TREE RINGS AND NATURAL HAZARDS: PRINCIPLES AND APPLICATIONS (I)

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ABSTRACT. Tree rings and natural hazards: principles and applications. A detailed understanding of how the earth surface is being continuously shaped and why it looks the way it does are essential prerequisites for an appraisal of geomorphic processes and related changes in space and time. Data on the occurrence of past geomorphic events remains, however, scarce and predictions on how the expected climate change may affect the frequency and volume of earth-surface processes have to be based on limited datasets. Tree rings have on varied occasions proved to be a reliable tool for the acquisition of data on past events. In this paper, examples are provided on how the recurrence of events can be assessed (*how often?*) or their timing determined with yearly and sometimes even monthly precision (*when?*). Based on the mapping of trees on the study site, it is also possible to determine the reach and lateral spread of events (*how far?*). Movement rates can be reconstructed (*how fast?*) or the magnitude of incidences assessed (*how big?*). In combination with meteorological, hydrological and/or seismological data, results from tree-ring studies can be consulted to identify triggers of previous events (*why?*).

Key-wors: natural hazards, principles, applications, dendrochronology

1. Introduction

Geomorphology is the study of landscapes and the processes shaping the earth's surface (Edmaier 2004, Selby 1985). One of the primary goals of all geomorphic research is to comprehend why the present-day earth surface looks the way it does, to understand landform history and dynamics as well as to predict potential future changes (Goudie 2006, Lavee et al. 1999).

The evolution of landscapes as well as the dynamics of earth-surface processes vary in time and space (Thornes & Brundsen, 1977). The temporal activity of earth-surface processes may depend on external disturbance and occur when activated by e.g., climatic change or tectonism. In this case, geomorphic activity will be important during an initial phase and events will become less

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frequent with time. In open systems, in contrast, triggers are very regularly activating earth-surface processes, resulting in a rather continuous activity (Brundsen & Thornes, 1979).

Earth-surface processes also have a spatial component (Schumm & Lichty, 1965). When geomorphic processes occur in areas of human occupation, they may pose a threat for the inhabitants or the built environment (Bloetzer et al., 1998). In order to cope with natural hazards and to reduce risks, one needs to obtain knowledge on the number of occurrences, the size or the spatial patterns of events (Wolman & Miller, 1960). However, the study of landscape evolution and the analysis of frequency and magnitude of geomorphic processes often remains qualitative, as direct observations of past occurrences are scarce and archival data remains fragmented.

Historical data from archives and the generation of chronometric data – such as radiocarbon dating, lichenometry, accelerator mass spectrometry or optically stimulated luminescence – are essential for a better understanding of process dynamics and changes in activity over time and space. Tree-ring analysis (i.e. dendrochronology) is one of the most precise and accurate methods for the dating of various geomorphic processes (Guzzetti et al., 1999; Lang et al., 1999; Bollschweiler et al., 2011) and allows for a determination of incidences with at least a yearly precision. As a result, dendrochronology has continuously evolved from a supplementary tool for the dating of wood to a widely recognized science and a real backbone for Holocene chronology reconstructions over the last few decades (Solomina, 2002).

This paper therefore aims at providing an overview (i) on how trees are affected by earth-surface processes, (ii) on how they are used in the analysis of geomorphic processes and (iii) on what they can tell about the occurrence and evolution of geomorphic processes in space and time.

2. The influence of geomorphic events on tree growth

2.1 Normal tree growth

Dendrochronology is based on the fact that trees growing in the temperate regions form distinct annual growth rings. In conifers (*gymnosperms*), tree-ring formation can be divided into two distinct periods (Camarero et al. 1998, Rigling et al. 2002): During the early stages of the growing season, reproductive cambium cells form large and thin-walled earlywood tracheids, which primarily serve the transport of nutrients and water. Later in the season, smaller and denser latewood tracheids are developed. These layers are darker in appearance due to thicker cell walls and serve to increase the stability of the tree. The amount and complexity of tissue formation in broadleaved trees (also called *angiosperms* or flowering plants) exceeds that of gymnosperms. In addition to the tracheids found in gymnosperms, the dividing cambium of broadleaved trees also produces vessels. Figure 1 illustrates how tree rings look in conifers (a, b) and in broadleaved trees (c, d).

The size of each tree ring is influenced by biotic and abiotic factors. Biotic factors include the genetic makeup as well as the aging of trees and are individual for each species and each tree. Abiotic factors includes light, temperature, water, nutrient supply or influence of strong wind and are more or less common for all trees growing at a specific site (Fritts,1976). Therefore, trees growing at the same site will record the same environmental impacts and fluctuations (e.g., temperature or precipitation) in their tree-ring series (Cook & Kairiukstis, 1990, Stokes & Smiley, 1968).

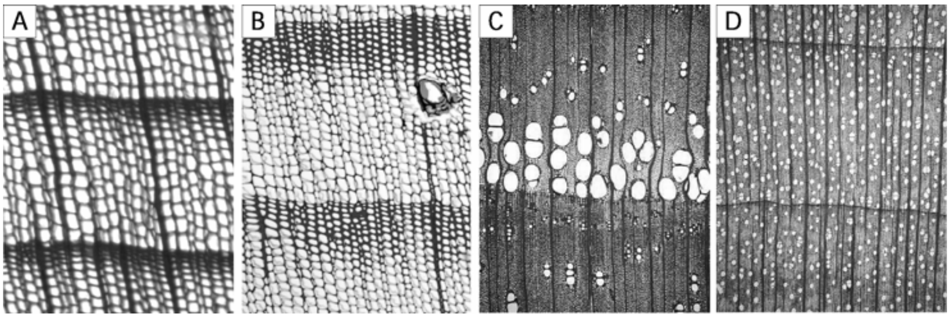

Figure 1. Micro-sections of tree rings prepared from conifer and broadleaved trees: In (a) Picea abies (L.) Karst. and (b) Pinus cembra L., bands of tracheids form the individual increment rings. In broadleaved trees, tracheids and vessels are formed by the dividing cambium. Depending on the distribution of vessels in the ring, we distinguish between (c) ring-porous (Fraxinus excelsior L.; photo: Schoch et al. 2004) and (d) diffuse-porous angiosperms (Acer pseudoplatanus L.; photo: Schoch et al. 2004).

Apart from site-specific information common to all trees at a location, individual trees also record the effects of mechanical disturbance caused by earth-surface processes (Bollschweiler & Stoffel 2010a; Stoffel & Wilford in press). Trees can be injured, their stems inclined, their stem base buried, their crown and branches broken or their roots denudated. These actions will be recorded in the tree-ring series of the affected tree. The analysis of geomorphic processes through the study of such growth anomalies in tree rings is called dendrogeomorphology (Alestalo 1971; Stoffel et al. 2010a). Dendrogeomorphic research is normally based on the "process–event–response" (Fig. 2) concept as defined by Shroder (1978). The "process" is represented by any kind of geomorphic agents, such as a debris flow, rockfall or snow avalanche. In the case of an "event", the geomorphic process will affect a tree, which will react upon the disturbance with a certain growth "response". In the following paragraphs, the different impacts ("events") that geomorphic processes may have on trees are illustrated and the specific "responses" of trees listed.

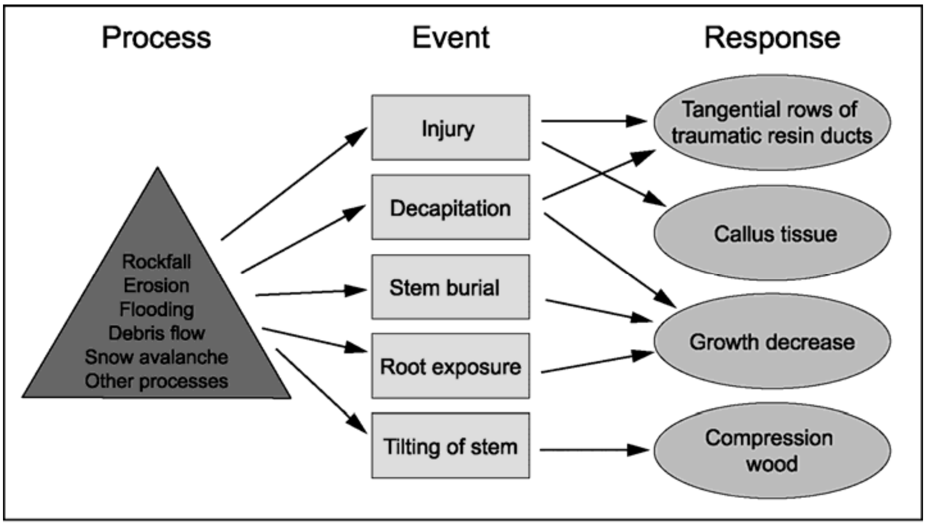

Figure 2. The process-event-response concept as defined by Shroder (1978).

2.2. Wounding of trees (scars) and resin- duct formation

Scratches on the outer bark and injuries are a very common feature in trees affected by geomorphic processes (Fig. 3a). Provided that the impacting energy

was important enough to locally destroy the cambium, increment formation will be disrupted in the injured segment of the tree. In order to minimize the risk of rot and insect attacks after impacts, the injured tree will almost immediately start with the production of chaotic callus tissue layers from the edges of the injury (Fig. 3c) in order to continuously overgrow the injury (Fig. 3b; Larson, 1994; Sachs, 1991). Wound healing greatly depends on the annual increment rate, tree age, and the size of the scar.

Following injury, tangential rows of traumatic resin ducts are produced in the developing secondary xylem of certain conifer species like European larch (*Larix decidua*), Norway spruce (*Picea abies*) or Silver fir (*Abies alba*), (Fig. 3d; Bannan, 1936; Bollschweiler et al., 2008 b; Nagy et al., 2000; Schneuwly et al., 2009 a, b; Stoffel, 2008). They extend both tangentially and axially from the injury. Given that wounding occurred during the growing season of the tree, resin production will start only a few days after the event and axial ducts will emerge less than three weeks after disturbance (Luchi et al. 2005; McKay et al., 2003; Ruel et al., 1998). When analyzing cross-sections, the intra-seasonal position of the first series of tangential rows of traumatic resin ducts can, therefore, be used for the reconstruction of events with up to monthly precision (Stoffel & Beniston 2006; Stoffel & Hitz, 2008; Stoffel et al.,2005 a, 2008), if the incidence occurred during the growing season.

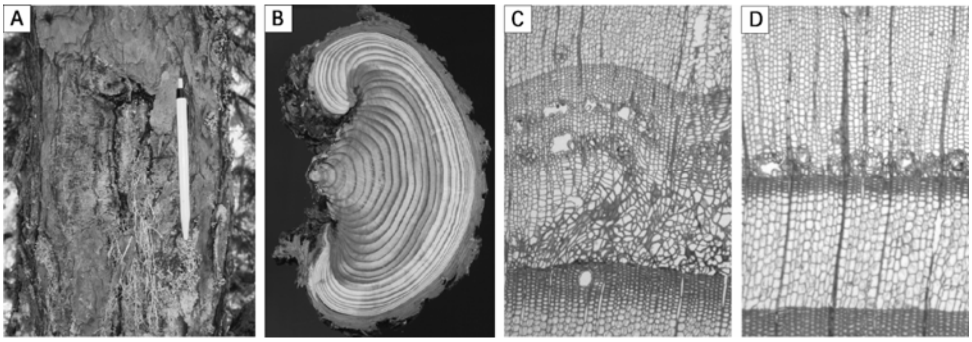

Figure 3. Injuries in European larch (Larix decidua Mill.): (a) Injured stem. (b) Cross-section with overgrowth starting from the lateral edges of the injury. (c) Callus tissue as observed in the overgrowing cell layers bordering the injury. (d) Next to the callus tissue, tangential rows of traumatic resin ducts are formed (source: Bollschweiler 2007).

2.3. Tilting of stems

The sudden pressure induced by the activity and deposition of material by mass-movement processes (e.g., avalanche snow, debris-flow material) or the slow ut ongoing destabilization of a tree through landslide activity or erosion can lead to the inclination of the stem (Lundström et al. 2007a, b). Tilted trees are a common sight in areas affected by geomorphic processes (Fig. 4a) and have therefore been used in many dendrogeomorphological studies to date previous events (Braam et al., 1987a, b; Casteller et al., 2007; Clague & Souther 1982; Fantucci & Sorriso-Valvo, 1999).

A tilted tree will try to regain its vertical position (Mattheck, 1993). In conifers, compression wood will be produced on the tilted side of the trunk. Individual rings will be considerably larger here and slightly darker in appearance as compared to the upslope side (Fig. 4b). The difference in color is due to the much thicker and rounded cell walls of early- and latewood tracheids (Timell 1986). In the tree-ring series, eccentric growth will be visible and thus allow accurate dating of the incidence (Fig. 4c). In contrast, broadleaves react upon stem tilting with the formation of tension wood (Westing 1965) and ring eccentricity will occur on the upslope side.

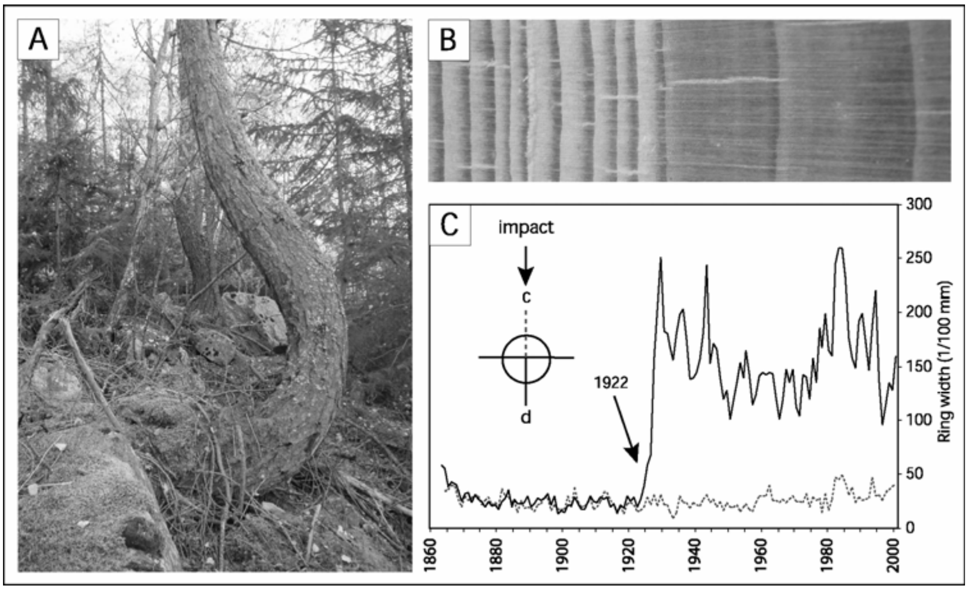

Figure 4. (a) Tilted stem. (b) Cross-sections of a tilted Larix decidua Mill. tree (Photo courtesy by Dominique M. Schneuwly, used with permission). (c) Increment curves of a tree tilted by a debris-flow event in 1922 (modified from Stoffel et al. 2005c).

2.4 .Stem burial

Debris flows, floods, lahars or landslides occasionally bury trees by depositing material around their stem base (Fig. 5a). Growth in these trees will normally be reduced as the supply with water and nutrients will be temporarily disrupted or limited (Fig. 5b; Friedman et al., 2005; Hupp et al., 1987; LaMarche, 1966). Exceptionally, the burial of a stem can also cause a growth increase, provided that the material left by the mass-movement process is rich in nutrients, the water supply guaranteed and the depth of the deposited material is not important (Strunk ,1995).

As soon as stem burial trespasses a certain threshold, trees die from a shortage in water and nutrient supply (Fig. 5b). According to case-study results from the Italian Dolomites (Strunk, 1991), *P. abies* might tolerate a maximum burial depth of 1.6 to 1.9 m in environments dominated by fine-grained debris flows composed of calcareous and dolomitic material (Strunk, 1997). Occasionally, buried trees produce adventitious roots close to the new ground surface (Fig. 5c; Bannan, 1941). As adventitious roots will be normally formed in the first five years after burial (Strunk, 1995), the moment of root sprouting can be used for an approximate dating of the sedimentation process, as shown by Marin & Filion (1992) or Strunk (1989, 1991). In case a tree has been repeatedly buried and several layers of adventitious roots formed, it is possible to estimate sedimentation depths of individual events at the location of the tree.

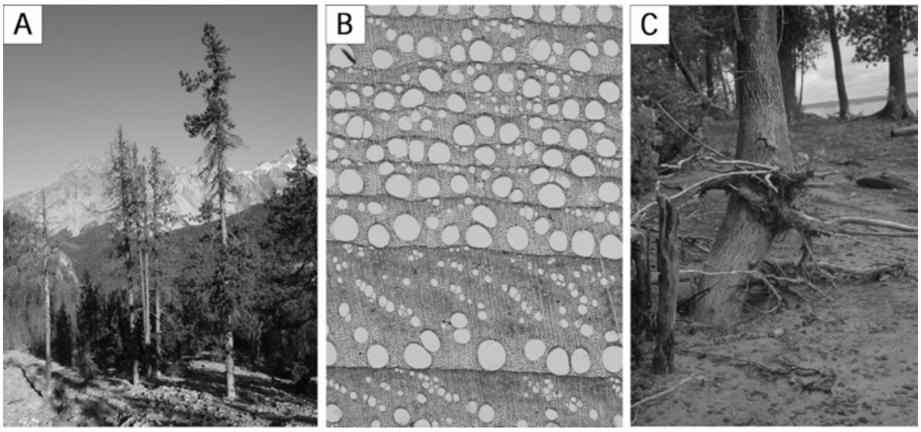

Figure 5. (a) Sedimentation and subsequent die-off of trees after sedimentation. (b) Micro-section showing an abrupt decrease in ring width in Castanea sativa Mill. following an event. (c) Several levels of adventitious roots (photo courtesy of (b) and (c) by F. H. Schweingruber, used with permission).

2. 5. Decapitation of trees and elimination of branches

Bouncing rocks and boulders, flowing water with solid charge (e.g., sediments, rocks, trees), debris flows and lahars or the windblast effect of snow avalanches may cause tree decapitation (Fig. 6a) or the break-off of branches. These effects are more common in larger trees, where stems have lost their suppleness. Trees react upon decapitation with distinct growth suppression in the years following the impact. In order to recover, one or several lateral branches will try to take the lead and thus replace the broken crown, resulting in a tree morphology that is called “candelabra” growth (Fig. 6b; Butler & Malanson, 1985). In addition, it is not unusual that the shock of the impact causes injuries and provokes the formation of tangential rows of traumatic resin ducts as well.

2.6. Root exposure

Erosive processes and the (partial) denudation of roots may generate different growth reactions, both in the stem and in the exposed roots (Osterkamp et al. in press). In addition, the type and intensity of the reaction(s) will depend on the nature of the erosive event, which can occur in the form of a continuous or a sudden process.

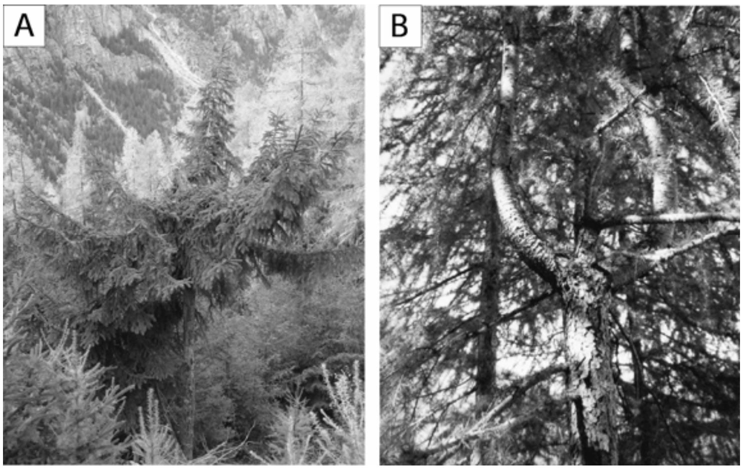

Figure 6. (a) (a) Picea abies (L.) Karst. decapitated by rockfall. (b) Candelabra growth in Larix decidua Mill. following apex loss (modified after Stoffel & Bollschweiler 2008).

Provided that several roots are completely denudated during a sudden erosive event (e.g., debris flow, lahar, flood, landslide), they will no longer be able to fulfill their primary functions and die off. As a consequence, the tree will suffer from a shortage in water and nutrient supply, resulting in the formation of narrow rings in the stem (Fig. 7a-c; Carrara & Carroll 1979, LaMarche, 1968, McAuliffe et al*.,* 2006).

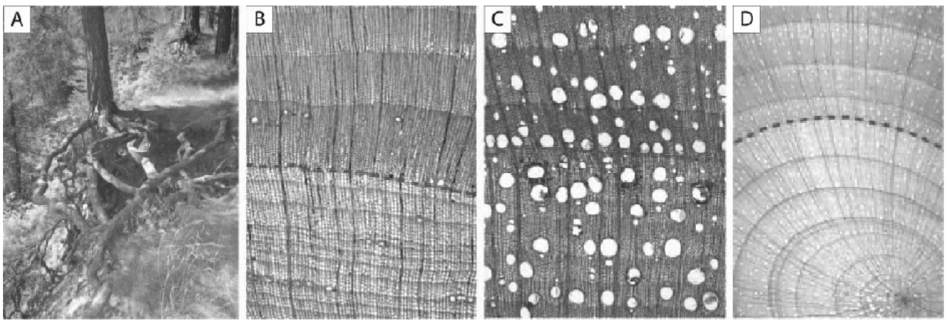

Figure 7. (a) Exposed roots, (b) wood anatomical changes in a Scots pine root (Pinus sylvestris L.) after sudden exposure. (c) wood anatomical changes in a root of Fraxinus excelsior L. affected by continuous exposure, (d) In addition to cell changes, tension wood is formed in this root of Acer pseudoplatanus L. (all photographs courtesy of O. M. Hitz, used with permission).

Corona et al. (2011 a, b) used anatomical changes in exposed roots of *Pinus sylvestris* to quantify continuous denudation rates. A total of 123 cross sections (75 from buried and 48 from exposed roots of 23 trees) were sampled in the Moulin basin. The size and position of roots at the time of exposure was determined via anatomical variations in the annual growth rings of roots. In cross sections of buried roots, a sharp reduction of earlywood tracheid lumen area – a growth signature which has traditionally been used to determine the moment of root denudation (Bodoque et al., 2006, Hitz et al., 2008) – was observed as soon as erosion reduced soil cover to ≤ 3 cm. As a consequence, estimates of eroded soil thickness had to be adjusted to take account of this bias. Bias-adjusted, averaged, medium-term erosion rates derived from exposed roots vary between 6 and 7 mm y^{-1} at Moulin basin depending on the importance accorded to the uplift of roots after exposure. Values are significantly correlated to slope angle and match with erosion rates derived from monitored iron stakes (5.7 mm y^{-1}) or measurements of sediment yield in retention dams (4.7 mm y^{-1}) at the outlet of the Moulin basin. Besides demonstrating that the interpretation of anatomical signatures in tree roots to erosion have to be revised, this paper has also shown that dendrogeomorphic analyses of roots are indeed a powerful tool for the quantification of minimal rates of soil erosion in environments where measurements of past activity are not available (Lopez Saez et al. in press).

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