Spatiotemporal analysis of channel wall erosion in ephemeral torrents using tree roots—An example from the Patagonian Andes

Markus Stoffel[1,2]*, Alejandro Casteller[1,3], Brian H. Luckman[4], and Ricardo Villalba[3]
[1]Laboratory of Dendrogeomorphology, Institute of Geological Sciences, University of Bern, Baltzerstrasse 1+3, CH-3012 Bern, Switzerland
[2]Chair for Climatic Change and Climate Impacts, Institute for Environmental Sciences, University of Geneva, Chemin de Drize 7, CH-1226 Carouge-Geneva, Switzerland
[3]Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales (IANIGLA), Avenida Ruiz Leal s/n, 5500 Mendoza, Argentina
[4]Department of Geography, University of Western Ontario, Social Science Building, London N6A 5C2, Canada

ABSTRACT

This paper presents absolute ages for flash floods and related sediment entrainment in headwater catchments to construct a spatiotemporal framework of process dynamics and locations of major areas of channel wall erosion. The most reliable method for dating erosion is through dendrogeomorphic studies of exposed tree roots. Based on the analysis of erosion signals in root-ring records we documented a time series of channel wall erosion and successfully dated 21 erosive flash flood events since A.D. 1870 in an ephemeral gully in the Patagonian Andes. The study was performed with roots from *Austrocedrus chilensis*, *Nothofagus dombeyi*, and *Pseudotsuga menziesii*. Results demonstrate the potential of root analyses for the determination of major areas of sediment entrainment. In addition, we show that the position of damage within individual root rings allows inferences about the seasonal timing of flash flood effects and thus an assessment of possible meteorological triggers of erosive events, short intense storms occurring primarily in austral fall and late winter in this case. The approach presented adds significantly to the documentation of sediment entrainment and facilitates identification of areas of rapid erosion in small, remote headwater catchments with ephemeral flash flood activity.

INTRODUCTION

The occurrence of hydrogeomorphic processes in small upland watersheds primarily depends on hydrological triggers and sediment availability (Kirkby, 2010; Stoffel and Wilford, 2012). The sediment load of floods and flows is often enhanced through the lateral erosion of riparian terraces (Beeson and Doyle, 1995; Rijsdijk et al., 2007) and scour of poorly consolidated material (Radice et al., 2009). In the past, a great deal of work in drainage basin systems concentrated on sediment transport or output signals such as the quantification of sediment loads in rivers (Swanson et al., 2008), and the effects of land use (Lewicki et al., 2007) or climatic changes (Aalto et al., 2003; Steffen et al., 2009) on sediment fluxes. More recently, research has included the analysis of denudation rates (Wittmann et al., 2009) and source-to-sink processes (Carter et al., 2010; Lugon and Stoffel, 2010). Nevertheless, while considerable work has been done on sediment transport in headwater catchments, few studies attempted to localize major areas of sediment entrainment in space and time (Carson et al., 1998; O'Neal and Pizzuto, 2011; Osterkamp et al., 2012).

In ephemeral torrents, lateral roots of riparian woody vegetation can increase bank stability (Schwarz et al., 2010). At the same time, partially exposed roots may also be used for the dating of past erosion pulses through assessment of anatomical evidence of erosion in the wood of exposed roots (i.e., erosion signals). Previous studies using increment rings in exposed roots (root rings) focused on long-term areal denudation rates (LaMarche, 1961; Hupp and Carey, 1990), or on sediment pulses resulting from gullying processes in badlands (McAuliffe et al., 2006, Lopez Saez et al., 2011). Exposed roots have not previously been used to reconstruct erosion pulses and define sediment sources in torrential drainage systems activated by episodic flash floods.

This study explores and illustrates the potential use of roots to assess channel wall erosion and sediment entrainment. Cross sections of *Austrocedrus chilensis*, *Nothofagus dombeyi*, and *Pseudotsuga menziesii* roots exposed by flash floods were collected from very steep (70°–90°) but shallow (<1.7 m) channel walls of an ephemeral torrent in the Patagonian Andes. These 64 samples were used to (1) establish the species' suitability to document evidence of past erosion; (2) identify new types of erosion signals in roots; and (3) recognize and map erosional zones that were sediment sources activated during specific past events. In addition, we explore potential triggers of erosive flash floods and the possibilities and limitations of using roots to assess and date past erosion pulses in ephemeral drainage basins. The case study is the Los Cipreses torrent in the Patagonian Andes (Argentina, 40°56′00″S, 71°24′45″W; Fig. 1A). The watershed area is ~7.5 km², with a channel length of 4.9 km, and an elevation range of almost 1.2 km between the highest summits (1958 m above sea level, asl) and the point where the torrent enters Nahuel Huapi lake (768 masl). The geology is dominated by tonalitic lithologies of Jurassic age. San Carlos de Bariloche airport, 33 km southeast, is the closest meteorological station with a long record. The mean annual precipitation (1914–2010) at Bariloche is ~975 mm, most of which is during late austral fall and winter (May, June, July, August). The study reach is 560 m in length and ~7000 m² in area and is located on the alluvial fan of Los Cipreses torrent. There is abundant evidence of flash flood activity on the fan, indicating frequent sediment entrainment and channel wall erosion events (Fig. 1B).

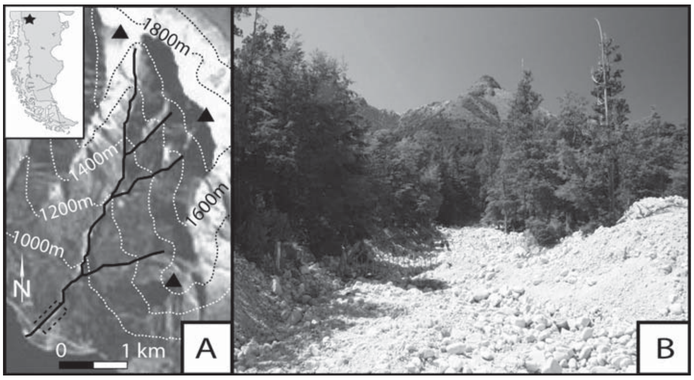

Figure 1. A: Study reach (dashed rectangle), located on fan of Los Cipreses torrent (Nahuel Huapi National Park, Argentina; 40°56′00″S, 71°24′46″W), a watershed with area of 7.5 km² (channel length 4.9 km) and elevation range of ~1.2 km. B: Deposits of recent flash floods.

*E-mail: markus.stoffel@dendrolab.ch.

MATERIAL AND METHODS

Ring-based chronologies from trees and roots in temperate regions provide annually resolved data on geomorphic activity that may span several centuries, thereby complementing available documentary data and allowing assessment and dating of events prior to instrumental and historic records (Stoffel et al., 2008, 2010). The investigation of past sediment entrainment at Los Cipreses was based on the analysis of root rings in cross sections of exposed roots of *A. chilensis*, *N. dombeyi*, and *P. menziesii*. Details of the samples analyzed are provided in Table 1.

TABLE 1. ROOT SAMPLES

Species	Trees (number)	Roots (number)	Mean root age (yr)	Mean diameter (cm)
Austrocedrus chilensis	22	53	106	7.7
Nothofagus dombeyi	2	2	59	8.4
Pseudotsuga menziesii	7	9	28	9.6
Total	31	64	80.2 (SD 54.3)	8.4 (SD 5.5)

Note: Austrocedrus chilensis (D. Don) Florin et Boutelje (Chilean cedar); *Nothofagus dombeyi* (Mirb.) Oerst. (Southern coihue beech); *Pseudotsuga menziesii* (Mirb.) Franco (Douglas-fir). SD—standard deviation.

Roots of the species investigated in this study have not previously been used in dendrogeomorphic work. The initial step in the analyses was to identify potential erosion signals in these roots such as abrupt changes in ring width and associated wood anatomical changes, such as the total number of cells per ring, cell lumen size, and/or cell-wall thickness (Corona et al., 2011). Because the cell structure of roots becomes stem-like after exposure (LaMarche, 1961; Sigafoos 1964; Friedman et al., 2005), we also assessed changes in root-wood anatomy in all samples to calendar date the timing of initial root exposure. In addition to these more conventional erosion signals, root samples were also analyzed to document evidence typically used to identify damage in tree (stem) rings, namely reaction wood due to gravitational disequilibria or unilateral pressure (Timell, 1986), callus tissue overgrowing scars, and tangential rows of traumatic resin ducts (TRD) formed next to wounds after abrasion by sediment (Bollschweiler et al., 2008; Stoffel and Hitz, 2008).

Years with erosion activity were determined based on (1) the number of roots showing erosion signals in the same year, (2) signal intensity (i.e., strong, medium and weak signals; Schneuwly et al., 2009), and (3) the spatial distribution of damaged roots along the channel. Analysis was limited to the period A.D. 1870–2009, with records for >20 roots. Two classes of events were defined: probable events when ≥10% of the roots showed simultaneous erosion signals, and possible events when 6%–10% of the samples exhibited simultaneous erosion signals. Events were only accepted when erosion signals were present in the roots of more than one tree. The positions of injuries and TRD were assessed within root rings (earlywood, latewood, and dormancy; see Stoffel et al., 2008, and references therein) to improve dating resolution and possibly identify intra-annual differences in erosive activity.

RESULTS

We sampled 64 cross sections of partially exposed *A. chilensis*, *N. dombeyi*, and *P. menziesii* roots from 31 living trees in austral fall 2009 and 2010. These roots yielded 152 characteristic erosion signals caused by the denudation of roots or physical impact of sediment (Table 2). Past erosive events were mainly identified via injuries (38.1%) induced through the abrasive action of sediments, or via abrupt growth increases (25%), i.e., changes in ring width and cell structure (size, number, and cell lumina characteristics) stemming from the sudden exposure of roots to atmospheric conditions. Abrupt growth reductions reflecting impaired growth

TABLE 2. GROWTH SIGNATURES IN ROOTS USED TO INFER PAST CHANNEL WALL EROSION EVENTS

Growth signature	*Austrocedrus chilensis*	*Nothofagus dombeyi*	*Pseudotsuga menziesii*	Total	Percent
Injury	36	6	16	58	38.1
TRD	-	-	22	22	14.5
Growth increase	34	1	3	38	25.0
Growth decrease	23	-	1	24	15.8
Reaction wood	5	-	5	10	6.6
Total	98	7	47	152	100.0

Note: TRD—tangential rows of traumatic resin ducts. Dashes = not present

conditions and reduced vitality were found in 15.8% of the samples. These signals were equally well represented in the three species analyzed.

Reaction wood and TRD accounted for 21.1% of erosion signals: TRD (14.5%) were only found on cross sections of introduced *P. menziesii*, and were key for the identification of erosive events using this species. The formation of reaction wood was relatively rare in roots and observed in only 10 samples (6.6%). Characteristic examples of erosion signals are presented in Figure 2.

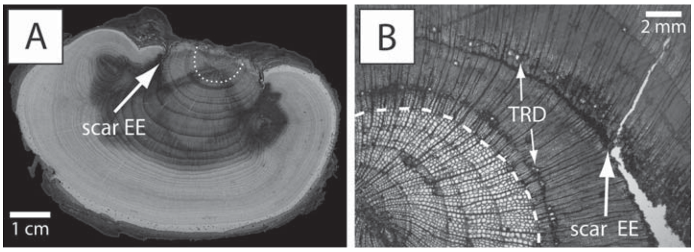

Figure 2. A: Cross section of exposed *Austrocedrus chilensis* root with initial exposure signature in A.D. 1956 (i.e., changes in cell structure; dashed line) and subsequent abrasion (arrow) in early earlywood (EE) 1960. B: Microsection of *Pseudotsuga menziesii* root with initial exposure (dashed line) in 2004, as well as scar (arrow) and traumatic resin ducts (TRD), in 2006 and 2007.

The innermost rings of the roots sampled were dated at between A.D. 1819 and 1999, with a mean root age of 80.2 yr (standard deviation [SD] 54.3). The assessment of signals occurring simultaneously in the roots of different trees within the study reach allowed the reconstruction of 21 events with channel wall erosion since A.D. 1870 (Fig. 3); of these, 11 are probable erosion events and 10 are possible events. The possible events were (1) spatially more limited, (2) older downtrack, where fewer samples were available for analysis, or (3) where the quality of signal was insufficient for an identification of a probable event.

Return periods of erosive events at individual locations were determined for individual trees and obtained by dividing root age by the number of erosion signals from the 21 recognized events. The recurrence interval of erosional events varied between 5 and 139 yr (mean 32.8, SD 26.2). An interpolation of return periods of channel wall erosion events is given in Figure 4 and covers the last 50 yr (1960–2009), as most roots (86%) sampled for analysis have innermost root rings predating 1960. The map of recurrence intervals points to distinct differences in sediment entrainment processes and the existence of major areas of sediment entrainment at the study reach. Return periods of erosion tend to be positively related to root age, suggesting that riparian vegetation is younger and sparser in areas with frequent erosion or that these areas have undergone more recent erosion. In addition, Figure 4 indicates that shorter return periods of erosion tend to be concentrated in wider channel sections with step-pool bed

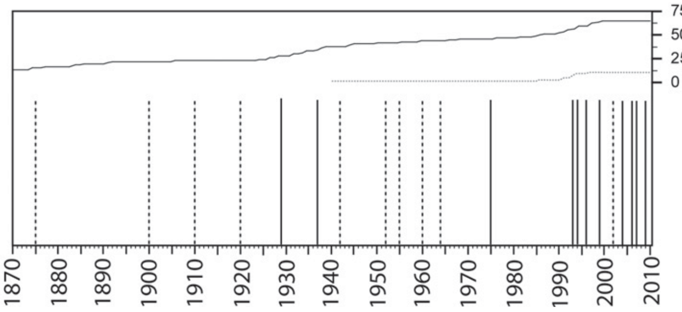

Figure 3. Inferred chronology of channel wall erosion and sediment entrainment at Los Cipreses (Argentina), A.D. 1870–2009. The 11 bold lines represent erosion events with synchronous reactions in ≥10% of samples, whereas 10 dashed vertical lines are events for which less evidence (6%–10%) is available. Upper solid line shows number of samples available for analysis (i.e., sample depth, SD). Upper dashed line gives sample depth of *Pseudotsuga menziesii*.

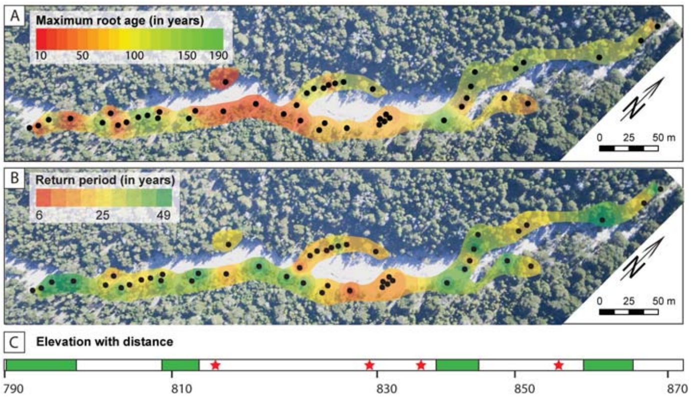

Figure 4. Spatial interpolation (inverse distance weighing) at Los Cipreses (Argentina) derived from erosion signals in roots. A: Maximum root age. B: Return periods of channel wall erosion events (A.D. 1960–2009). C: Elevation with distance; major areas of sediment entrainment are much more common in wider channel segments downstream of steps (red stars) than in flatter, less turbulent, segments of study stretch (green surfaces).

morphologies. In contrast, erosive activity was less important in the flatter, more regular segments of the study reach, where gentler gradients and channel geometry favored sedimentation of flood material in the past.

Detailed microscopic analysis of the position of injuries and TRD within root rings (see Fig. 2B) points to two distinct seasonal peaks of channel wall erosion events. A high concentration of damage is recorded at the very beginning of root rings (i.e., dormancy or earliest earlywood rows; 75.9%) or in the final rows of latewood cells (16.8%). Erosive events occurring during the growing season of roots were scarce (i.e., earlywood-latewood transition; 7.3%). Therefore, erosional events are likely to occur most frequently as a result of rainfall events in austral spring and secondarily in fall, with discharge being possibly enhanced through snowmelt in the spring. The paucity of meteorological data in the study region plus the shortness and incomplete nature of regional records prevent identification of individual triggering storms or the precipitation thresholds responsible for generating the flash floods and related erosion pulses at Los Cipreses. Nevertheless, daily precipitation records from San Carlos de Bariloche and Lago Gutierrez (33 km southeast and 28 km south, respectively, from the study reach) indicate that short-lived (<24 h), intense storms in fall or late winter and/or spring with daily precipitation totals >50 mm would represent the main trigger of erosive flash floods across the larger case-study region.

DISCUSSION

This study reports the application of erosion signals in tree roots to document time series of channel wall erosion in an ephemeral torrent of the Patagonian Andes back to A.D. 1870 and to identify major areas of sediment entrainment during episodic flash flood activity. The study utilized records from roots of tree species that have not previously been used in dendrogeomorphic work and describes new biological indicators from roots for the reconstruction of erosion (i.e., TRD and reaction wood). In this paper root-ring data are used to document erosion by rapid and abrupt events (Sigafoos, 1964) rather than to examine long-term denudation rates where root exposure has been used primarily in the past (LaMarche, 1961; Corona et al., 2011; Lopez Saez et al., 2011). The position of damage within the root ring also allows inferences about the seasonal timing of possible meteorological triggers (e.g., Stoffel et al., 2008; Schneuwly et al., 2009), i.e., rainstorms occurring primarily in austral fall and late winter and/or spring.

Root-ring records were very effective in the detection of major areas of erosion at Los Cipreses and are a promising approach for the dating of past channel wall erosion and sediment entrainment. However, partially exposed roots will only form rings and survive as long as their tips are unexposed (Schulman, 1945). Therefore, reconstructions based on roots growing adjacent to torrential systems are unlikely to yield time series as long as those from their parent trees, which can produce new roots or remain vital with a smaller root biomass. Datable evidence of erosion also tends to disappear with time through complete root exposure and death, and therefore root-derived records result in a better preservation of more recent events. In addition, species differences may be critical in the development of root records. Of the sampled species only *P. menziesii* produces TRD following abrasion and distortion, evidence particularly useful for the identification of erosion signals in roots. As *P. menziesii* was only introduced into Patagonia in the 1950s, the inclusion of data from this species resulted in the recognition of more events for the more recent segment of the reconstruction.

It is clear that root-ring records cannot produce quantitative information on return periods of erosion pulses from parts of the study reach without trees. Lacking the stabilizing effect of trees and their roots (Schwarz et al., 2010), these sites may be subject to the most rapid and intense erosion and therefore have more frequent erosive activity compared with neighboring channel walls. Erosive activity may therefore be underestimated in these segments of the channel.

Despite these limitations, the application of dendrogeomorphic techniques to roots for the dating of channel wall erosion processes and identification of major areas of erosion has advantages over other types of retrospective assessments of sediment source activation in torrential drainage basins. While short-term field-based observations of contemporary erosion (e.g., Sheridan et al., 2007; Berger et al., 2011) yield exhaustive information on current process activity, they cannot estimate longer term spatial changes in erosion patterns. Dendrogeomorphic studies allow the assessment and documentation of past channel wall erosion and the identification of major areas of sediment entrainment and yield both highly resolved (i.e., up to seasonal dating accuracy; Stoffel and Beniston, 2006) and longer term (i.e., decadal time scales; Stoffel et al., 2008) data on hydrogeomorphic processes in remote headwater catchments. In the present case, based on the age of samples and the spatial distribution of roots, we were able to identify a significant number of flash floods with related channel wall erosion for at least the past ~50 yr.

This new technique augments standard tree-ring dating of deposits outside the channel (Stoffel and Wilford, 2012) with information on erosion within the channel and extends the reconstruction time scales available to the investigator. Moreover, it can record erosion events within the channel that are not seen in dendrogeomorphic records from trees growing outside the channel, and thus results in the dating of more frequent though less extreme events. In addition, we have also been able to demonstrate that highly resolved dating and localization of past erosion activity in small drainage basin systems are possible using root rings from two South American species (*A. chilensis*, *N. dombeyi*), but that evidence of erosive activity is more abundant in *P. menziesii*, which forms TRD. These studies may be a valuable tool for the documentation of the most active areas of channel wall erosion and construction of time series of erosion pulses in new geographic areas, although we recognize that further research is needed to develop ways to extend these calendar-dated frequency series of erosion pulses farther back in time and to evaluate the magnitude of individual erosion pulses.

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