that flows northeast from Volcán Sierra Nevada and forms the headwaters of Alto Río Bío-Bío. The bedrock in the region is composed of predominantly andesitic and basaltic volcanic material and lithosols derived from lava, scoria, pumice and tephra prevail across the landscape (Peralta, 1980). Four stratovolcanos (active over the historic period) lie less than 45 km west of the site: Volcán Llaima (2920 m a.s.l., 44 km); Volcán Tolhuaca (2806 m a.s.l., 31 km); Volcán Sierra Nevada (2554 m a.s.l., 27 km); and Volcán Lonquimay (2865 m a.s.l, 21 km) (Fig. 1).

### 2.2. Climate

The Andes Cordillera induces a dramatic drop in annual rainfall from a maximum of ca 3000 mm on the western slopes of the Andes (Las Raíces climate station, Chile: 38°32′S, 71°32′W, 1010 m a.s.l.) to ca 200 mm in Provincia del Neuquén (Las Lajas meteorological station, Argentina: 38°32′S, 70°23′W, 713 m a.s.l.) over a distance of less than 100 km (Peralta, 1980; Paez et al., 1997). The study site lies ~35 km west of the continental divide and receives 1919 mm of annual precipitation (73% falling during autumn/winter; Lonquimay climate station, Chile: 38°27′S, 71°22′W, 900 m a.s.l.). The thermal amplitude is considerable, reflecting the continental location, with winter (JJA) temperatures at the site as low as −20 °C and summer (DJF) temperature as high as 35 °C (although sub-zero summer temperatures are not uncommon) (Peralta, 1980). Average annual temperature recorded at Lonquimay is 8.3 °C with an average annual thermal amplitude of 13.2 °C, while east of the site in the sub-humid region (Las Lajas climate station) annual thermal amplitude reaches 29.3 °C as continentality increases (Peralta, 1980; Paez et al., 1997). Laguna San Pedro freezes in winter and the broader region is blanketed in over 2 m of snow (Rondanelli-Reyes, 2000). The growing season is short, ca 120 days (between December 10-April 10), and summer (JFM) precipitation is a key determinant of plant growth (Peralta, 1980).

Inter-annual climate variation in this part of Chile is predominantly associated with ENSO and SAM (Montecinos and Aceituno, 2003; Garreaud, 2007; Garreaud et al., 2009). While there is an overall increase (decrease) in precipitation and temperature over the region during El Niño (La Niña) events, much of the additional rain falls in winter and spring (SON) as snow. The most salient feature in the seasonal breakdown of the influence of ENSO over the climate of the study region is the tendency for warm (cool) and dry (wet) summers resulting from a southward (northward) displacement of the cool moisture-bearing SWW related to a strengthened (weakened) South Pacific sub-tropical high pressure system during El Niño (La Niña) events (Montecinos and Aceituno, 2003; Garreaud et al., 2009). Oscillations of the SAM, the leading inter-annual mode of the extra-tropical SWW, impact primarily on spring rainfall in the study region, with positive (negative) SAM resulting in decreased (increased) rainfall over the region as the SWW migrate southward (northward) (Garreaud, 2007; Garreaud et al., 2009).

### 2.3. Vegetation

Much of the vegetation of the flatter arable areas within Valle Lonquimay has been converted to exotic pasture. The native vegetation of the broader region is considered 'transitional', reflecting the influence of the steep precipitation and thermal gradients imparted by the Andes: the west to east precipitation gradient exerts the greatest influence over vegetation composition, with temperature (along the altitudinal gradient) inducing a secondary influence (Michell, 1980). The region is characterised by a double treeline, with *Nothofagus pumilio* forming the lower treeline at ca 1500 m a.s.l. and *Araucaria araucana* forming the upper treeline at ca 1800 m a.s.l. (Mc Queen, 1977; Michell, 1980). Michell (1980) identified seven plant communities occurring in the