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ORIGINAL ARTICLE

Fire history data as reference information in ecological restoration

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Abstract

Fire plays a fundamental role in the ecology of *Araucaria-Nothofagus* forests. This paper highlights the utility of dendrochronological techniques in providing the historical reference conditions to guide ecological restoration. In the Araucarian region human activity has dramatically changed the fire frequency in the *Araucaria-Nothofagus* forest ecosystems. Although further critical evaluation is required, our preliminary data show that, compared with the Native American period (pre-1883), there was widespread burning of forests associated with the subsequent Euro-Chilean settlement phase. Vast areas of subalpine forest were deliberately burned to increase pasture for cattle ranching. This process is documented by a major increase in the frequency of fires in the forested *Araucaria-Nothofagus* landscape during the 20th century. Prior to the 1880s the fire regime was characterized by infrequent catastrophic fires with long intervening periods of stability. The immediate reduction of human-induced fire is necessary to move these altered forest ecosystems towards the range of natural structural conditions and reestablish the historical variability of this ecological process. A better understanding of the fire ecology seems crucial in developing strategies for the restoration and management of these fire-dependent forest ecosystems.

Keywords: *Araucaria*; Fire-scars; Dendrochronology; Ecological restoration; Reference conditions

Introduction

The use of historical knowledge provides a long-term perspective for understanding ecosystem processes and patterns. This type of information is increasingly being used by scientists and resource managers to determine the historical range and variability of ecological processes (Kaufmann et al., 1994; Landres et al., 1999). One of the expanding fields where historical perspectives have been useful in evaluating and deciding ecologically relevant objectives is that of ecosystem restoration. This preliminary research report discusses the value of considering long-term perspectives, exemplified in this case by historical fire records derived by dendrochronology, for the conservation and restoration of Chilean *Araucaria* forests.

Fire history and conservation status of *Araucaria* forests

Araucaria araucana is a distinctive evergreen conifer that can grow to a large size and live more than 1000 years (Kozdon, 1958; Montaldo, 1974; Veblen, 1982). In Chile, more than 95% of the *Araucaria* forests are found in the Andes at an altitude of 1000–1600 m a.s.l. between 37°30′S and 39°40′S. Also, two small populations are located in the coastal range between 37°40′S and 38°40′S (Veblen, 1982; Veblen et al., 1995). When the Spanish arrived approximately 1550 *Araucaria* forest cover was

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estimated as ca. 500,000 ha (Lara et al., 1999). During the 1920–1970s the area covered by the species was reduced almost 50% by logging and fires (Lara et al., 1999). In 1976, *A. araucana* gained the status of Natural Monument which prohibited its logging (Veblen et al., 1995). However, permanent pressures to revoke the status (it was revoked in 1987 and reinstated in 1990) remain a continued threat to the species. Indeed, *Araucaria* populations outside national parks are still affected by logging, livestock grazing and burning. Additionally, the seeds of *Araucaria* are an important item in the diet and subsistence economy of local inhabitants who view it as a common property resource. Historically, the native population has collected seeds every year with unknown effects on *Araucaria* forest dynamics (Tacón, 1999).

Human or naturally caused fires have occurred in the Araucarian region for at least 44,000 years (Heusser, 1994). For several centuries the native tribes of this region (e.g., Pehuenche and Mapuche people) have used the area to traverse the Andes, for hunting and grazing activities and to collect *Araucaria* seeds (Aagesen, 1998; Tacón, 1999; Bengoa, 2000). Fires set by native tribes were typically used for hunting guanaco (Veblen and Lorenz, 1988). With the early introduction of livestock (by the late 1500s) brought by the Spanish conquerors (Nuñez de Pineda y Bascuñan, 1863; Guevara, 1899; Bengoa, 2000), human fires might have increased since native people may have needed to clear more travel corridors and manipulate forage. These new practices caused profound cultural and economic changes in the native population (Bengoa, 2000), which in turn could have had a significant effect on the fire regime.

With the arrival of Euro-Chilean settlers to the Araucarian region (officially after 1882) human-caused fires increased dramatically. Fire was used as the main tool to clear forests for agriculture and cattle grazing. This massive and uncontrolled forest burning led to a general perception by scientists, resource managers, and the public that fire was a threat and unnatural disturbance agent in the dynamics of these southern temperate forests (González, 2002). Thus, until recently forest fires have been portrayed as something negative and alien to the Andean temperate forest ecosystems.

Catastrophic fires occurred during the 2001–2002 fire season in Chile affecting several National Parks (one burned over 60% of the total area of Tolhuaca National Park) and private lands covered by *Araucaria* forests. These fires stirred public, political and scientific concern due to the ecological and cultural importance of *Araucaria* (Echeverría, 2002). Unaware of the past role of fire, resource managers initially refused to accept a natural cause for this fire event. The Chilean government and large forestry companies initially blamed the native Mapuche people. However, contrary to previously established opinion, the fires were caused by lightning storms, a natural ignition source not completely understood and recognized by scientists and resource managers. In fact, the historical fire statistics reported by the Chilean Forest Service do not list lightning as a cause of fire (CONAF, 2000). Therefore, in 2002 a special meeting was held to update and review the role of fire in *Araucaria* forest dynamics and landscape patterns (CONAF-FORECOS, 2002).

Following the 2002 fires plans have been designed and implemented for the restoration of burnt *Araucaria* forests and there is continued pressure for salvage logging of these areas. In this context, historical information and understanding of past fire regimes (e.g., frequency, severity, and spatial extent) should provide informed inputs that guide restoration plans and decisions about salvage logging. In the context of ecological restoration, this requires answers to key questions such as: what has been the historical fire frequency affecting the *Araucaria* landscape? How has human land-use changed the fire regime since the Euro-Chilean settlement? Do modern fire regimes differ greatly from historic fire regimes? Did historic fire regimes include fire events similar to those of the 2002 fire season? Paleoecological reconstructions of fire history are needed to answer all these questions.

Methods

A. araucana is long-lived (Kozdon, 1958; Montaldo, 1974) and can be used to develop fine-resolution fire records over the past millennium for the Andean cordillera of south-central Chile. Fire scars preserved within the boles of surviving *Araucaria* provide a direct record of fire occurrence (Fig. 1). *Araucaria* is able to resist the effects of the most intense wildfires due to its thick bark (>20 cm in adult individuals; Kozdon, 1958). Fire scars are caused by heat that kills part of the

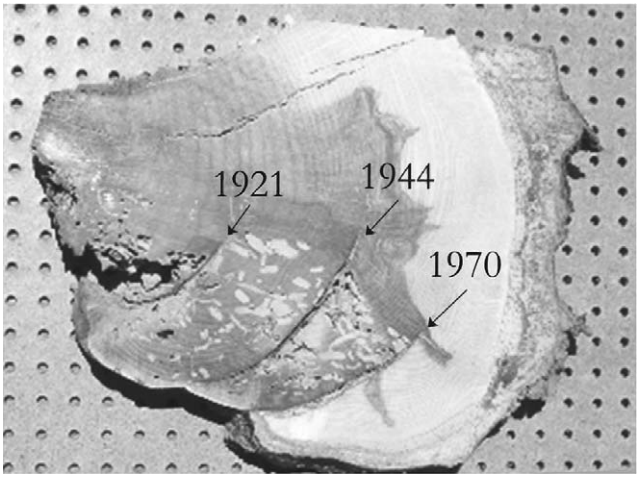

Fig. 1. Multiple fire scars on *Araucaria araucana*.

cambium (Agee, 1993). New rings partially grow over these wounds preserving this record (Fig. 1). These marks or injuries can be used to provide the precise year and approximate season of past fire events by cross dating the annual rings and by determining the position of the fire scars (innermost injury) within the cells of individual tree rings (Dieterich and Swetnam, 1984).

In Tolhuaca (38°10′S–72°W) and Villarrica National Parks (39°35′ S–71°30′ W), *Araucaria-Nothofagus* forests were sampled for fire-scar data to reconstruct the temporal variation of historical fires. To determine fire dates we cut partial cross-sections from fire-scarred trees (McBride, 1983). In both areas forest patches were searched intensively for fire-scarred trees, and whenever possible, samples were collected in clusters of several trees to improve chances of obtaining the most complete fire record possible. The preliminary fire history presented here for Tolhuaca National Park is based on 43 cross-section samples (M. González, unpublished data). For Villarrica National Park fire history is based on 144 cross-section samples (González, 2002). Standard methods were used to prepare cross sections for dating of fire scars (Arno and Sneck, 1977; McBride, 1983). On sanded samples, fire dates were determined by counting backwards from the outermost ring and were verified by visually crossdating against marker rings from a master tree-ring chronology. Fire scars from trees with suppressed growth were crossdated using the computer program COFECHA (Holmes, 1983). Fire-interval data analysis utilized the program FHX2 (Grissino-Mayer, 1995).

Results and discussion

Human influences on *Araucaria* fire regime

In Villarrica National Park (established 1940) fire has been a pervasive disturbance shaping the *Araucaria-Nothofagus* forest landscape (González, 2002). Fire records indicate a high variation of fire activity associated with human-land use (Fig. 2). Pre-settlement fire intervals (pre-1882) were larger compared with the Euro-Chilean settlement period (Figs. 2 and 3; Table 1). More frequent and less severe fire events during the 20th century were the result of the massive burning and livestock grazing carried out by new settlers. Although the fire-scar evidence persisting in the landscape shows significantly fewer fires prior to 1883, overburning by more recent fires – particularly those high-severity fires – may have partially destroyed the fire evidence of earlier fires resulting in an underestimation of the fire frequency during the Native American period (Figs. 2 and 3). A similar fire activity pattern is also shown by an ongoing study in Tolhuaca National Park (M. González, unpublished data). Moreover, preliminary fire data showing the same fire event in widely dispersed trees indicates that there has been at least one catastrophic fire (~1762) of similar magnitude to 2002. Therefore, human land use has effectively changed both the fire frequency and intensity in the *Araucaria* forested landscape.

Although it is not known whether these historical fires were ignited by lightning or humans (except, of course,

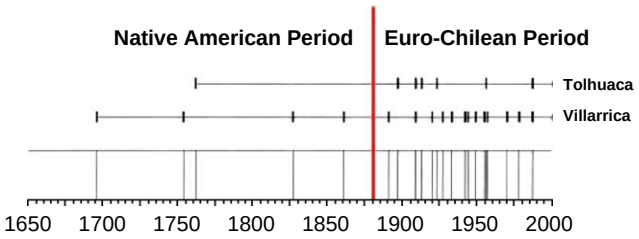

Fig. 2. Composite fire-scar records for Tolhuaca and Villarrica National Parks indicating years in which a minimum of two recorder trees were scarred in each area. Dates of fire scars are indicated by short vertical lines. Vertical lines extending to the *x*-axis indicate dates of all fires.

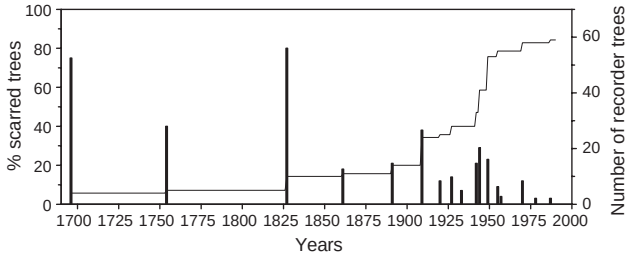

Fig. 3. Percentage of fire-scarred *Araucaria* trees (recorder trees) per year in Villarrica National Park. This diagram shows all years in which ⩾2 scarred trees recorded fire. The sample depth (horizontal line) is the cumulative number of recorder trees over the same time period.

Table 1. Fire interval statistics for the *Araucaria araucana* fire record over the complete period (1696–2000), the Native American period (1696–1882), and the Euro-Chilean settlement period (1883 to present)

Time period	No. of fire intervals	MFI	SD	Min. F.I.	Max. F.I.
1696–1882	3	55 a	19.7	34	73
1883–2000	12	8 b	4.5	2	18
1696–2000	16	18.2	20.7	2	73

Fire event years defined as years in which two or more trees recorded fire scars. MFI is the mean fire interval, and SD is the standard deviation of the MFI. Min. F.I. and Max. F.I. are minimum and maximum fire intervals, respectively. Means marked with different letters indicate statistical significance ($p<0.05$).

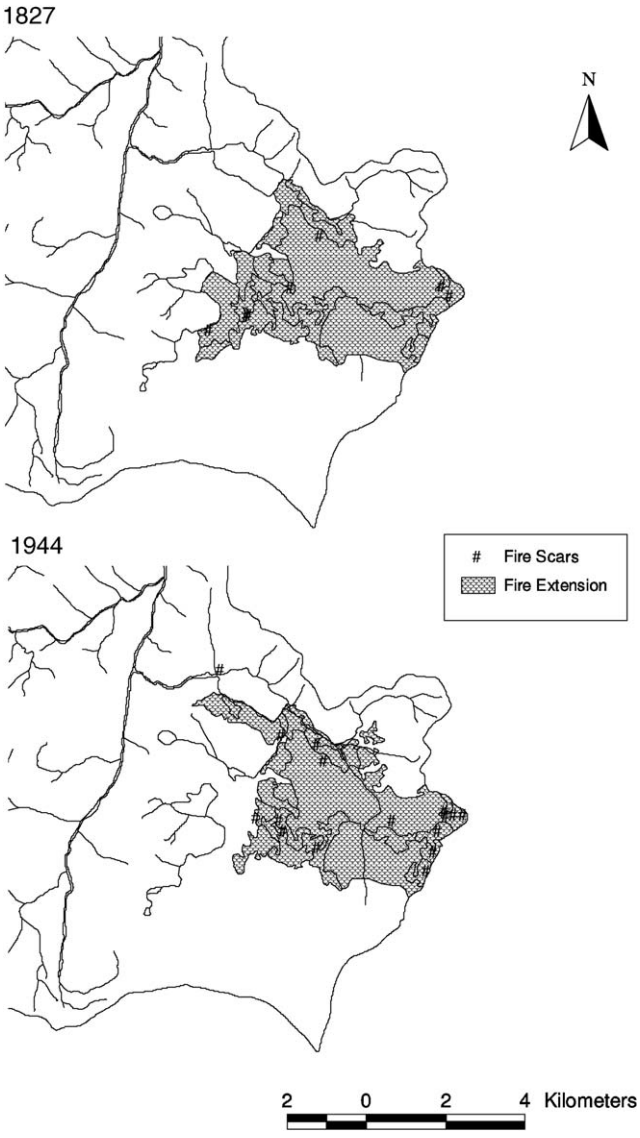

Fig. 4. Maps showing the spatial extent of the 1827 and 1944 catastrophic fires and locations of fire-scarred trees in Villarrica National Park (Modified from González, 2002).

for 2002), these fires were clearly driven by extreme weather conditions such as those that occurred in Tolhuaca National Park during February 2002. In Villarrica National Park, evidence of few relatively widespread and severe fires is indicated by abundant and widely dispersed fire-scarred trees and the conspicuous presence of post-fire *Nothofagus* cohorts (González, 2002). The very severe fires of 1827 and 1944 affected about one third of the forested area (Fig. 4) and were associated with severe drought conditions based on available instrumental and tree-ring proxy records (González, 2002). In this region, critical fire weather (i.e., lightning storms and frequent strong dry winds from the east called ''Puelches'') occurs during the summer. Documentary records for the past century indicate that most large fires occur between January and February (Urrutia and Lanza, 1993), which is the drier period of the austral summer. Investigation of the seasonality of fires from the tree-ring record is hampered by difficulties in defining details of the tree-ring records in *Araucaria* – this is the first fire history for *Araucaria* forests – but preliminary observations seem to confirm the seasonality shown by the written records.

Historical ecology in *Araucaria* ecological restoration

Natural archives such as historical fire data are useful for defining baseline conditions of forest communities. In the *Araucaria* forest communities fire is a significant agent in shaping the forest mosaic (Burns, 1993; González, 2002). The examples illustrated here show the pervasive influence of fire in the *Araucaria* forest ecosystems. In Villarrica National Park, the rates and severity of fires have been strongly changed by human activities, altering the vegetation mosaic. Large patches, originally covered by *Araucaria* forests, now have a sparse tree cover or are densely covered by bamboo (González, 2002). Also, a higher fire frequency has changed the stand age mosaic, which is currently dominated at stand and landscape scales by young *Nothofagus* post-fire stands 60–150-year old. This changed forest structure could be more susceptible to insect pests, fungal diseases and large, destructive fires (Veblen and Lorenz, 1991; Allen et al., 2002). Thus, human-induced changes in fire regime and vegetation patterns have resulted in current *Araucaria-Nothofagus* forest structures outside their historical and natural range of variability (Morgan et al., 1994). The preliminary fire records for Tolhuaca National Park indicate that large catastrophic fires similar to 2002 have impacted the landscape in the past. Under natural (or pre-European) conditions these Andean subalpine forests seem to have been mostly shaped by infrequent natural large-scale, stand-replacing fire events that are episodic in nature.

Restoration ecology typically involves returning an ecosystem to a natural or pre-existing state after disturbance by humans (Frelich and Puettmann, 1999). Restoration efforts strive to restore natural species composition and stand structures and, perhaps more importantly, to restore natural processes that maintain the ecological integrity, resilience, and sustainability of ecosystems (White and Walker, 1997; Landres et al., 1999). With that goal in mind, ecologically sound restoration approaches should aim not only to replicate and reestablish particular stand reference conditions but also to restore the natural variability and resilience of *Araucaria-Nothofagus* forests (Allen et al., 2002). Most forests in the southern region of Chile, including

Araucaria forests, have been affected by fire, clearing of land, high-grading, and intense browsing and grazing by cattle. This land-use change has directly or indirectly prompted other negative effects such as biological invasion, soil and water quality degradation. For example, a higher fire frequency and the introduction of cattle into natural areas have favored the invasion of non-native plant species. Anthropogenically caused fires that have altered the natural fire regime in *Araucaria* communities should be suppressed and the dominant historic fire regime of less frequent high-severe fires restored. In addition, all burned areas (natural or anthropogenic) should be protected from grazing or salvage felling that reduce the potential for recovery and encourage the rapid development of nonforest vegetation (van Nieuwstadt et al., 2001). Unfortunately, opening up some areas to livestock grazing after the 2002 fires will delay establishment of *Araucaria* and *Nothofagus* trees on the recently burned sites.

Understanding the historic fire regime of *Araucaria-Nothofagus* forests is a fundamental requirement for sound ecological restoration and fire hazard management efforts. According to our first reconstructions of fire regimes for this region, mesic *Araucaria-Nothofagus* ecosystems are mostly characterized by long intervals between catastrophic fires. Therefore, ecological restoration efforts should focus on returning this ecological process to its natural and historic range of variability.

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