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What Tree Rings Can Tell About Earth-Surface Processes: Teaching the Principles of Dendrogeomorphology

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Abstract

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 article, 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?).

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 and Brunsden 1977). The temporal activity of earth-surface processes may depend on external disturbance and occur when activated by, for example, climatic change or tectonism. In this case, geomorphic activity will be important during an initial phase and events will become less frequent with time. In open systems, in contrast, triggers are very regularly activating earth-surface processes, resulting in a rather continuous activity (Brunsden and Thornes 1979).

Earth-surface processes also have a spatial component (Schumm and 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 and 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) 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; Stoffel et al. 2009).

This article 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

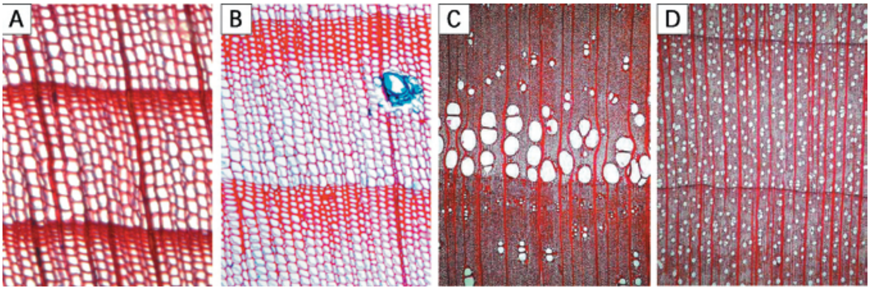

Fig. 1. Micro-sections of tree rings prepared from conifer and broadleaved trees: In (A) *Picea abies* (L.) Karst. and (B) *Pinus cembra* L., bands of tracheids form the individual increment rings. In broadleaved trees, tracheids and vessels are formed by the dividing cambium. Depending on the distribution 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).

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; Schweingruber 1996). 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 and Kairiukstis 1990; Stokes and Smiley 1968).

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. 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). Dendrogeomorphological geomorphic 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:

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.

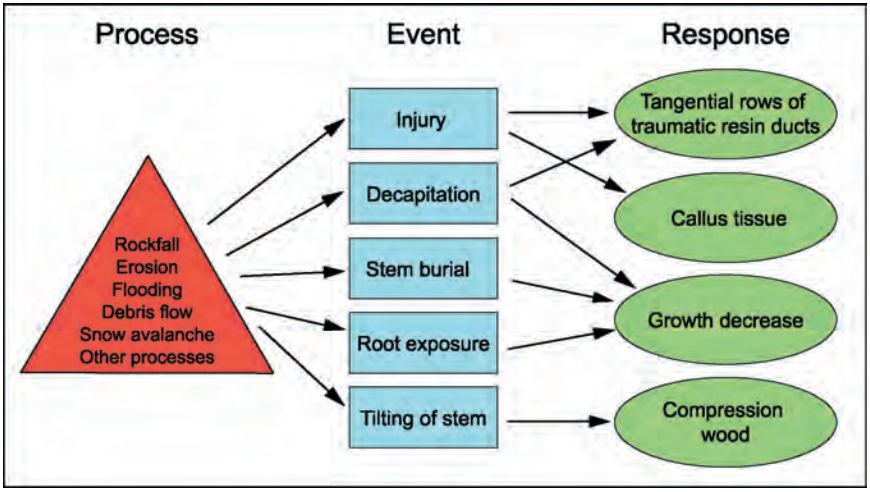

Fig. 2. The process-event-response concept as defined by Shroder (1978).

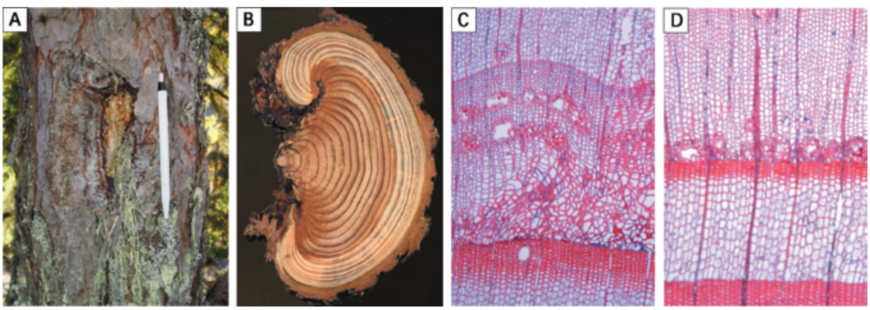

Fig. 3. Injuries in European larch (*Larix decidua* Mill.): (A) Injured stem. (B) Cross-section with overgrowth starting from the lateral edges of the injury. (C) Callus tissue as observed in the overgrowing cell layers bordering the injury. (D) Next to the callus tissue, tangential rows of traumatic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

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; Schweingruber 2001) so as 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. 2008b; Nagy et al. 2000; 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

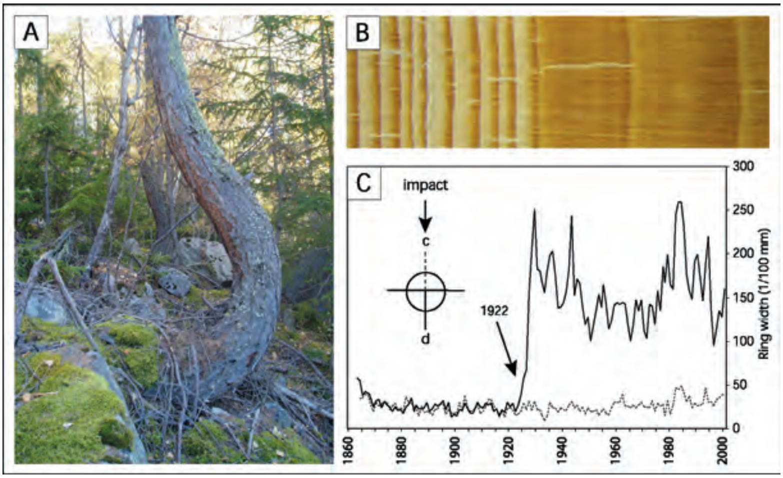

Fig. 4. (A) Tilted stem. (B) Cross-sections of a tilted *Larix decidua* Mill. tree (Photo courtesy by Dominique M. Schneuwly, used with permission). (C) Increment curves of a tree tilted by a debris-flow event in 1922 (modified from Stoffel et al. 2005c).

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 a monthly precision (Stoffel and Beniston 2006; Stoffel and Hitz 2008; Stoffel et al. 2005a, 2008), if the incidence occurred during the growing season.

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 but 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 and Souther 1982; Fantucci and 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

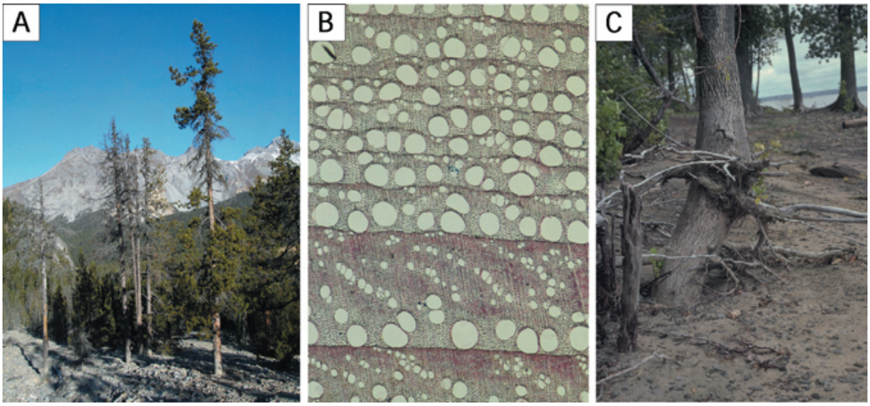

Fig. 5. (A) Sedimentation and subsequent die-off of trees after sedimentation. (B) Micro-section showing an abrupt decrease in ring width in Castanea sativa Mill. following an event. (C) Several levels of adventitious roots (photo courtesy of (B) and (C) by F. H. Schweingruber, used with permission).

tension wood (Schweingruber 1983; Westing 1965) and ring eccentricity will occur on the upslope side.

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 and 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.

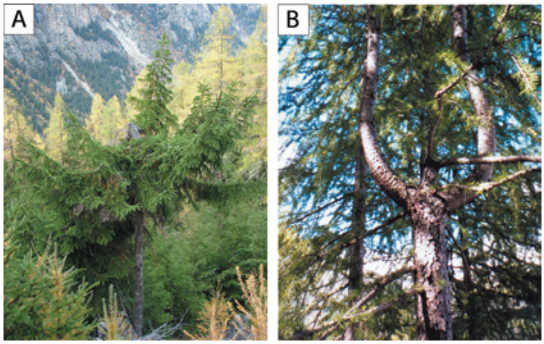

Fig. 6. (A) *Picea abies* (L.) Karst. decapitated by rockfall. (B) Candelabra growth in *Larix decidua* Mill. following apex loss (modified after Stoffel and Bollschweiler 2008).

2.5 DECAPITATION OF TREES AND ELIMINATION OF BRANCHES

Bouncing rocks and boulders, flowing water with solid charge (e.g., sediments, rocks, and 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 and 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. 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.

Provided that several roots are completely denudated during a sudden erosive event (e.g., debris flow, lahar, flood, and 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. 7c; Carrara and Carroll 1979, LaMarche 1968, McAuliffe et al. 2006).

In cases of partial root exposure (Fig. 7a) with the root end still in the ground, the root will continue to grow and fulfill its functions. In the exposed part, however, wood-anatomical changes will occur and growth

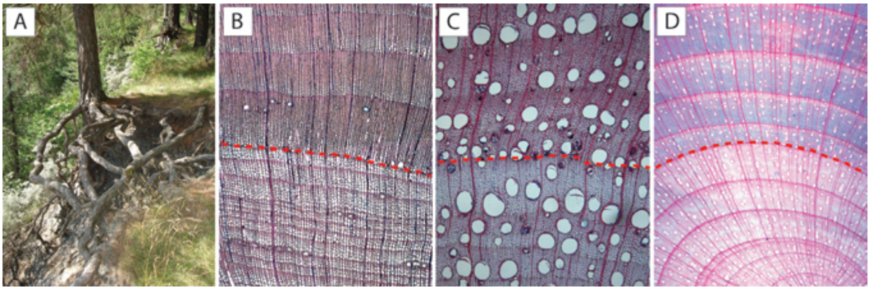

Fig. 7. (A) Exposed roots. (B) Wood anatomical changes in a Scots pine root (*Pinus sylvestris* L.) after sudden exposure. (C) Wood anatomical changes in a root of *Fraxinus excelsior* L. affected by continuous exposure. (D) In addition to cell changes, tension wood is formed in this root of *Acer pseudoplatanus*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

rings similar to those in the stem or branches will the formed. The localization of this change in the tree-ring series will allow determination of the moment of exposure (Fig. 7b–c; Bodoque et al. 2006; Hitz et al. 2008). The continuous exposure of roots is usually related with slow processes and low denudation rates. Provided that the roots are gradually exposed with time, it is also possible to determine erosion rates.

3. Tree-Ring Analysis of Earth-Surface Processes – Selected Applications

As shown in the previous section, trees react to the impact of geomorphic processes with different 'anomalous' growth responses. Through the analysis of these reactions, the moment of the event can be determined and the recurrence of incidences accurately assessed (how often?). The position of the growth anomaly within the tree ring allows for an assessment of the moment of events with yearly and sometimes even with monthly precision (when?). Based on a mapping of geomorphic forms and trees, the reach and lateral spread of events can be determined (how far?), movement rates identified (how fast?) or the magnitude assessed (how big?). In combination with meteorological, hydrological and/or seismological data, results from tree-ring studies can be consulted to identify triggering factors of previous events (why?). In the following, we provide examples on how tree-ring analyses can be used for the reconstruction and the understanding of geomorphic processes and their dynamics.

3.1 HOW FREQUENTLY DID EVENTS OCCUR IN THE PAST?

Destructive geomorphic events of the recent past have normally been analyzed in detail and are extensively documented in many regions of the world. In contrast, archival data on smaller, more isolated or older events is scarce or even completely inexistent. However, the knowledge on

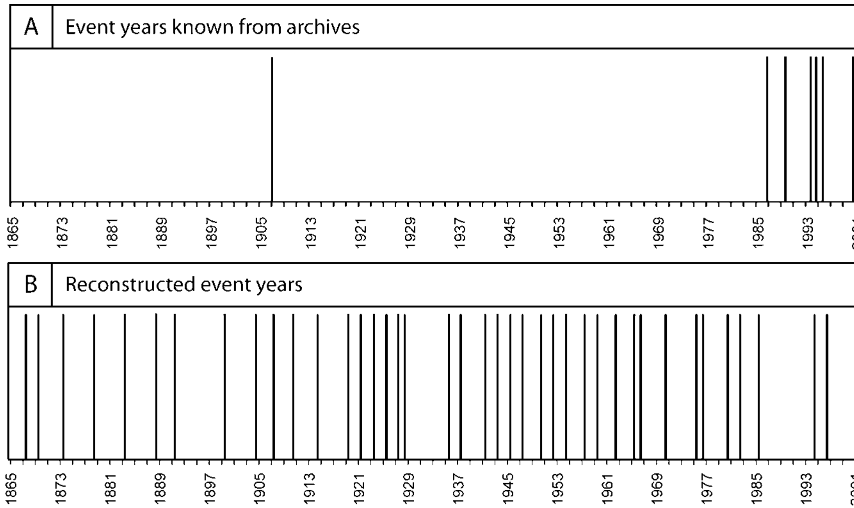

Fig. 8. Reconstructed frequency of debris flows in the Bruchji torrent. (A) Archival data reported seven events for the twentieth century, with six events concentrated to the last 20 years (Jossen 2000). (B) Tree-ring records of disturbed trees revealed, in contrast, data on 40 events between AD 1867 and 2005 (adapted from Bollschweiler et al. 2007).

previous events is crucial for the understanding of past landscape evolution, current changes in process dynamics and the possible evolution of earth-surface processes in a future greenhouse climate. Here, the investigation of tree rings can considerably contribute to the reconstruction of past incidences and to the improvement of archival data.

Tree-ring data has extensively been used for the reconstruction of debris-flow frequencies (Baumann and Kaiser 1999; Bollschweiler and Stoffel 2007; Bollschweiler et al. 2008a; Stoffel et al. 2008; Strunk 1991). On a debris-flow cone in the Swiss Alps, activity was noted in local archives for the period 1905–1907 as well as for four events after 1987. Between 1907 and 1987, events did not apparently affect the cone. Dendrogeomorphological investigations of 401 *L. decidua* and *P. abies* trees allowed for the reconstruction of 40 events between 1867 and 2005 (Bollschweiler et al. 2007; Fig. 8). Data also show that the apparent absence of events during most of the last century was a result of incomplete archival records rather than of an absence of incidences.

Detailed information on past events is especially crucial when geomorphic processes interact with human activity. As soon as transportation corridors cross debris-flow paths, a profound understanding of the process at the location is needed to respond to resulting hazards. Wilkerson and Schmid (2003) studied the occurrence of debris flows in Glacier National Park (Montana, USA), where roads and hiking trails cross debris-flow channels and where events resulted in several near fatalities. Here, tree-ring analyses clearly helped to understand process dynamics and to mitigate hazards.

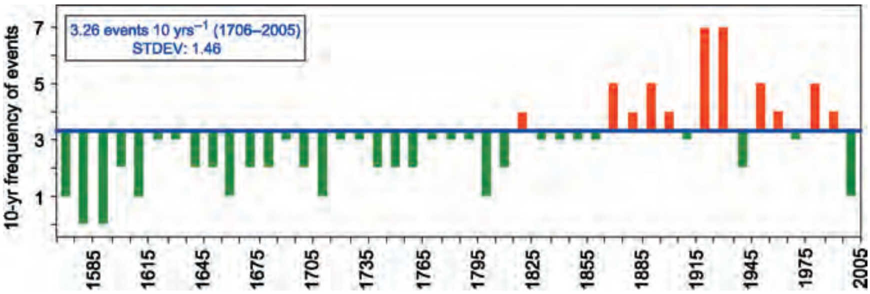

Fig. 9. Reconstructed 10-year frequencies of debris-flow events between 1566 and 2005 for the Ritigraben torrent (Switzerland). Data are presented as variations from the mean decadal frequency of debris flows of the last 300 years (1706–2005), corresponding to the mean age of trees sampled (modified from Stoffel and Beniston, 2006).

The life expectancy of certain conifer species may be centuries long and that lifespan allows reconstruction of past events over several centuries. Stoffel et al. (2008) extended the debris-flow record of a torrent in the southern Swiss Alps back to the sixteenth century. This broad record with 123 reconstructed incidences allowed determination of long-term trends and evolutions in the frequency of past events (Fig. 9). During the Little Ice Age (LIA, 1570–1900; Grove 2004) the number of events per decade remained well below average. In contrast, the decades after the end of the LIA and the period 1916 to 1933 show increased activity due to warm and wet summer conditions favorable for the event activity (Stoffel and Beniston 2006). This example illustrates that a solid database on past events and a profound knowledge of local process dynamics are essential prerequisites for a realistic prediction of debris-flow activity in a future greenhouse climate.

The recurrence of past events can be assessed for other earth-surface processes as well, like flooding (Friedman et al. 2005; Jones et al. 1984; Shapley et al. 2005; St. George and Nielsen 2000), snow avalanches (Boucher et al. 2003; Butler 1979; Butler and Malanson 1985; Butler and Sawyer 2008; Muntan et al. 2004), volcanic (Yamaguchi 1983, 1985) or rockfall activity (Fig. 10, Perret et al. 2006; Schneuwly and Stoffel 2008a,b; Stoffel et al. 2005a,b).

It is important to stress that tree-ring based reconstructions of past incidences provide minimum frequencies. Small-scale events occurring within channels or on slopes do not always affect trees and large-scale events may eliminate entire stands. In both cases, an exhaustive reconstruction of past incidences will not be possible.

3.2 At what time of the year did events occur?

In temperate regions with distinct seasons, tree-ring analysis allows dating with yearly precision. Provided that data exist on the onset and timing of

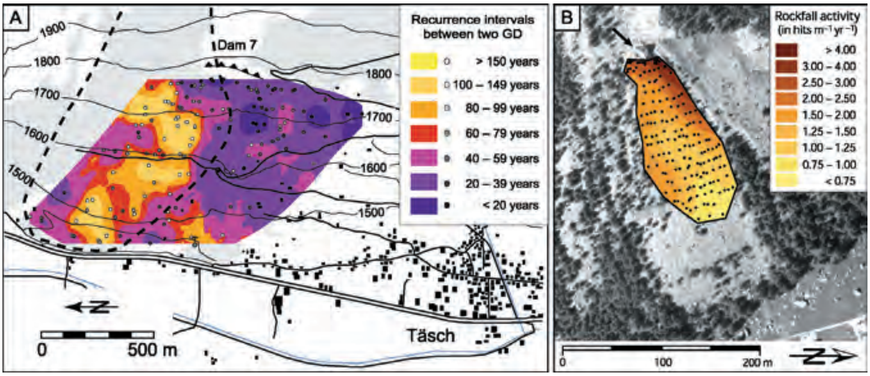

Fig. 10. Rockfall activity as reconstructed from tree-ring analyses at (A) Täschgufer and (B) Schilt (both Valais Alps, Switzerland). Recurrence intervals designate the number of years passing between two reconstructed growth disturbances in a single tree (adapted from Stoffel et al. 2005b and Schneuwly and Stoffel 2008b).

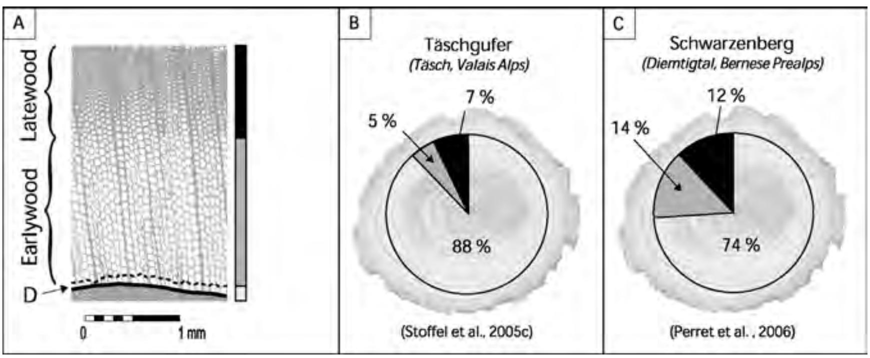

Fig. 11. (A) During the period of cell growth, conifer trees first form thin-walled earlywood cells (E) before they start to produce thick-walled latewood (L) cells. At the end of the growing season, cell formation ceases and dormancy (D) sets in. The seasonal timing of rockfall activity was assessed on two different slopes in Switzerland, namely, on the (B) Täschgufer (Swiss Alps) and the (C) Diemtigtal (Swiss Prealps) slopes. While permafrost exists locally at Täschgufer, seasonal frost occurs during the winter months at Diemtigtal (Stoffel 2006).

the local growing season of trees, the position of the growth anomaly within a tree ring can be used to refine the dating of the event. As injuries, bordering callus tissue and tangential rows of resin ducts are being produced almost immediately after an event, they allow a more accurate dating, sometimes to the degree of a monthly precision (Stoffel 2008).

In rockfall research, the intra-seasonal dating can be used to identify periods with higher activity during the year. In the Swiss Alps, the dormant season lasting from approximately October to May has proved to be the period with the largest rockfall activity (Fig. 11; Perret et al. 2006; Schneuwly and Stoffel 2008a,b; Stoffel et al. 2005b). This culmination in activity during winter and spring is due to repeated and surficial freeze-thaw

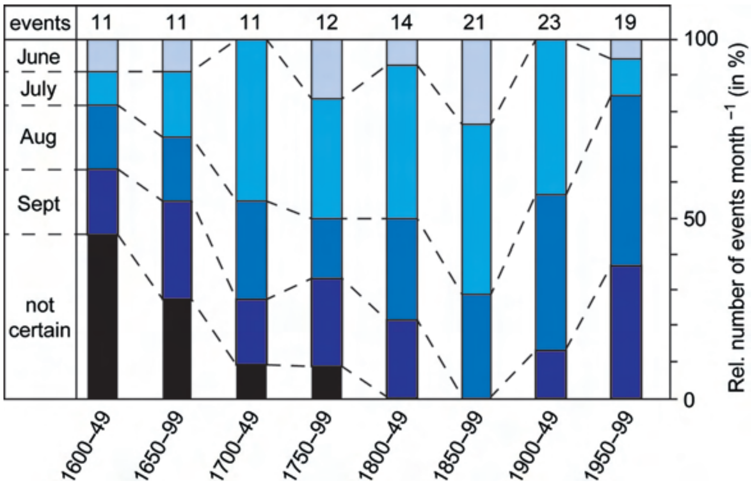

Fig. 12. Seasonality (JJAS) of past debris-flow activity as inferred from the intra-annual position of tangential rows of traumatic resin ducts in the tree ring, archival data on flooding as well as meteorological data since AD 1864 (adapted from Stoffel et al. 2008).

cycles in the rockwalls and the seasonal thawing of locally existing permafrost in April and May (Stoffel 2006).

Similarly, the intra-seasonal position of tangential rows of resin ducts in comparison with local rainfall records and data on flooding in neighboring catchments allow the reconstruction of past debris-flow events in the southern Swiss Alps. Results are illustrated in Figure 12 and clearly indicate that the main season for the release of events shifted from June and July during the second half of the nineteenth century to August and September over the last 50 years (Stoffel and Beniston 2006).

Jacoby et al. (1997) used tree rings to refine the dating of an earthquake in northwestern USA. The Cascadia earthquake was known to have occurred at the end of the seventeenth or the beginning of the eighteenth century along the Cascadia subduction zone west of Oregon and Washington as well as in northern California. However, neither radiocarbon nor other dating approaches could yield a precise year or month of the earthquake. Through the investigation of tree-ring widths and anatomical changes in the increment rings, Jacoby et al. (1997) were able to date the event to the very restricted time slot between late 1699 and early 1700. The analysis also provided evidence that this earthquake event in North America was the cause of a tsunami recorded on 27 January 1700 in Japan (Satake et al. 1996).

3.3 How far did past events reach?

When records on the temporal occurrence of earth-surface processes are coupled with spatial data, the reach of such processes can be determined.

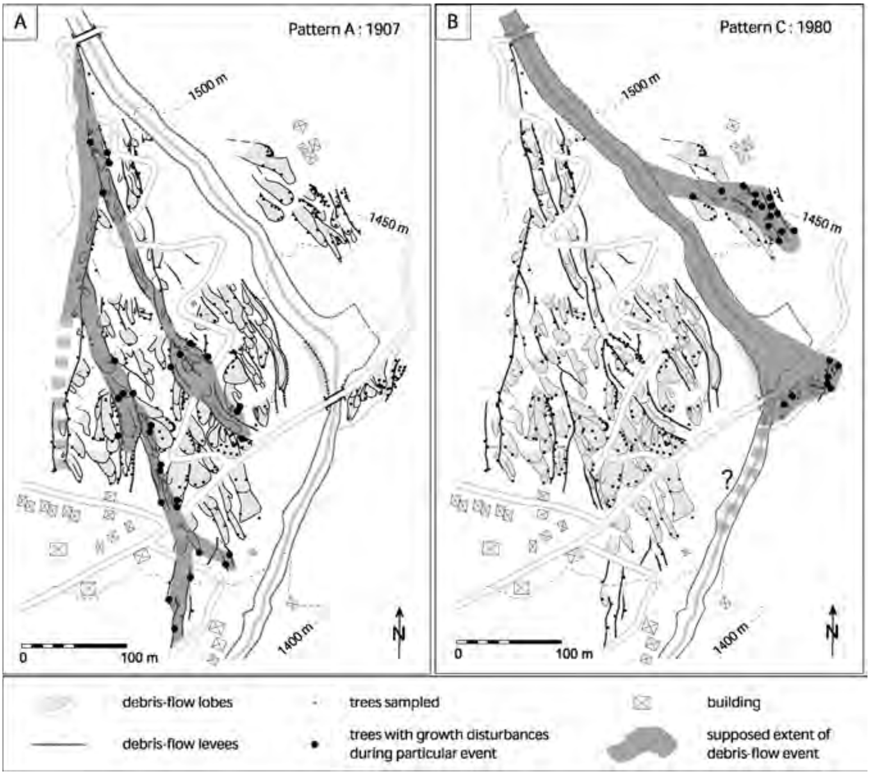

Fig. 13. Spatial patterns of past debris-flow events at Bruchji torrent. (A) Example for event affecting the western and central part of the cone as in 1907. (B) The event of 1980 influenced only the eastern part of the cone (adapted after Bollschweiler et al. 2007).

In particular, the application of detailed geomorphic mapping and the accurate positioning of trees considerably increase the information on the reach and spread of mass movements.

For example, the spatial patterns of past debris-flow activity were reconstructed on the cone of a debris-flow torrent in the Swiss Alps, using a detailed geomorphic map (1 : 1000) of the debris-flow deposits and tree-ring analyses (Bollschweiler et al. 2007). The position of trees showing growth responses following an event was used to identify spatial patterns of past incidences. Examples for two different types of incidences are provided in Figure 13: Type A events affected the western and central part of the cone whereas type B events were restricted to the eastern part of the cone. From the data, a clear shift of the main channel was observed. While the main channel passed on the western part of the cone until the 1930s, it started moving its bed to its current position on the eastern part of the cone.

Likewise, spatial information obtained from tree-ring records are also crucial for the reconstruction and understanding of snow avalanche

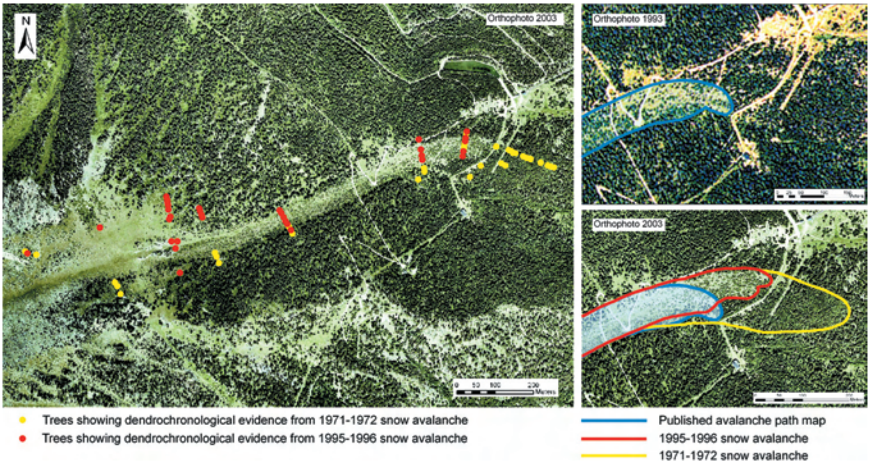

Fig. 14. Avalanche map improvement. In an avalanche track in the Southeastern Pyrenees, the dendrogeomorphological analysis revealed the occurrence of an event in 1971–1972. Notice that the published avalanche map did not have detailed knowledge about the actual extent of exceptional events such as those in 1995–1996 or 1971–1972 (1993 and 2003 ortophotoimages, ICC; modified from Muntán et al. 2008).

activity (Boucher et al. 2003; Butler 1979, 1987; Butler and Sawyer 2008; Hebertson and Jenkins 2003). In the Spanish Pyrenees, Muntán et al. (2008) depicted the importance of tree-ring reconstructions for the determination of the spatial reach of snow avalanches. Several events were noted in the archives for the investigated avalanche path and an avalanche map was published indicating the runout zone of avalanches. Dendrogeomorphological analyses revealed, however, that a snow avalanche in winter 1971–1972 (Fig. 14) has surpassed the maximum run-out distance indicated in this map by more than 200 m (Muntán et al. 2008).

Similarly, tree rings are widely used in glacier research (dendroglaciology), where they assist the reconstruction of glacier advances and retreats through the determination of death dates of trees killed by advancing glaciers, the moment of inclination of tree stems close to a glacier or the age of successor trees colonizing the surfaces cleared by retreating glaciers (Luckman 1995, 1998, 2000; Smith and Lewis 2007). Extensive dendroglaciological investigations, coupled with radiocarbon dating as well as lichenometry (Innes 1985), have mainly been performed in North America. The spatial and temporal complexity of LIA glacier activity has been reconstructed for several regions including the Canadian Rocky Mountains (Luckman 2000), coastal Alaska (Calkin et al. 2001; Reyes et al. 2006) and more recently for the Coast Mountains of British Columbia (Allen and Smith 2007; Larocque and Smith 2003; Lewis and Smith 2004; Smith and Desloges 2000).

3.4 HOW FAST DID THE LANDSCAPE CHANGE?

Tree-ring dating cannot only provide information on the time of occurrence or on the spatial spread of a geomorphic event, but it can also be used to determine movement rates of different earth-surface processes. The cell-structural change in the roots of trees and growth reactions in stem rings can be used for the reconstruction of sudden or continuous erosion rates in torrents, gullies or on slopes (LaMarche 1961). For instance, Bégin et al. (1991) have studied the recent shoreline forest degradation caused by erosion occurring during high-water events along the upper St. Lawrence estuary (Canada). Similarly, Fantucci (2007) assessed horizontal shore-erosion rates at different locations around Lake Bolsena in central Italy. McAuliffe et al. (2006) coupled hillslope erosion in the Colorado Plateau with climate variations during the past 400 years. Marin and Filion (1992) have used radial growth patterns in white spruce (*Picea glauca*) to calculate rates of accumulation, erosion and migration of cold-climate sand dunes along the eastern coast of Hudson Bay (Québec, Canada).

Slow movements in periglacial environments can be studied with tree rings as soon as forest cover exists. The movement rates of gelifluction lobes have been studied by Jonasson (1988) and Jakob (1995). Similarly, dendrogeomorphology has been used to study the rise and evolution of thermokarst bodies in Western Siberia (Agafonov et al. 2004).

In addition, rock glaciers were documented in several case studies. In his pioneering investigation of a glacier-like boulder deposit on Table Cliffs Plateau (Utah), Shroder (1978) documented 200 years of movements and suggests that precipitation would possibly be the trigger for the main episodes of movements. Other studies on movements in permafrost complexes have been performed in North America ever since (Bachrach et al. 2004; Cannone and Gerdol 2003; Carter et al. 1999; Giardino et al. 1984), but are inexistent in other alpine regions.

3.5 HOW BIG WAS THE EVENT?

Based on the height or dimension of visible growth defects on the stem surface, the spatial distribution of trees showing simultaneous signs of disturbance in their tree-ring record or the dating of individual deposits, it is sometimes also possible to assess magnitudes of past events.

Following the approach of Sigafoos (1964), flood-scar heights on trees have been used to provide minimum estimates of peak flood stages in rivers and streams. In subarctic Québec (Canada), Bégin (2001) has used ice-push scars on trees and tilted stems to reconstruct major ice floods and wave-erosion events resulting from extreme lake levels.

In the Swiss Alps, reconstruction of rockfall activity at two different locations allowed identification of more than 1500 small magnitude–high frequency events consisting of one or a few rocks and boulders since AD

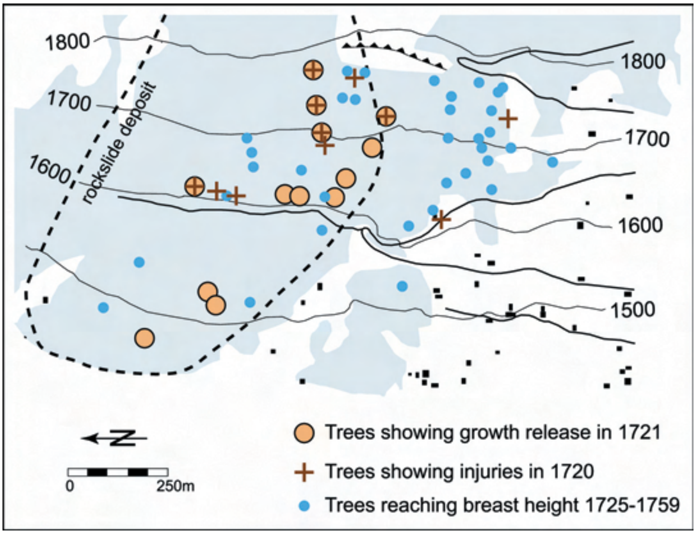

Fig. 15. Damage resulting from the 1720 rockfall. Thirteen trees have been injured (red crosses) and 11 trees show an abrupt growth release starting in 1721 (yellow circles). The (re-)colonization of the rockfall slope (blue dots) in the succeeding decades (1725–1759) most probably represents a reaction to the 1720 rockfall event (adapted from Stoffel et al. 2005b).

1394 (Schneuwly and Stoffel 2008a,b; Stoffel et al. 2005b). At the same time, only one high magnitude–small frequency event (i.e. rockslide) was reconstructed per site, namely, in 1720 (Fig. 15) and in winter 1960/61. While a quantification of material transported during incidences is not feasible with tree-ring analysis, it is possible to determine event magnitudes and to distinguish rockslide from rockfall events.

While there is a plethora of data available on sites being affected by landslides and on periods of landslide activity (Bégin and Filion 1988; Corominas and Moya 1999; Fantucci and Sorriso-Valvo 1999), there is, in contrast, very limited knowledge available on volumes involved.

The amount, type, size, condition, and distribution of vegetation on snow avalanche paths can reveal an abundance of information about past avalanche events (Butler 1979). Based on the position of injured trees or the height of damage on the stem surface, it is possible to infer the extent, depth or size of past occurrences (McClung 2003). The assessment of high-magnitude avalanches is often based on index numbers (Butler and Malanson 1985; Shroder 1978), meaning that a certain percentage of all sampled trees must show signs following snow avalanche activity. Butler and Sawyer (2008) have set the threshold to 40%, arguing that only during years where their index number was exceeded, there was also some historical documentation available for avalanches in the Glacier National Park region.

Based on the nature of damage in trees, it is also possible to determine the type of and forces involved in snow avalanches, which in turn have

Fig. 16. Deposition of debris-flow material on the intermediate cone between 1902 and 1934. Only events that are associated with > 600 m^3 on the present-day surface of the cone are indicated on the map. Deposits shown in black are dated, but are older than the time segment illustrated (adapted from Stoffel et al. 2008).

different impact loads on buildings and the assessment of hazards: Mears (1975) has used data on tree-trunk failures to calculate velocities and impact pressures of dense-snow avalanches, whereas Stoffel et al. (2006) were distinguishing the extent of snow deposits from the area affected by windblast for dry- or powder-snow avalanches.

The size of debris flows has rarely been assessed, as signs of previous activity are often eroded or overridden by subsequent events and as it is very difficult to assess the size of individual debris-flow deposits on cones. In his pioneering work about debris flows at Mount Shasta (California), Hupp (1984) states that events of small magnitudes have shorter recurrence intervals than do large-magnitude discharges. Strunk (1988) has coupled tree-ring data with stratigraphic investigations (i.e. layer thicknesses) and presents a rough volume estimate for episodic debris-flow events in the Italian Dolomites. Based on the spread of individual surges, the amount of material left on the cone (Fig. 16), the seasonality of incidences, rainfall intensities and mean rock sizes, Stoffel (forthcoming) has inferred five classes of debris-flow magnitudes (XS to XL) for 62 events since AD 1858.

3.6 Why did it happen?

The occurrence of geomorphic events depends on the presence of triggers in the form of precipitation, snow melt, changes in mean and extreme temperatures or earthquakes. A coupling of tree-ring based event chronologies with meteorological or seismological records helps the understanding of contemporary process activity and dynamics and may be used for the prediction of potential future events occurring under greenhouse climate conditions.

In subarctic Québec (Canada), Bégin (2001) observes that heavy snowfalls in winter between the 1930s and 1980s have had a significant influence on spring ice-flood events. In the Swiss Alps, meteorological data indicate that the frequency of convectional rainfall in summer (thunderstorms) has decreased over the last decades and that important precipitation sums are more frequently due to cyclonic rainstorms in late summer and early autumn today. As a result, Stoffel and Beniston (2006) observe a clear shift of reconstructed debris-flow activity from summer (June, July, and August) to late summer and early autumn (August and September).

Fantucci and McCord (1995) state a correlation between increased landslide activity and particularly wet summer conditions on an unstable slope in Viterbo (Italy). At the same time, Fantucci and Sorriso-Valvo (1999) did not find comparable reactions in a landslide in Calabria (Italy). Here, extreme meteorological events could only explain one third of all landslide incidences, whereas 80% of historical earthquakes had an impact on landslide activity. The presence of earthquake-triggered landslides was also analyzed by Carrara and O'Neill (2003) in southwestern Montana, where they could link multiple periods of landslide re-activation following regional earthquake activity during the twentieth century. The influence of earthquakes on earth-surface processes has also been demonstrated on a rockfall slope in the Swiss Alps, where Schneuwly and Stoffel (2008a) observe a partial destruction of the forest stand and a large number of scars in surviving trees as a result of co-seismic rockfall activity.

4. Outlook

The surface of planet Earth is continuously subjected to external forces and drivers and landscapes are, as a result, continuously changing. A detailed comprehension of process dynamics, landscape history and of the reasons why the present-day earth surface looks the way it does are crucial for an accurate assessment and reliable predictions on how earth-surface processes might influence our environment in a future greenhouse climate (Collison et al. 2000; Dehn et al. 2000; Goudie 2006; Soldati et al. 2004).

Trees may register signs of past earth-surface processes in their increment rings and therefore represent a valuable tool for the analysis of past, contemporary and potential future process activity. The method has been widely used in the analysis of snow avalanche, debris-flow, landslide or flood analysis. In contrast, tree-ring based reconstructions of past rockfall activity have been scarce so far, yet yielded promising results. Based on the physics of the processes involved and the nature of damage observed in the trees' morphology, we believe that there is also a potential for the tree-ring based analysis of other processes, such as glacier-lake outburst floods, ice avalanches or the occurrence of volcanic lahars.

Furthermore, tree-ring based research on geomorphic processes has largely focused on mountain regions in general and the North American chains and European Alps in particular. Although there seems to be potential for dendrogeomorphological studies, tree rings have only rarely been used in other regions of the world to assess past geomorphic process activity, such as the analysis of landslides in subtropical Argentina (Paolini et al. 2005) or the reconstruction of snow avalanches in Patagonia (Casteller et al. 2008; Mundo et al. 2007). We therefore call for more dendrogeomorphological research in South America, the Indian subcontinent, Africa, Northern and Eastern Europe or Russia.

The past is the key to the future and a detailed knowledge of process dynamics will help the understanding and management of contemporary as well as the forecasting of future incidences. It is therefore important to realize that besides the pure dating of events and the creation of valuable event chronologies, dendrogeomorphological data should also be used as a tool and as the most complete database for the assessment of hazards and risks.

Essential progress has been made in dendrogeomorphology over the last few years, but more work is needed to further promote this unique technique. Research performed with new species or parts of trees needs to go beyond simple ring counting and should include more rigorous statistical comparisons of ring chronologies or event-response replications. Otherwise, investigations can lead to spurious errors. At the end, tree-ring research will help to even better understand the complex dynamics, mechanisms or triggering factors of geomorphic processes and to mitigate or reduce the problems they may pose.

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