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SCIENTIFIC ADVISORY

THE FIRST MILLENNIUM-AGE *ARAUCARIA ARAUCANA* IN PATAGONIA

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GENERAL BACKGROUND ON *ARAUCARIA ARAUCANA* FORESTS

The iconic conifer *Araucaria araucana* (Araucaria), called Pehuén by native people, is an endemic species of the Andes of northern Patagonia in Chile and Argentina. Its range encompasses only three degrees of latitude (37°20′ – 40°20′S) with a small outlying presence in the coastal mountains of Chile (Veblen *et al*. 1995). The species is classified as endangered (Premoli *et al*. 2013) because of extensive logging and human-set fires. *Araucaria araucana* has a long history of ethnobiological importance. For centuries the Pehuén fruits have been a vital sustainable food source for the Pehuenche people (Mapuche) and today the growing industry of ecotourism indirectly serves to protect these forests (Aagesen 1998; González *et al*. 2013). After a long history of human destruction of *A. araucana* forests, which reduced its range to half its original distribution, Chile and Argentina now legally protect this endangered species. These ecosystems continue to be threatened by logging, fires, and extensive livestock use. These factors, and the potential threats posed by climate change, are among the main challenges to *A. araucana* conservation (González and Lara 2015).

THE CHALLENGE OF FINDING OLD *A. ARAUCANA* TREES

In the mid-1950s, Edmund Schulman was the first dendrochronologist to carry out sampling in Argentina and Chile, and he built the first chronologies of *Fitzroya cupressoides* and *A. araucana* (Schulman 1956). After Schulman, from 1973 to 1978 Richard Holmes and Valmore LaMarche

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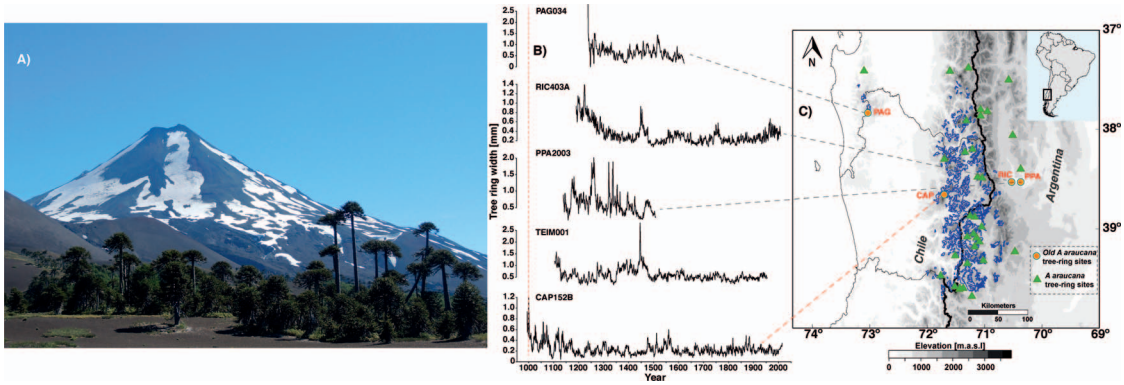

Figure 1. (A) An image of the *A. araucana* tree-ring collection site at Captrén, Llaima Volcano, Chile. (B) Five of the longest *A. araucana* tree-ring growth series of individual trees from different sites across the Andes are plotted. Notice that the millennium-age tree from Captrén displays a continuously crossdated growth series over a thousand years in length. (C) A map of northern Patagonia displays the distribution of *Araucaria araucana* in blue, green triangles indicate the locations of *A. araucana* tree-ring collection sites, and orange circles indicate the locations of the longest growth series plotted in (B).

were the first researchers to extensively collect tree-ring samples of *A. araucana*, crossdate the tree rings and develop chronologies (Holmes 1978; LaMarche *et al*. 1979, Suarez *et al.* 2014). Additional information about the first dendrochronological sampling campaigns in the Southern Andes can be found in Suarez *et al.* (2014). During these early collections, some of the oldest individuals of *A. araucana* were discovered, reaching more than 800 years old. After more than 50 years of tree-ring research and contrary to the popular belief in Chile and Argentina of the existence of millennium-aged *A. araucana* trees, not a single tree-ring sample reaching one thousand years old had been documented. Over these five decades of tree-ring research in *A. araucana* forests, challenges to building long tree-ring chronologies have been (i) the scarcity of virgin stands of old trees given the high impact of logging and human induced fires, (ii) the difficulty of finding well-defined growth rings in samples from sites experiencing growth-limiting conditions such as high elevations or well-drained volcanic substrate, and (iii) *A. araucana* wood decomposes at a high rate. Sub-fossil wood quickly degrades on the forest floor, although some living trees experience heart-rot, where the core of the stem rots out, making it impossible to reach the pith and accurately determine the age of the tree. The examination of sub-aquatic wood preserved in Andean lakes could provide a new approach to extending chronologies of the species.

INFORMATION FROM *A. ARAUCANA* TREE-RING RESEARCH

Scientists from Chile, Argentina, and other countries have analyzed more than 1780 tree-ring samples of *A. araucana*, producing more than 37 tree-ring chronologies from sites across its entire distribution (Figure 1). This valuable tree-ring material has been used for dendroclimatological studies reconstructing streamflow variability of Chilean and Argentinean rivers (Holmes *et al.* 1979; Mundo *et al*. 2012a; Muñoz *et al*. 2016), temperature (Villalba *et al.* 1989), hemispheric-scale variations in modes of atmospheric circulation (Villalba *et al.* 2012), and to fill gaps in century-long instrumental precipitation records from the Chilean Patagonia (González-Reyes and Muñoz 2013). *Araucaria araucana* also has been used in dendroecological studies of forest dynamics (González *et al.* 2010; Hadad *et al.* 2015a), tree-growth, climate and seed production relationships (Hadad *et al.* 2016), spatio-temporal climate-growth analyses (Mundo *et al.* 2012b; Muñoz *et al.* 2014), and fire history reconstructions (González *et al*. 2005, 2006; Mundo *et al.* 2013). During the last decade, *A. araucana* tree rings have been used to detect the ^{14}C "Bomb Peak" corroborated by the annual resolution of its growth rings (Hadad *et al.* 2015b), utilized in preliminary $\delta^{13}C$ and $\delta^{18}O$ isotopes studies (Tognetti *et al.* 2012), and in the analysis of chemical element markers to detect the occurrence of past volcanic

eruptions (Puchi *et al.* 2016). Furthermore, the need for developing millennium-long climate reconstructions in the Southern Hemisphere has renewed the interest of the international tree-ring community in the use of *A. araucana* records from the northern Patagonian Andes (Mundo *et al.* 2012b).

THE DISCOVERY

In the summer season of 2015–2016, colleagues from Chile, United States, and Canada, collected samples from an old-growth stand of *A. araucana* at the Captrén site near Llaima volcano (38°39′S, 71°41′W) in Conguillío National Park, southern Chilean Andes. This collection provides the first sample of a living, annually crossdated tree growing over 1000 years, reaching 1021 years old. Previous to this campaign, the Captrén chronology started in the year 1664, but now this chronology is the longest of the *A. araucana* network, beginning in the year 994. The second oldest tree in this chronology was 975 years old at the time of sampling, implying the existence of more trees of great age at the site. From the complete network of *A. araucana* chronologies, only a few came from sites located close to volcanoes, probably because the main dendrochronological studies of the species have been related to fire ecology and climatic signals in the growth patterns. In addition, the existence of these old trees on the slopes of Llaima volcano indicates the relative stability and moderate severity of the eruptions at the site even though this volcano is one of the most active in the southern Andes. The relatively short historical record of the Llaima Volcano eruptive activity starts in the year 1640 (Dzierma and Wehrmann 2010). Although some researchers have reconstructed eruptions using varve sediments, this new *A. araucana* chronology from the Captrén site could provide a higher resolution inter-annual record of volcanic activity and serve to corroborate both the historical and reconstructed records.

CONCLUSIONS

Millennial-length tree-ring chronologies of *A. araucana* have great potential to help answer relevant questions posed by climate change and natural hazards such as volcanic activity and fire. Therefore, the effective protection of *A. araucana* must be secured to preserve one of the world's most important botanical legacies. This finding serves to commemorate and recognize the efforts of the many dendrochronologists who have studied *A. araucana* and reinforces the importance of future tree-ring studies of this species. Finally, this finding confirms the popular belief of the existence millennium-aged *A. araucana* individuals.

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