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Authors	Stoffel, M.; Corona, C.
Citation	Stoffel, M., Corona, C., 2014. Dendroecological dating of geomorphic disturbance in trees. Tree-Ring Research 70(1):3-20.
DOI	10.3959/1536-1098-70.1.3
Publisher	Tree-Ring Society
Journal	Tree-Ring Research
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Download date	25/08/2022 10:29:44
Link to Item	http://hdl.handle.net/10150/630491

TREE-RING RESEARCH, *Vol. 70(1), 2014, pp. 3–20*
DOI: http://dx.doi.org/10.3959/1536-1098-70.1.3

DENDROECOLOGICAL DATING OF GEOMORPHIC DISTURBANCE IN TREES

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ABSTRACT

The initial employment of tree rings in geomorphic studies was simply as a dating tool and only rarely were other environmental information and records of damage contained within the tree exploited. However, these annually resolved tree-ring records also preserve valuable archives of past geomorphic processes on timescales of decades to centuries. As many of these processes are significant natural hazards, understanding their distribution, timing and controls provides crucial information that can assist in the prediction, mitigation and defense against these hazards and their effects on society. This contribution aims at presenting a proposal on the types of growth disturbances to be included in future work focusing on geomorphic disturbance, the intensity of reactions, and on the minimum requirements needed for growth disturbances to be considered in event histories. We present possibilities and limitations of dendrogeomorphic applications in geomorphic research and propose a range of techniques and approaches that may become standard practice in the analysis and understanding of earth-surface processes and related natural hazards in the future.

Keywords: dendrogeomorphology, wood anatomy, earth-surface process, hydrogeomorphology, geomorphology, injury, resin duct, reaction wood, vessel, tracheid.

INTRODUCTION

A major key to the assessment of ongoing hazards and risks is the documentation of geomorphic processes and related natural disasters (Stoffel and Huggel 2012). In many cases, because of the absence of documentary records, this information must be developed from natural archives or "silent witnesses" (Aulitzky 1992) that remain visible in the landscape after an event. In addition to the geomorphic or sedimentologic evidence, key information is required on the dating and history of past events. The significant contribution of tree rings to these endeavors lies in their capacity to preserve evidence of past geomorphic activity – in the context of this paper, the generic term "geomorphic activity" summarizes falls, topples, slides, spreads, and flows (Varnes 1978), as well as the interactions and linkages of hydrologic processes with landforms and the interaction of geomorphic processes with water (*i.e.* hydrogeomorphology; Sidle and Onda 2004) – and to provide critical information on their dating with annual or sub-annual resolution. Therefore, in many climates, the tree-ring record may represent one of the most valuable and precise natural archives for the reconstruction and understanding of past and ongoing processes during the past several hundred years (Stoffel and Bollschweiler 2008; Stoffel *et al.* 2010).

The initial employment of tree rings in geomorphic studies was simply as a dating tool (Douglass 1941; Stokes and Smiley 1968) – it rarely exploited other environmental information that could be derived from studies of ring-width variations and records of growth anomalies contained within the tree. However, these unique, annually resolved, tree-ring records preserve potentially valuable archives of past geomorphic processes. As many geomorphic processes are also

Table 1. Growth disturbances used to infer geomorphic process activity. Analysis is based on 206 contributions published in journals and indexed conference proceedings. Over the past five years, studies have increasingly focused on tangential rows of traumatic resin ducts (TRDs), whereas papers focusing on adventitious roots and germination have become more scarce.

Growth disturbance	Citations (all)	%	Citations (2008–2012)	%
Injuries/callus tissue	142	0.25	63	0.26
TRDs	51	0.09	34	0.14
Tracheid anomalies	4	0.01	3	0.01
Vessel anomalies	20	0.04	9	0.04
Reaction wood	122	0.21	51	0.21
Growth reduction	114	0.20	46	0.19
Growth release	55	0.10	23	0.10
Kill dates	18	0.03	5	0.02
Germination	30	0.05	5	0.02
Adventitious roots	15	0.03	3	0.01
Total	571	1.00	242	1.00
Papers		n = *206*		n = *75*

significant natural hazards, understanding their distribution, timing and controls provides valuable information that can assist in the development of mitigation and defense against these hazards and their effects on society (Osterkamp *et al.* 2012; Stoffel and Wilford 2012).

Apart from the site-specific information common to many trees at any site, individual trees also record the effects of mechanical disturbance caused by external processes. In his seminal work, Alestalo (1971) illustrated that the occurrence of earth-surface processes will typically injure trees, tear off their crown or branches, tilt their stems, partially bury them or expose their roots. Evidence of these events can be recorded in growth-ring records of affected trees (Shroder 1978). Based on the principles presented in these seminal papers (Butler and Stoffel 2013), a set of characteristic growth disturbances has been typically used in dendrogeomorphic studies (Stoffel *et al.* 2013a) with a clear focus on injuries, reaction wood and growth suppression (Table 1). Other indicators, such as tangential rows of traumatic resin ducts (TRDs), have been used much less often and only became a widely accepted signal for past geomorphic disturbance in trees over the past few years (9% overall, but 14% since 2008). Despite the ever increasing popularity of dendrogeomorphology (Table 1), a common understanding of parameters to be used and a weighting of indicators is largely missing, and the reconstruction of time series of events is still based on largely varying criteria.

This contribution thus aims at presenting a proposal on (i) which growth disturbances (GDs) to focus on in future work addressing geomorphic disturbance, (ii) how to determine their intensity, (iii) what minimum requirements for GDs should be considered in event histories, which will then eventually lead to (iv) the establishment of a range of techniques and approaches that may become standard practice in the analysis of specific geomorphic, geologic and hydrologic processes in the future.

GROWTH REACTIONS INDUCED BY GEOMORPHIC PROCESSES

Injuries and Callus Tissue

Partial bark removal and wood-penetrating injuries are a common feature in trees affected by geomorphic processes (Lundström *et al.* 2009; Trappmann and Stoffel 2013). Wounds can occur on the tree's stem (Figure 1A), its branches or on roots. If impacts locally destroy the cambium, incremental cell formation will become disrupted and new cell formation will cease in the injured segment of the tree. To minimize rot and the negative effects of insect attacks after damage, the injured tree will compartmentalize the wound (*e.g.* Shigo 1984; Stoffel and Klinkmüller, 2013) and start the production of chaotic callus tissue at the edges of the injury (Figure 1B). Through the production of callus tissue, cambium cells will continuously overgrow the injury from its edges

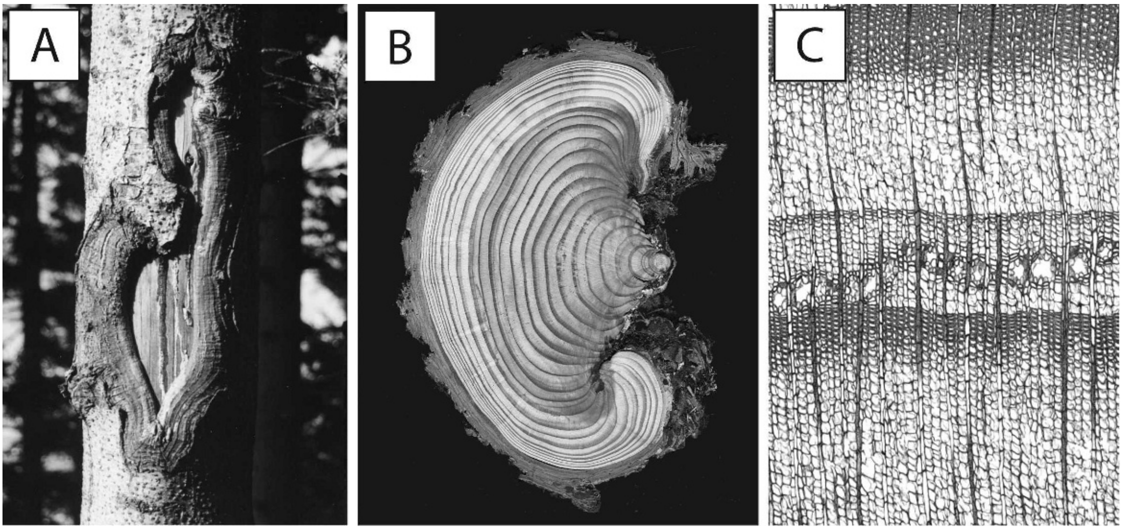

Figure 1. (A) Open injury in *Abies alba* and (B) on a cross-section of a wounded *Larix decidua* tree. (C) Micro-section of a tangential row of traumatic resin ducts in *Larix decidua*. Note the delayed response with increasing distance from the wound (left to right).

(Sachs 1991) and ideally can lead to the complete closure of the wound. The extent of wound healing will, however, greatly depend on the annual increment rate, tree age and on scar size (Bollschweiler *et al.* 2008a; Schneuwly *et al.* 2009a).

The presence of injuries and chaotic callus tissue is commonly regarded as a valuable and reliable indicator of past geomorphic process activity. Provided that trees are selected with sufficient care in the field and that disturbances other than geomorphic (*e.g.* anthropogenic, ungulate browsing or fraying, lightning strike, or hail) can be excluded, they represent the most unambiguous witness of past disturbance. As a rule of thumb, we recommend excluding elongated (>2 m) and very small (<20 cm^2) injuries from analyses, and not to take injuries in very small trees (DBH <5 cm) into account. In addition, whereas scars will remain largely visible on the stem surface of tree species with smooth barks (*e.g. Abies*, *Alnus*, *Betula*, *Fagus*; Trappmann and Stoffel 2013), they may become fully blurred in species with thicker bark structures such as *Larix*, *Picea*, *Pinus* or *Quercus* (Stoffel and Perret 2006; Trappmann *et al.* 2013).

Tangential Rows of Traumatic Resin Ducts

Following cambium disturbance, TRDs are produced in the developing secondary xylem of certain conifer species such as *Larix*, *Picea*, *Pseudotsuga* or *Abies* (Bannan 1936; Yamaguchi and Lawrence 1993; Jacoby 1997; Stoffel 2008; Butler *et al.* 2010), where they extend both tangentially and axially from the injury (Bollschweiler *et al.* 2008a; Schneuwly *et al.* 2009a,b). When wounding occurs during the vegetation period of the tree, resin production will start within a few days after the impact and ducts will emerge within three weeks after the disturbance (Ruel *et al.* 1998; Luchi *et al.* 2005; Kaczka *et al.* 2010). Therefore, when analyzing cross-sections, the intra-seasonal position of the first series of TRDs can be used to reconstruct previous events with monthly precision (Stoffel *et al.* 2005b, 2008; Stoffel and Beniston 2006; Schneuwly-Bollschweiler and Stoffel 2012), provided that the incidents occurred during the vegetation period. With increasing axial and tangential distance from the impact, however, TRDs tend to migrate to later portions of the tree ring (Figure 1C; Bollschweiler *et al.* 2008a; Schneuwly *et al.* 2009a). The intra-seasonal dating with monthly precision thus has to be based on cross-sections or a large number of increment cores at the same elevation on the stem. This technique cannot be used in *Pinus* because TRDs do not occur in this genus that produces copious amounts of resin and resin ducts unrelated to mechanical wounding (Phillips and Croteau

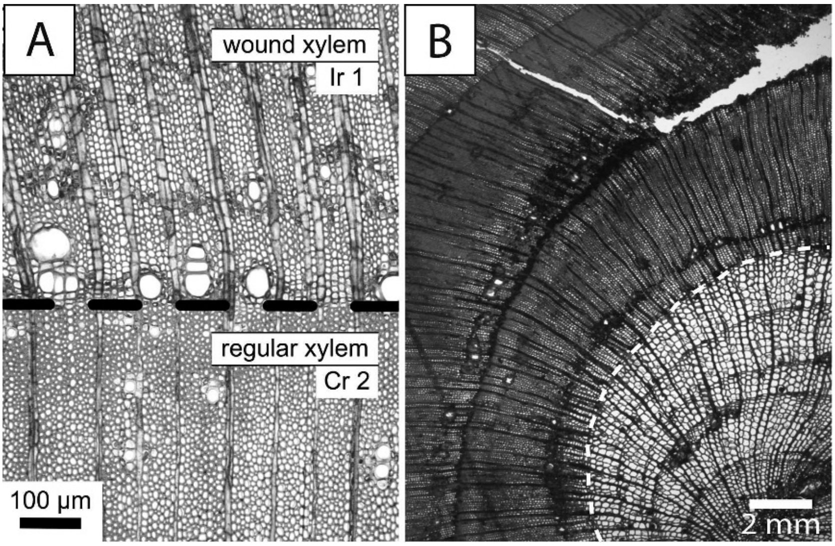

Figure 2. (A) Microscopic views of *Fraxinus excelsior* wood anatomy prior to and after cambial injury. The dashed line shows the position of the cambium at the time of wounding. More and narrower earlywood vessels were formed in the injury ring (Ir 1) as compared to the control ring (Cr 2). Wound xylem also differed from regular xylem through the enlargement of pre-existing rays. (B) Changes in tracheid lumina, tracheid number and ring width in a *Pseudotsuga menziesii* root following sudden exposure. The moment of exposure is indicated with the dashed line.

1999; Ballesteros *et al.* 2010a). Similar to wounds in young trees, trees with DBH <5 cm should not be considered and the 10–15 innermost growth rings should be excluded, as tree rings in seedlings tend to produce more resin ducts per unit area in general (Larson 1994), but only a few ducts around wounds located near the pith (Bannan 1936).

Tracheid and Vessel Anomalies

Anomalies in tracheids and vessels have only rarely been used in the past to extract signals of geomorphic activity. Most work has been realized on riparian trees affected by floods and/or debris flows (*e.g.* St. George *et al.* 2002; Ballesteros *et al.* 2010b; Arbellay *et al.* 2010a,b; Wertz *et al.* 2013). Other processes, such as snow avalanches, were not studied frequently in the past (Arbellay *et al.* 2013). Tree microscopic response to wounding was primarily studied between rings formed in the year of disturbance and subsequent years as well as in uninjured control rings (Figure 2A). The authors state that injured rings are characterized by much smaller (but more) vessels as compared with uninjured rings, and that fiber and parenchyma cells (FPCs) would not differ significantly in numbers and size between injured and uninjured rings. Arbellay *et al.* (2010a) also stated that vessel and FPC parameters mainly remained constant with increasing tangential distance from the injury, except for a higher proportion of vessel lumen area opposite to the injury within *A. incana*. These results highlight the existence of anatomical tree-ring signatures – in the form of smaller vessels – related to past geomorphic process activity and address an innovative methodological approach to date injuries inflicted on broadleaved trees with minimally destructive techniques. More recently, Arbellay *et al.* (2012a,b) have expanded their approach to analyze the thickness-to-span ratio of vessels, xylem relative conductivity and xylem vulnerability to cavitation, and state that the wound-induced anatomical changes in wood structure express the functional need of trees to improve xylem hydraulic safety and mechanical strength at the expense of water transport. They conclude that xylem hydraulic efficiency was restored in one year, whereas xylem mechanical reinforcement and resistance to cavitation and decay lasted over several years.

Research on tracheid changes in conifers was basically limited to root exposure, with the

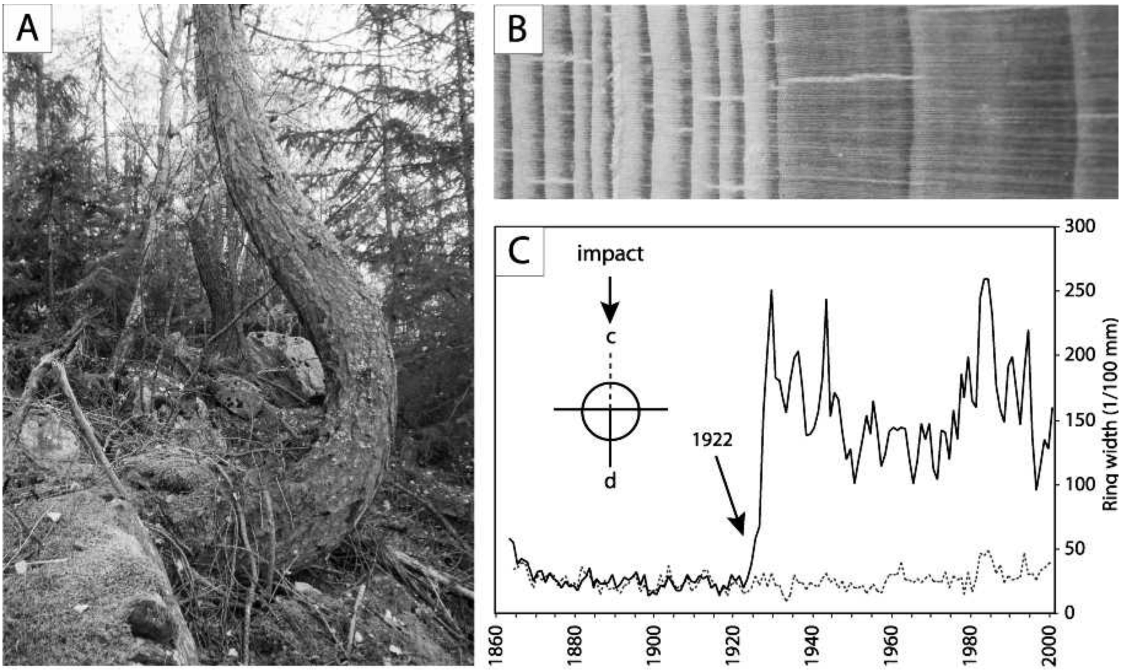

Figure 3. Evidence of tilting: (A) Tree morphology and (B) partial cross-sections of a tilted *Larix decidua.* (C) Increment curves of the upslope (dashed line) and downslope (solid line) radii from a *Picea abies* tree tilted by a debris flow in 1922.

exception of Stoffel and Hitz (2008) who identified changes in lumina of earlywood tracheids after wounding by snow avalanches and rockfalls. Exposed roots will continue to grow and fulfill their functions as long as their outer tips remain in the ground. In the exposed portion of the root, however, anatomical changes will occur (Stoffel *et al.* 2013b) and individual growth rings similar to those in the stem or branches will be formed. The localization of such changes in the tree-ring record allows determination of the moment of exposure (Figure 2b; Bodoque *et al.* 2006; Rubiales *et al.* 2008; Corona *et al.* 2010b, 2011; Lopez Saez *et al.* 2011; Stoffel *et al.* 2012). The continuous slow exposure of roots is usually caused by gradual processes and relatively low denudation rates, *e.g.* overland flow, slow opening of cracks in soils (*e.g.* soil creep, landslides) and in disintegrated bedrock, along rivers, streams, lakes and oceans (floods, shore erosion) as well as with faulting activity and displacements in relation to earthquake activity. Provided that the roots are gradually exposed with time, it is also possible to determine erosion rates in such cases (Carrara and Carroll 1979).

Reaction Wood

Inclination of the stem may result from the sudden pressure induced by hydrogeomorphic processes directly, by the associated deposition of material (*e.g.* avalanche snow, debris-flow material), or by the slow but ongoing destabilization of a tree through landslide activity or erosion (Lundström *et al.* 2007a,b). Tilted trees are common in most areas affected by geomorphic processes (Figure 3A) and have therefore been used in many publications focusing on the dating of event histories (*e.g.* Clague and Souther 1982; Braam *et al.* 1987a,b; Fantucci and Sorriso-Valvo 1999).

Subsequent growth in the trunk of a tilted tree will attempt to restore its vertical position and the reaction will be most clearly visible in that segment of the tree to which the center of gravity has been moved through the inclination of the stem axis (Mattheck 1993). In the tree-ring record, eccentric growth will be visible after a tilting event and thus will allow accurate dating of the disturbance. In conifers, compression wood (also referred to as reaction wood) will be produced on the underside of the trunk. Individual rings will be considerably larger and slightly darker in appearance as compared to the upslope side (Figure 3B). The difference in color results from much thicker and rounded cell walls of earlywood and latewood tracheids (Timell 1986; Du and Yamamoto 2007). Compression wood also tends to have a higher proportion of latewood, higher lignin content and higher density (Timell 1986). Multiple tilting events in the same stem may be recognized by changes in the amount, color or orientation of reaction wood series in the tree-ring record. In contrast, stem tilting in broadleaved trees leads to the formation of tension wood (Westing 1965) on the upper side facing the tilting agent. Broadleaved trees react upon tilting with ultra-structural modifications (*e.g.* fewer vessels of smaller diameter, higher cellulose content and a gelatinous layer oriented nearly parallel to the fiber axis) that are only visible when studied on micro-sections (Pilate *et al.* 2004).

Growth Reduction

Debris flows, floods, landslides or "dirty" snow avalanches may bury trees by depositing material around their stem base. Growth suppression after burial with debris is caused, on the one hand, by a reduced activity of the roots, and on the other hand, by mechanical effects caused by the enormous weight of debris. The effect of pressure on the cambial activity of trees has already been described by Kny (1877) and Rubner (1910). The pressure on the cambium exerted by bark and phloem impedes the cell division and leads to a reduced number of cells with narrower lumen (Kny 1877). Thus, the supply of water and nutrients will be temporarily disrupted or at least limited (LaMarche 1966; Hupp *et al.* 1987; Friedman *et al.* 2005) and the yearly increment will be diminished (Kogelnig-Mayer *et al.* 2013). By the pressure on the stem, the width of the growth rings may be reduced to a quarter of the original width (Rubner 1910). Reductions in annual ring widths in tilted trees are thought to be related to the partial destruction of root mass in the case of unstable slopes (Mayer *et al.* 2010).

If stem burial exceeds a certain threshold, trees will die from a shortage of water and nutrient supply (Figure 4A). According to case-study results from the Italian Dolomites (Strunk 1991), *Picea abies* may 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). Although there are no data available for other species or lithologies, it is believed that survivable burial depths will be much smaller in regions where debris flows are composed of massive or larger materials.

Bouncing rocks and boulders, debris in flowing water, debris flows and lahars or the windblast of snow avalanches may cause decapitation of trees (Figure 4B) or the removal of branches. The loss of the crown or branches is more common in bigger trees, when stems have lost their flexibility. Apex loss has also been observed as a result of rockfall impacts close to the ground level. In such cases, the sinusoidal propagation of shockwaves in the stem results in the break-off of the crown. This phenomenon has been described as whiplash or "hula-hoop" effect (Dorren and Berger 2006; Lundström *et al.* 2009).

Trees react upon decapitation or branch loss with distinct radial growth suppression (Figure 4C) in the years following the impact. One or several lateral branches will form a "leader" that replaces the broken crown, resulting in the tree morphology called "candelabra" growth (Butler and Malanson 1985; Stoffel *et al.* 2005a). "Leaders" may also be formed from prostrated trunks knocked over by geomorphic events.

Erosional processes and the (partial) denudation of roots may generate different growth reactions, both in the stem and in the exposed roots. The type and intensity of the reaction(s) will depend on the nature of the erosive event, which may be instantaneous or progressive and gradual. If several roots are completely denuded during a sudden erosive event (*e.g.* debris flow, lahar, flood or landslide), they are no longer able to fulfill their primary functions and quickly die. The tree subsequently suffers from a shortage of water and nutrient supply, resulting in suppressed tree

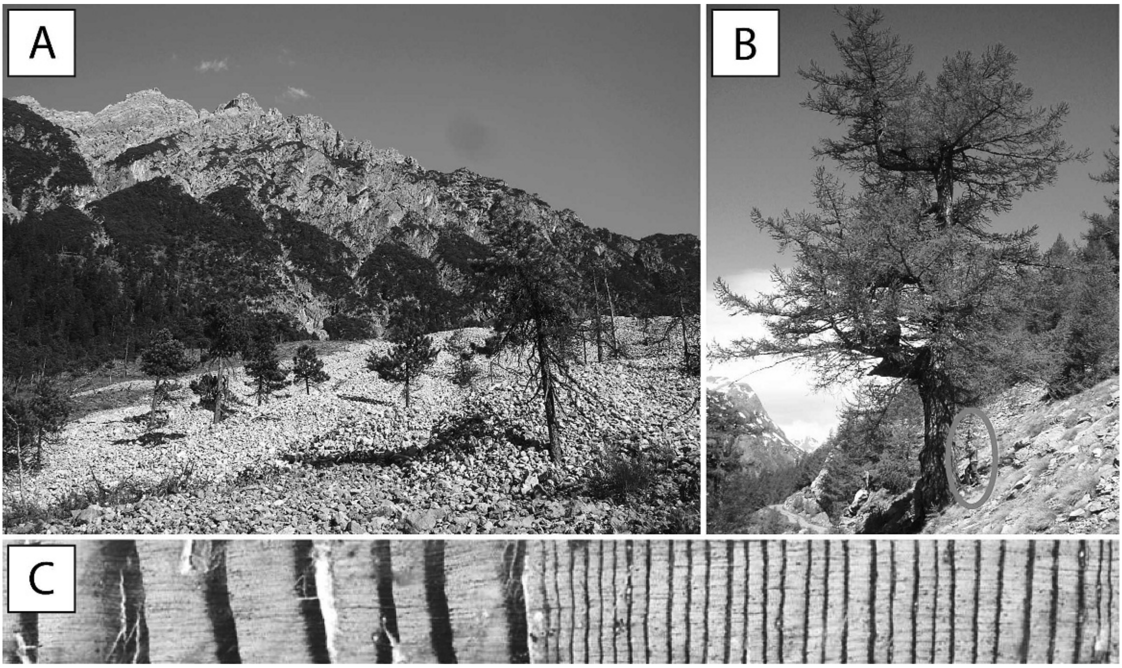

Figure 4. (A) The partial burial of trees, as illustrated here with *Pinus mugo* growing on a debris-flow cone, is one of the main reasons for the occurrence of abrupt growth suppression. (B) The loss of apices also causes growth suppression and can occur repeatedly in century-old *Larix decidua* trees affected by rockfall or snow avalanches. (C) Sudden growth suppression in *Picea abies*.

growth and the formation of narrow rings in the stem (LaMarche 1968; Carrara and Carroll 1979; McAuliffe *et al.* 2006).

Growth Release

Geomorphic processes do not only disturb trees in their growth, but large and devastating hydrogeomorphic events can also eliminate trees along channels or couloirs through uprooting and stem breakage while leaving their neighbors intact. This phenomenon can be observed with rockfalls (Stoffel *et al.* 2005a, 2011), debris flows (Stoffel *et al.* 2006; Bollschweiler and Stoffel 2010), lahars (Bollschweiler *et al.* 2009), extreme floods (Ruiz-Villanueva *et al.* 2010; Ballesteros *et al.* 2011a,b), landslides (Lopez Saez *et al.* 2012a,b, 2013a,b) or snow avalanches (Butler 1979; Corona *et al.* 2010a, 2012, 2013b). The elimination of neighboring trees can result in a new environment with less competition, more light, nutrients and/or water. Survivor trees will benefit from the improved conditions and respond with a growth increase and wider tree rings (Strunk 1997). However, several observations indicate that this growth release in survivor trees can be delayed and that it may only become effective as soon as surviving vegetation can take full benefit of the excess availability of water, nutrients and light (Stoffel and Bollschweiler 2008). Therefore this GD cannot always be used to date past destructive events with precision. Because release phases may also be triggered through a combination of climatic and geomorphic effects (Strunk 1991), suddenly larger rings in survivor trees should not be used as the single indicator of past process activity, but as a means to corroborate the dating of geomorphic events identified in other trees of the same site and with other types of growth disturbances (Stoffel *et al.* 2010).

Germination and Kill Dates

Many geomorphic processes can eliminate surface vegetation including entire forest stands and therefore leave no direct dendrogeomorphic

Table 2. Proposal for the definition of intensities of growth disturbances (GDs) based on their appearance and/or persistence in the tree-ring series. Note that tangential rows of traumatic resin ducts (TRDs) are formed in some conifer species (*e.g. Abies*, *Larix*, *Picea*, *Pseudotsuga*), but not in *Pinus* or in broadleaved species. Vessel anomalies are related to injuries and typical for broadleaved tree species.

GD	Parameter	weak GD	moderate GD	strong GD
Injuries, callus tissue		N/A	N/A	clear indicator of an event
TRDs		tangentially aligned row with clear gaps between ducts	compact, but not fully continuous row	extremely compact and continuous row
Vessel anomalies	Decrease in lumen area (%)	N/A	N/A	≥30%
	Decrease in vessel number (%)	N/A	≥30%	≥50%
Kill dates		N/A	N/A	clear indicator of an event
Reaction wood	≥50% of ring width consists of compression wood cells			
	Duration	≥3 yr	3–8 yr	≥8 yr
Growth suppression	change in ring width (%)	<60%	≥100%	≥200%
	Duration	≥4 yr	<8 yr but ≥4 yr	≥8 yr
Growth release	change in ring width (%)	<50%	≥100%	≥150%
	Duration	≥4 yr	<8 yr but ≥4 yr	≥8 yr

evidence. Surfaces cleared by devastating events will be recolonized with trees. Germination ages of trees growing on bare surfaces can be used to approximate the time of surface-clearing events (McCarthy and Luckman 1993; Pierson 2007; Bollschweiler *et al.* 2008b).

This approach provides a minimum age for that surface and has been used repeatedly to date landforms or to assess the minimum time elapsed since the last devastating event. Germination ages have been used in the past to date destructive snow avalanches, debris flows or floods (Sigafoos and Hendricks 1969; McCarthy and Luckman 1993; Heikkinen, 1994; Winter *et al.* 2002; Stoffel *et al.* 2006; Pierson 2007; Bollschweiler *et al.* 2008b). Yet, the assumption underpinning this approach is that new forest stands establish soon after the event. However, trees do not always immediately seed on new surfaces and there may be a period (so-called ecesis interval) between the time the new surface becomes available and the time that trees become established on it. Ecesis intervals have been discussed extensively in dendroglaciology (Koch 2009; McCarthy and Luckman 1993), indicating they range from one to almost 100 years, depending on the tree species, the nature of the substrate, and climate (Sigafoos and Hendricks 1969; Smith *et al.* 1995; Wiles *et al.* 1999; Lewis and Smith 2004). Somewhat shorter ecesis intervals have been reported for fluvial terraces cleared by lahars (10–15 years; Pierson 2007) and for a rockslide deposit with proximal seed sources (1–2 years; Van der Burght *et al.* 2012).

Trees killed by hydrogeomorphic events can be used for indirect dating of past process activity. Calendar kill dates (*sensu* Luckman 2000) were first used to crossdate stumps and logs with long-lived, regional tree chronologies within the glacier forefield, which were overridden by a glacier. More recently, however, kill dates have also been used in avalanche research (*e.g.* Reardon *et al.* 2008).

DEFINITION OF REACTION INTENSITY

The expression of disturbance in the tree-ring record may vary in intensity as well as in the spatial and temporal extent between processes, species and age classes of trees. As a consequence, and based on the process and tree species analyzed, different classification systems have been used in the past. In the following, we present a synthesis of indicators commonly used in dendrogeomorphic research (Table 2) and make a proposal on how to analyze and interpret GDs in the future. Distinction is made between weak, moderate and strong GDs, following, *inter alia*, the classifications of Frazer (1985), Stoffel *et al.* (2005a) and Schneuwly *et al.* (2009b).

Table 3. Proposal for the weighting of reactions in trees. Scars and strong TRDs are considered the most reliable indicators of past geomorphic disturbance. The presence of strong growth releases or weak reaction wood/TRDs in tree-ring records should be used only to confirm events, but not to date them in the first place.

Intensity	GDs in tree-ring record
Intensity 5	impact scar, strong TRDs
Intensity 4	kill date, moderate TRDs, callus tissue, strong decrease in vessel lumen area and/or vessel number, strong reaction wood, strong growth reduction
Intensity 3	moderate reaction wood, moderate growth reduction, moderate decrease in vessel number
Intensity 2	strong growth release, weak reaction wood
Intensity 1	weak TRDs, moderate growth release

All GDs listed in Table 2 are typically induced by geomorphic disturbance, but several of them can be caused by other processes as well (*e.g.* anthropogenic or climatic disturbances, ungulate fraying or browsing). In addition to carefully analyzing the occurrence of geomorphic processes and other influences at the study site, one should therefore further minimize the risk of misdating events by maximizing signals and minimizing noise in the tree-ring record. As a rule of thumb, strong reactions in trees should be clearly preferred and weak reactions should be neglected. Based on the empirical rating systems proposed in the literature (Dubé *et al.* 2004; Reardon *et al.* 2008; Germain *et al.* 2009; Corona *et al.* 2010a, 2012, 2013b; Schläppy *et al.* 2013), which have been used mainly for the reconstruction of snow avalanches so far, we suggest the weighting of reactions as presented in Table 3.

Provided that a careful field reconnaissance precedes dendrogeomorphic sampling of trees, **intensity 4** and **5** GDs can be considered the consequence of the geomorphic disturbance under investigation with high certainty. Depending on the nature of the process, **intensity 3** reactions can be regarded as unequivocal signals of hydrogeomorphic disturbance as well (also see chapter 4 for details). **Intensity 1** and **2** reactions, in contrast, should not be used as indicators of hydrogeomorphic disturbance in the first place, but can be included where appropriate, when it comes to the documentation of spatial patterns of past event occurrences (in terms of spread and reach), and only once the event years have been defined with **intensity 4** and **5** reactions.

Identification of events is somewhat different in dendrogeomorphic rockfall research, where each strong and unequivocal GD will be considered an event. As a consequence, the selection of trees on rockfall slopes is even more crucial, so we suggest limiting the list of GDs considered for analysis to scars, TRDs, massive changes in anatomical signatures in broadleaved trees, strong growth reductions and compression wood of intensity classes 4 and 5. Figures 5 and 6 provide characteristic examples of intensity class 4 and 5 reactions.

Reactions of the same nature occurring in the same tree over several years should not be identified as individual events, but considered as a continuing response of the tree to initial disturbance. As a rule of thumb, one should consider that reactions were induced by different disturbance events as soon as a minimum of four “normal” rings exist between two rings with anomalous features. In conifers suffering from insect infestations, reactions to geomorphic disturbance – in particular compression wood – can be overprinted temporarily, and reactions to an initial geomorphic disturbance have been reported to occur again a few years after the insect infestation.

DIFFERENT PROCESSES – DIFFERENT TYPES AND INTENSITIES OF REACTIONS

The expression of disturbance in a tree (ring) will depend on the nature and intensity of the impact as well as on the sensitivity and vitality of the tree. The ability of a tree to react to disturbance is believed to be driven by the species-specific (genetic) make-up as well as by its age (Silhan *et al.* in press). Along this line of thought, observations of the authors suggest that (i) older trees tend to be less sensitive recorders of disturbance and that (ii) species with thick bark structures would require

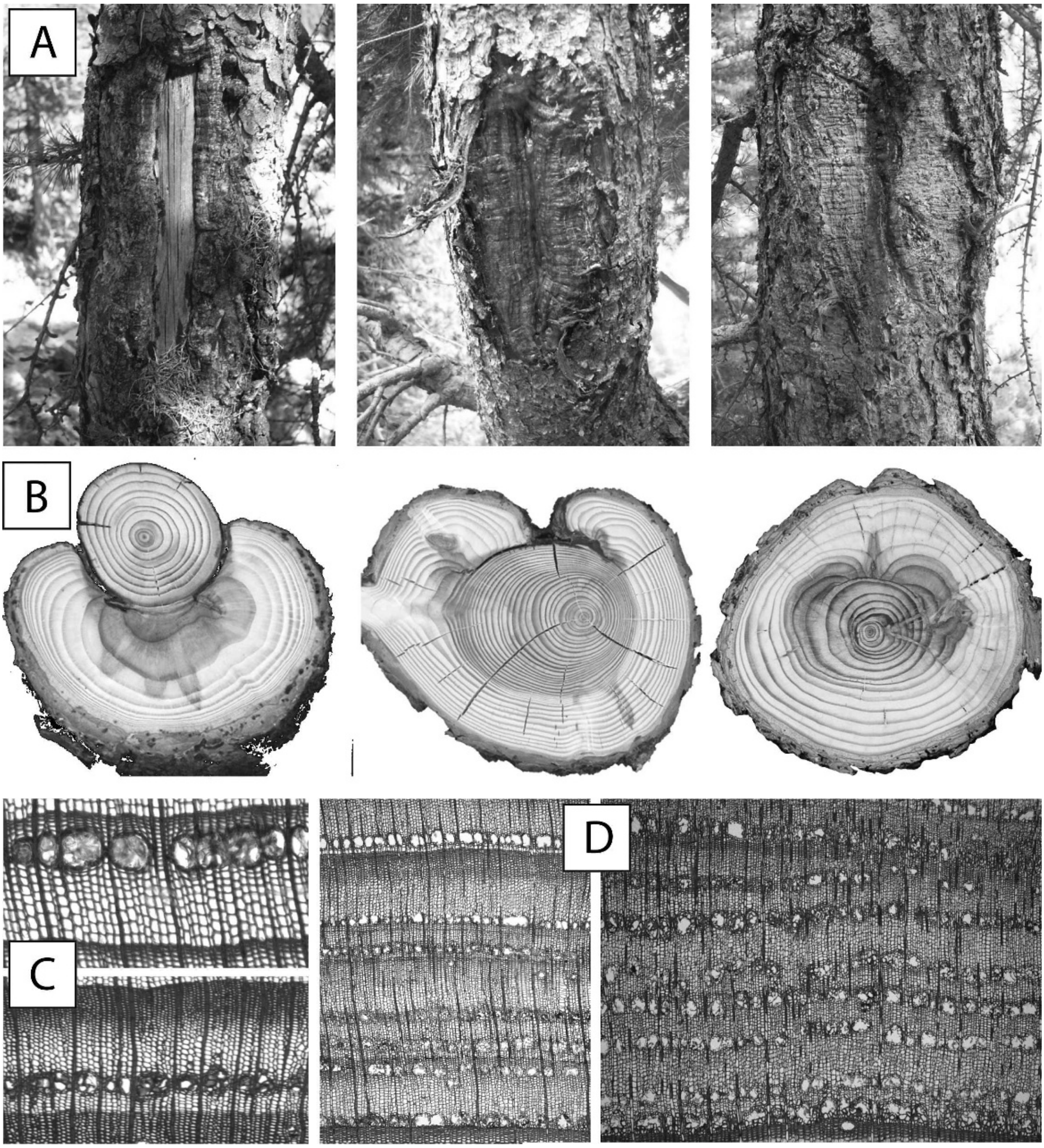

Figure 5. Overview of typical **intensity 5** reactions: (A) Characteristic examples of and different stages of wound closure in *Larix decidua* injured by rockfall with (B) associated cross-sections. (C) Examples of strong tangential rows of traumatic resin ducts (TRDs) in *Picea abies* (top) and *Larix decidua* (bottom). (D) The production of TRD may persist over several years, depending on the production of hormonal signals. However, only the initial reaction should be considered the result of a geomorphic disturbance.

more intense impacts to record signs of geomorphic disturbance (Stoffel and Perret 2006; Trappmann and Stoffel 2013). The strength and/or onset of reaction wood, for instance (measured by the change in color, ring thickness, eccentricity, and/or degree of circumference coverage of the crescent), has been demonstrated to vary from event to event within a single tree (Butler and Sawyer 2008), thereby pointing to changing sensitivity of recording trees with age.

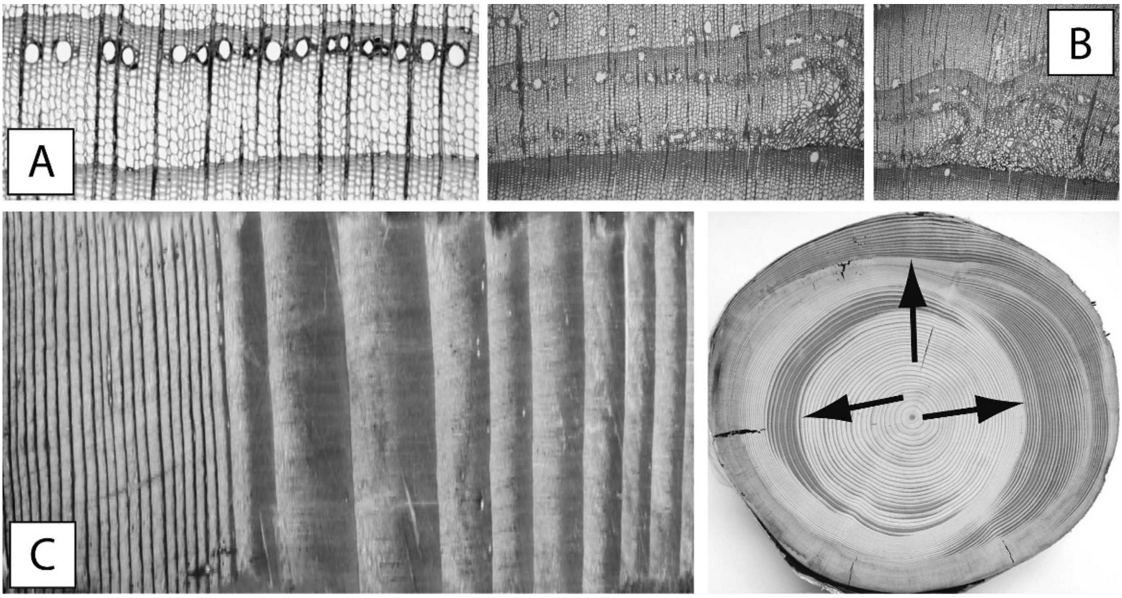

Figure 6. Overview of characteristic **intensity 4** reactions: (A) Moderate TRD in *Abies alba* (left) and *Larix decidua* (right). Ducts are still aligned, but gaps exist between individual ducts. (B) Callus tissue occurring next to an injury in *Larix decidua* wounded by a snow avalanche. (C) Strong reaction wood in *Larix decidua* (left) and on a cross-section of *Picea abies* (right). At least three distinct events (arrow points to the initiation of each phase) can be identified in this tree sampled on a landslide body.

Moreover, the expression and intensity of disturbance as observed in the tree-ring record will also depend chiefly on the position of sampling, and reactions may be well developed in the vicinity of the impact but completely absent elsewhere in the stem. A spatially limited expression of disturbance is most obvious in the case of impact scars, associated TRDs (Bollschweiler *et al.* 2008a; Schneuwly *et al.* 2009a,b) and reaction wood (Timell 1986; Schneuwly *et al.* 2009b), whereas growth releases, abrupt growth suppression or vessel anomalies will be more widespread and visible throughout the stem (Arbellay *et al.* 2010a; Kogelnig-Mayer *et al.* 2013).

Remarkable differences also exist in the number, expression and intensity of GDs induced by different processes. In this way, processes with a large spatial footprint (*e.g.* snow avalanches, landslides) will tend to leave growth anomalies in a large number of trees. On an avalanche site, for instance, one may expect a distinct source area, a main track and a depositional surface, with GDs in trees being found (inside and) on both sides of the main track as well as in the depositional area. By contrast, rockfall will be characterized by a small-sized slope movement that typically involves a few boulders (<5 m^3) and which will only cause damage to one or a few trees along its trajectory (Stoffel and Perret 2006; Moya *et al.* 2010; Corona *et al.* 2013a; Trappmann *et al.* 2013). In the same line of thought, Kogelnig-Mayer *et al.* (2011) demonstrated that the number of GDs induced by snow avalanches tends to be higher than that of debris flows because spread of debris flows tends to be more limited, thus resulting in a smaller number of potentially affected trees (Schneuwly-Bollschweiler *et al.* in review).

Different geomorphic processes have also been demonstrated to determine the nature of GDs. Earthflows and rotational slides, for instance, usually result in the disruption and remodeling of topographic surfaces. As a consequence, survivor trees on landslides will preferably display tilting and root-plate damage (Moya *et al.* 2010), which will initiate the formation of reaction wood (Astrade *et al.* 1998) and abrupt growth reductions. Data from seven rotational landslides of the French Alps (Lopez Saez *et al.* 2013a) illustrate quite clearly the predominance of growth reductions (64% of all GDs) and compression wood (33%). Injuries were, by contrast, virtually absent (3%) in their study

Table 4. The nature and abundance of specific types of growth disturbances (GDs) in trees will be dictated by the nature of the geomorphic process, tree species considered for analysis and lithology (geologic units, mean and maximum grain sizes). LD = Larix decidua Mill.; PA = Picea abies (L.) Karst. Sources: A = Stoffel *et al.* (2005a); B = Trappmann and Stoffel (2013); C = Bollschweiler *et al.* (2007); D = Kogelnig-Mayer *et al.* (2011); E = Mayer *et al.* (2010); F = Stoffel *et al.* (2006); G = Savi *et al.* (2013).

Site/GD characteristics	Rockfall	Rockfall	Debris flow	Debris flow	Debris flood	Avalanche	Avalanche	Landslide
Study site	Täschgufer	Hechenberg	Bruchi	Reiselehne	Gratzental	Reiselehne	Birchbach	Schimbrig
Sample size (nb)	564	144	802	772	500	772	520	416
Species	LD	PA	LD, PA	PA	LD, PA	PA	LD	PA
Lithology	Gneiss	Limestone	Granite	Granite	Limestone	Granite	Granite	Flysch
Scars/callus tissue	2%	11%	4%	6%	1%	4%	7%	1%
TRDs	**86%**	**89%**	**59%**	**80%**	**35%**	**57%**	**61%**	21%
Reaction wood	3%	<1%	15%	3%	6%	**17%**	**22%**	**25%**
Growth suppression	6%	0%	12%	9%	**28%**	**17%**	6%	**47%**
Growth release	3%	0%	10%	2%	**30%**	5%	4%	6%
Author	*A*	*B*	*C*	*D*	*E*	*D*	*F*	*G*

focusing on *Pinus nigra*. Based on the analysis of snow avalanches and debris flows known from archival records, Kogelnig-Mayer *et al.* (2011) demonstrated that trees from the same study site will react differently to different processes. In their case, debris flows were primarily causing injuries and TRDs (Table 4), whereas trees impacted by avalanche snow formed a much higher percentage of compression wood, growth reductions, and growth releases. When studying different processes, one thus needs to adapt the list of criteria used for process reconstructions.

Similarly, signal strength will not only depend on the nature of the process (debris floods with limited solid charge *versus* debris flows with limited water but much more solids, for example), but also on the nature of the material involved. In the Austrian Alps, Mayer *et al.* (2010) and Procter *et al.* (2011) have shown quite clearly that the deposition of calcareous debris may have fertilizing effects on *Picea abies* and *Pinus uncinata*, and therefore dampen or eliminate signs of growth reduction after stem burial. Provided that other types of disturbances are largely missing, weaker reactions (**intensities 1** or **2**) might need to be taken into account as well to allow reconstruction of all events.

RECONSTRUCTION OF EVENTS – REDUCTION OF NOISE

A single reaction does not make a geomorphic event – with the exception of rockfalls – and criteria therefore need to be defined for the definition of events and for the exclusion of noise. First of all, process reconstruction should focus clearly on the most obvious and strongest reactions (*i.e.* intensity classes 4 and 5; **intensity 3** reactions should be considered as described in sections 3 and 4). The required minimal number of GDs for an event to be accepted will depend on the spatial footprint that the process under investigation can leave in the field, and may thus need to be adjusted on a case-by-case basis. Thresholds for the selection of events can be based on expert approaches (*sensu* Stoffel and Bollschweiler 2008) or indices (*sensu* Shroder 1978).

In the expert approach, event histories are obtained via a semi-quantitative analysis of trees disturbed by past geomorphic process activity (*e.g.* Stoffel *et al.* 2005c, 2006; Bollschweiler *et al.* 2007, 2008b). Definition of events is based on a careful site selection and on the position of reacting trees in their geomorphic context. Past process activity is not defined with a fixed threshold of reacting trees, but based on the spatial distribution of trees simultaneously showing GDs following geomorphic activity. At least three to five strong GDs (**intensities 4** or **5**) need to occur in the same sector of the study site or along the same flow path for an event to be accepted. The threshold is rather low, but facilitates the dating of smaller or erosive events (with incision rather than avulsion) to be detected in the tree-ring record. The semi-quantitative approach therefore allows detection of small and larger geomorphic events.

Reconstructions based on index values *(It)* go back to the work of Shroder (1978), who defined a fixed threshold based on the ratio between reacting and sampled trees (Butler and Sawyer 2008). Butler *et al.* (1987) suggested that the use of the "tree-ring response index" be dictated by the nature and geographic extent of the hazard under study, and argued that more samples and the use of a higher minimum response index would allow greater confidence in the event chronology constructed from tree rings. The authors also suggested that chronologies for geographically discrete processes (*e.g.* snow avalanches) should aim for a high sample density, whereas studies focusing on processes such as slow landslides or the movement of permafrost bodies would require less dense, but larger sample size. In avalanche research, index values ranged from 10% (*e.g.* Larocque *et al.* 2001; Reardon *et al.* 2008) to 40% (Butler and Malanson 1985; Muntan *et al.* 2009), with the latter being suitable for the identification of extreme events. In debris-flow research, Kogelnig-Mayer *et al.* (2011) and Procter *et al.* (2012) proposed the use of a weighted index (W_{it}) for which the number of GDs, their intensity, number of trees available as well as the intra-seasonal timing of GDs are taken into account.

Recent work by Corona *et al.* (2012) has demonstrated quite clearly that rigid index values may hamper an extensive and well-balanced reconstruction of past snow avalanche activity, and illustrated that the use of flexible index values (where *It* and GD are adjusted based on the number of samples available for analysis) would provide much more reliable results over the entire period covered by the reconstruction.

Interestingly, based on a classification and regression tree (CART) analysis, Schläppy *et al.* (2013) has recently demonstrated that the criteria used in the expert's approach to reject or accept snow avalanche events are comparable to those used in studies based on indices, and that results of both approaches are virtually identical in the end. On a site affected by debris flows, Schneuwly-Bollschweiler *et al.* (2013) reconstructed event histories with the expert's approach and with indices, and obtained virtually the same results as well (*i.e.* in terms of event frequency and event years).

OUTLOOK AND CONCLUSIONS

In this contribution, we illustrate the broad array of dendroecological indicators that are currently being used to reconstruct and interpret geomorphic disturbance events in trees. A large body of dendrogeomorphic papers has been published over the past few years (*i.e.* at least 75 papers for the period 2008–2012), and the focus of indicators used to infer past geomorphic events has clearly shifted towards scars and TRDs (Table 1). Although most studies are still performed with conifers, broadleaved species are slowly becoming more popular in dendrogeomorphology. A need for more fundamental research on broadleaved trees clearly exists, both in terms of wood anatomy of tension wood or scars and related changes in wood anatomy. An inclusion of new parameters will be likely more difficult for conifers, but new attempts should be undertaken to include wood density or isotope data contained in the tree-ring records for dendrogeomorphic purposes. Based on Table 4, one might also consider restricting dendrogeomorphic analyses to specific types of GDs, because different processes would preferentially cause certain types of reactions in the tree-ring record.

Recent advances in dendrogeomorphology have also demonstrated that the selection of trees and an adequate mixture of species and age classes are fundamental for the reconstruction of well-balanced and minimally biased time series of past geomorphic activity (Trappmann and Stoffel 2013). Finally, the definition of events will need to be based on adequate absolute (GDs) and relative (*It*) numbers of trees with simultaneous growth disturbances to reconstruct geomorphic events from the tree-ring series (Stoffel *et al.* 2013a). Together with the optimization of minimum sample sizes, a more systematic definition, identification and weighting of GDs in dendrogeomorphology will ultimately lead to more robust, comparable and more reliable time series in the future, and thereby help to promote dendrogeomorphic techniques even further.

ACKNOWLEDGMENTS

The authors are indebted to Associate Editor Håkan Grudd, John (Jack) Shroder and three anonymous reviewers for insightful comments and constructive feedbacks on an earlier version of the manuscript.

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Received 15 April 2013; accepted 1 August 2013.