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ORIGINAL ARTICLE

Precipitation variability and landslide occurrence in a subtropical mountain ecosystem of NW Argentina

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Abstract

Landslides are common on the steep slopes of the subtropical montane forests in Northwestern (NW) Argentina (Yungas). Instrumental and tree-ring records from this region indicate that rainfall has increased during the second half of the 20th century and there has also been an increase in landslide events. We used dendroecological techniques to date the occurrence of landslides during the past 50 years and examine the relationships with regional precipitation trends. *Alnus acuminata* H.B.K. is the dominant species in the upper montane forest and colonizes the bare areas exposed by landslides. Landslide dating was based on the identification of suppression-release patterns in ring-width series from trees growing along the landslide scarps, in combination with age determination of trees growing on the landslide failure or depositional surfaces. We cored *A. acuminata* in three areas that span the latitudinal range of the montane forest in NW Argentina: Los Sosa (27°S), Hualinchay (26°S) and Yala (24°S). The results show that landslide occurrence (and therefore probability) is more frequent during summers with abundant rainfall. As General Circulation Models for subtropical South America predict an increase in summer precipitation during the 21st century, increased precipitation could induce changes in landslide regime that would lead to important environmental changes in these montane ecosystems.

Keywords: landslides; precipitation; subtropical montane

Introduction

Climate, disturbance and forest dynamics are strongly related. Climate affects vegetation directly, conditioning the establishment and growth of species and, indirectly, by modifying the type, frequency, and magnitude of disturbances (Prentice, 1992; Beniston and Fox, 1996). Disturbances, in turn, release resources that are colonized by species better adapted to the new environments.

Interactions among climate, disturbance and vegetation determine the structure and diversity of natural ecosystems (Pickett and White, 1985; Wessman, 1992; Turner et al., 1993). In some cases, when a critical threshold is passed, small but gradual incremental changes in these components (e.g., precipitation) could trigger large changes in the ecosystems (Scheffer and Carpenter, 2003). These changes can lead to non-linear climate-vegetation relationships, including positive or negative feedbacks. In this paper we describe how possible changes in the precipitation regimes resulting from global climate changes could lead to significant shifts in the disturbance regime of the montane forest

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independently of the direct effects of climate on tree growth.

Landslide occurrence has strong effects on the ecology of montane forests (Veblen and Ashton, 1978; Garwood et al., 1979; Guariguata, 1990), generating extreme biotic and abiotic spatial gradients inside the effected area (Fernández and Myster, 1995), and altering the successional processes of vegetation. Landslides are a major component of the disturbance regime on steep slopes of the subtropical montane forests in Northwestern (NW) Argentina (Grau, in press). Landsliding not only promotes the establishment of pioneering species inside mature forest, thereby increasing local species richness (Grau and Brown, 1995), but also affect human settlements. Three major cities in NW Argentina (total population > 1 500 000 people) are located in the foothills of the mountains where landslide events could have direct and indirect (e.g. changes in water quality) impacts on human activities.

Many studies have shown strong relationships between landslide occurrence, soil-water content and precipitation (e.g. Keefer and Johnson, 1983; Schwab, 1983; Iverson and Major, 1987; Bovis and Jones, 1992; Schwab, 2002). Thus, a precipitation increase over relatively long intervals should favor landslide occurrence.

Variability is an intrinsic characteristic of climate that alters the relationships between disturbances regime and vegetation patterns (Prentice, 1992). Instrumental and tree-ring records show a precipitation increase during recent decades in NW Argentina (Minetti and Vargas, 1997; Villalba et al., 1998), which appears to be associated with changes in the regional atmospheric circulation related to Global Warming during the 20th century (Labraga and López, 2000; Villalba et al., 1998). If future climatic changes related to global warming involve increases in precipitation this could trigger an increase in landslide frequency. This would result in forests that contain an increased proportion of early successional vegetation patches, changing the species richness and biodiversity of these forests (Overpeck et al., 1990).

Dendrogeomorphic techniques have successfully been applied to date landslide occurrence in high latitudes of the Northern Hemisphere (Shroder, 1978; Schweingruber, 1988, 1996). Trees affected by geomorphic processes can be used to produce annually resolved dating for these events that cannot be obtained using other natural archives. Sudden mass movements also affect tree-ring eccentricity, induce changes in tree-ring patterns (suppression-release) and produce scars on the stems or exposed roots of the trees that survive the event (Alestalo, 1971; Schweingruber, 1996, and references therein). Recent studies have shown the potential of dendrochronology to date fire, flood and landslide events using tree-rings from species of subtropical ecosystems in Argentina (Grau et al., 2003).

In this paper we evaluate the relationships between precipitation variations and landslide occurrence in the upper part of the subtropical montane forest of NW Argentina. We used tree-ring studies from *A. acuminata* to reconstruct landslide events for the last 50 years in this region. The potential use of this species for dating landslides has already been indicated (Grau et al., 2003) but, in this study we further demonstrate the dating precision of this methodology in NW Argentina. Finally, to establish the relationships between landslides and climate, we compared the landslide chronology with regional precipitation records.

Study area

The subtropical mountain forests of NW Argentina are the southernmost part of the "Yungas" biogeographic province (Cabrera and Willink, 1980), which extends along the tropical Andes from Central America to northern Argentina (Fig. 1). Two main forest types can be differentiated along the elevation gradient. The lower montane forest between 400 and 1700 m is a

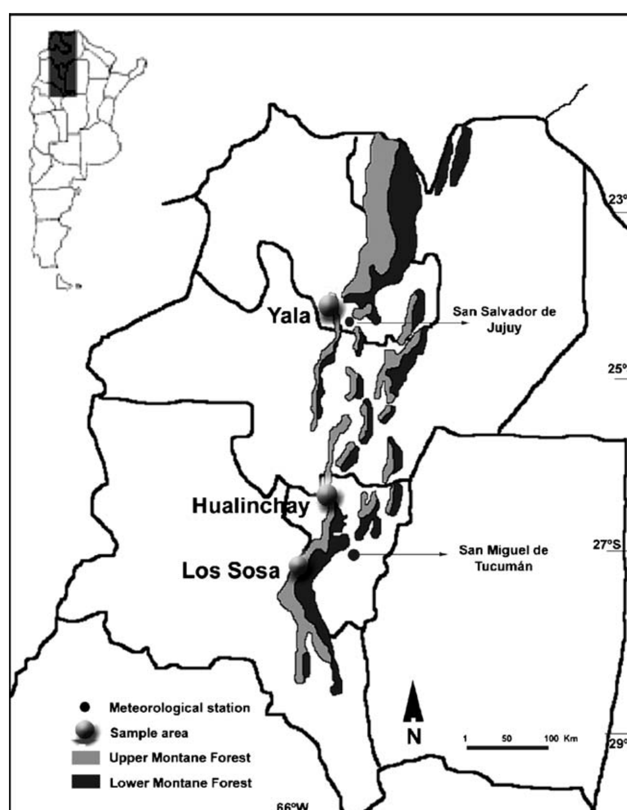

Fig. 1. Location of subtropical mountain forests and study sites in Northwestern Argentina.

relatively diverse semi-evergreen forest. At these elevations, landslides and tree-fall gaps are the dominant natural disturbances. The upper montane forest, which extends from 1700 to 2700 m, is a savanna-like mosaic with grasslands, shrublands and woodlands dominated by *A. acuminat*. The dominant natural disturbances are landslides and fire. *Alnus acuminata* is a deciduous species with a mean longevity of 80–120 years. It is the first colonizer of the new surfaces opened by landslides. Annual rings are well defined in the wood of *A. acuminata* (Villalba et al., 1986; Villalba, 1995). Grau (1985) has documented a recent (last century) expansion of the treeline dominated by *A. acuminata*, possibly favored by changes in fire frequency and extent (Grau and Veblen, 2000).

The climate of the region is subtropical with well-defined wet and dry periods. Summer precipitation accounts for 70–90% of the annual total and is followed by a dry winter season (Fig. 2). The rainy season extends from December to March with maximum precipitation in January. In the montane forest, precipitation increases with elevation reaching a maximum over 1500 mm/year at approximately 1100–1200 m.

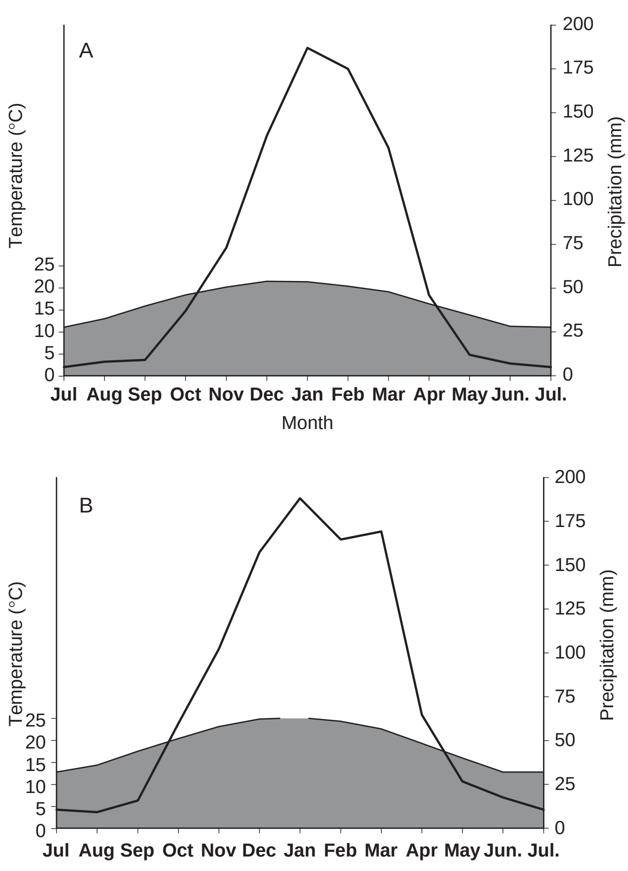

Fig. 2. Climatic diagrams for San Salvador de Jujuy (A) and San Miguel de Tucumán (B) stations, representative of the climatic conditions of the Argentine Yungas. Most landslides occur between November and March.

Methodology

Sampling was conducted in three areas (Fig. 1): Los Sosa (27°S) in southern Tucumán; Hualinchay (26°S) in northern Tucumán and Yala (24°S) in central Jujuy. Sites were selected to cover a latitudinal range (more than 400 km) across the montane forest in NW Argentina. Increment cores and cross-sections were collected from at least 10 trees in each of the 21 sampled landslides. The landslide of known age is located at site Reyes, in the Yala area. In this landslide we sampled six survivor trees growing along the landslide scarp and 15 trees established on the freshly exposed surface originated by the landslide event to establish the dating precision of this technique. Increment cores and cross-sections were processed following traditional dendrochronological methods (Stokes and Smiley, 1968; Fritts and Swetman, 1986).

Reconstructing landslide history

We used a combination of two dendrochronological techniques to date landslide occurrence. The *minimum age* for a landslide was established by dating trees growing on the landslide scar and its deposits. The age of the oldest tree growing on the new surface provides an estimate of the minimum age for the deposit. In the subtropical montane forest, abundant seed resources surround landslide sites and colonization occurs relatively quickly. For example, Blodgett (1998) found that colonization of new surfaces by *A. acuminata* occurs between the first and third year after the event in the Bolivian montane forests.

The occurrence of a disturbance can also alter the ring-width patterns of trees growing along the landslide scar. Trees affected by landslides can show a sudden reduction in the thickness of the annual rings (suppression) due to partial damage of their crown and root systems. In other cases, landslides produce a marked increase (release) in tree-growth by eliminating the competition from nearby trees. These *changes in tree-ring patterns* were also used for dating the occurrence of the landslide events.

Precipitation – landslide relationships

The landslide chronologies were compared with regional precipitation records in order to establish the relationship between landslide occurrence and precipitation fluctuations over time. We used Principal Component Analysis (Cooley and Lohnes, 1971) from 31 meteorological stations across NW Argentina to establish the dominant pattern of precipitation variation.

Results

Dating landslides

The Reyes landslide covers 7 ha and occurred in the summer of 1998. There is a strong correspondence in the results from the two dating techniques used at this site (Fig. 3). Most trees growing on the new surface created by the landslide in 1998 established between 1999 and 2000. In the six trees sampled along the landslide scarp, 1998 is the narrowest ring since 1990 and was followed by a sudden increase (release) that peaked in 2000. Due to topographic (elevation, slope) similarities between landslides, and the ability of *A. acuminata* to colonize new surfaces rapidly, we applied observations from the Reyes site to date the occurrence of 20 additional landslides of unknown age in the region.

In most cases (>90%), we found a good agreement between suppression-release patterns of tree growth and the ages of trees growing on the new surfaces. For these 20 landslides the mean lag between the oldest tree established on the landslide and suppression/release indicators from surviving trees was 1.8 years (median 2 years) indicating good agreement between the two records.

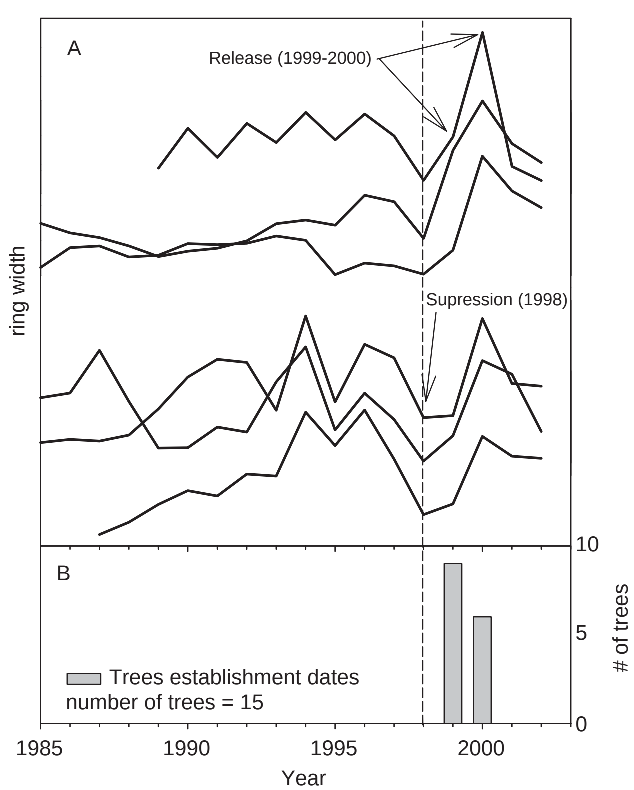

Fig. 3. Suppression and release patterns from trees growing along the scarp (A) and age structure of trees established on the failure surface (B), after the event.

Climate-landslide relationships

The results presented here are preliminary and based on a limited sample but they nevertheless indicate a strong relationship between landslide occurrence and regional rainfall variations as shown by the first principal component of annual precipitation (PC1, Fig. 4). Landslide dating is more consistent after 1950. Seventeen of the 21 landslide events occurred during years with above average precipitation and the mean precipitation in years with landslides is significantly greater than the mean precipitation in years without landslides ($t = 3.66$; $p < 0.001$; Table 1). Landslide occurrence was concentrated between 1973 and 1984 and coincides with the wettest interval during the 20th century.

Discussion and conclusions

Our study demonstrates the potential of dendrochronological methods to date landslides in subtropical mountains, and suggests the need to combine different techniques for the successful dating of landslide events in NW Argentina. Although severe erosion and falling debris may continue for several years after a landslide event, limiting the forest establishment in the new surfaces, our data indicate that the colonization by *A. acuminata* starts a year after the event in the most stable areas of landslides. It is important to note that *A.*

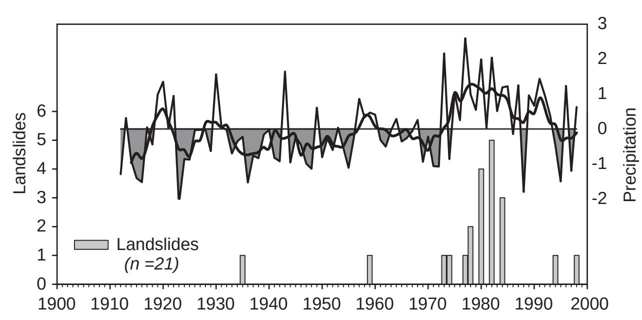

Fig. 4. Relationship between landslide events and annual precipitation, 1912–2000.

Table 1. Precipitation in years with and without landslides for the period 1935–2000

	N	Precipitation	SD
Years with landslides	11	0.955	1.164
Years without landslides	54	−0.131	0.834

Precipitation is expressed as amplitudes of the PC1. Differences are statistically significant ($t = 3.66$, $p < 0.001$).

acuminata produces seeds in spring prior to the onset of the rainy season when most landslides occur (Grau, 1985). Consequently seed production early in the growing season may delay the colonization of the new surfaces until the following year.

These limiting ages for tree establishment on the landslide surface do not, by themselves, provide the precise date for the occurrence of a landslide, but can be used to identify related suppression-release patterns from surviving trees adjacent to the landslide that confirm the date of occurrence. For *A. acuminata* trees affected by landslides, important changes in tree-growth patterns were observed 1 or 2 years before the date of establishment of the oldest trees growing on the new surfaces (Fig. 3).

The timing of landslides during the growing season may influence the lag in the response to the event. If the landslide occurred early in the growing season, the change in the tree-ring pattern could be seen in rings of the same year whereas this effect would not occur until the following year if the landslide occurred at the end of the growing season or during winter.

Due to the rapid colonization of new open areas, we estimate that landslides older than 50 years are difficult to identify. However, we have been successful in dating a landslide in the year 1935. A careful search in the field has allowed us to identify tilted trees with large epicormic branches related to nearby landslide scars, presently eroded and covered by vegetation. We believe that the lack of events prior to the 1970s is a real feature in our landslide chronology and it is not due to the inability to identify earlier landslides during the second part of the 20th century.

In the subtropical montane forests of NW Argentina, landslides are more probable during summers with abundant rainfall. Also, long-term periods (more than 3–5 years) with abundant precipitation favor greater landslide occurrence. Long wet periods increase water recharge in soils, which in combination with individual rainy events may facilitate landslide occurrences.

Remote sensing studies carried out in the Yala region show that landslides could affect up to 1.5% of the montane forest (Paolini et al., 2002). Understanding the relationship between climate fluctuations and disturbances on interannual to decadal scales is fundamental to project environmental changes in landscapes. In predicting the possible environmental consequences of global climate changes, an accurate dating is needed for establishing consistent relationships between precipitation variations and landslide events. This study has demonstrated the potential to produce absolute dates for landslides and demonstrates a consistent relationship between precipitation and landslide occurrence in this region at interannual to decadal timescales. Land use is not a major issue in our study due to their low strength in the area. The general trend in NW Argentina is a decrease in land use intensity in montane forests. This reinforces the role of precipitation as the main triggering factor for landslide occurrence. Simulations from the General Circulation Models predict an increase in summer precipitation for subtropical South America during the 21st century (Labraga and López, 2000) that could increase the frequency and magnitude of landslides in this region. Subsequent changes in forest structure and biodiversity would result from these changes that could have important environmental and human impacts on these montane ecosystems.

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