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ORIGINAL ARTICLE

Debris-flow activity along a torrent in the Swiss Alps: Minimum frequency of events and implications for forest dynamics

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Abstract

This study reports on a tree-ring-based reconstruction of geomorphic activity and illustrates impacts of such processes on tree germination along a debris-flow torrent in the Swiss Alps. Analysis included the identification of growth disturbances and the assessment of germination dates for 28 trees along the channel of the Geisstriftbach torrent (Valais, Swiss Alps). Provided that recolonizing trees indicate the minimum time elapsed since the last deposition, germination dates suggest that a devastating debris-flow event in the 1880s had cleared the surface and scoured the currently active channel. This interpretation is supported by two topographic maps showing a dislocation of the channel. Analyzing the age structure of trees along the channel in more detail, we observe higher tree ages with increasing distance from the cone apex. In addition, dendrogeomorphic methods allowed for the reconstruction of 13 debris-flow events between AD 1913 and 2006. In combination with geomorphic mapping, the spatial distribution of trees affected by individual events was assessed and a minimum frequency of previous debris-flow events reconstructed. Although the present study was based on a limited set of tree-ring records, it illustrates that tree-ring analysis in combination with cartographic methods holds much promise for dating minimum ages of surfaces cleared by destructive events as well as for determining the spatio-temporal impacts of past debris-flow activity.

Keywords: Dendrogeomorphology; Mountain forest; Germination; Disturbance events; *Larix decidua* Mill.; *Picea abies* (L.) Karst.

Introduction

Mountain forests provide many ecosystem goods and services worldwide (Huber et al., 2005), among others by protecting human infrastructure from gravitational natural hazards such as snow avalanches and rockfall (Frehner et al., 2005). At the same time, mountain forests are subject to harsh growth conditions, which render them susceptible to natural and anthropogenic disturbances (Ott et al., 1997; Körner, 2003). For example, in many countries of the temperate zone, current mountain forests carry the legacies of past over-exploitation, being characterized by even-aged stands that are particularly susceptible to disturbance agents. An in-depth understanding of future forest dynamics and the

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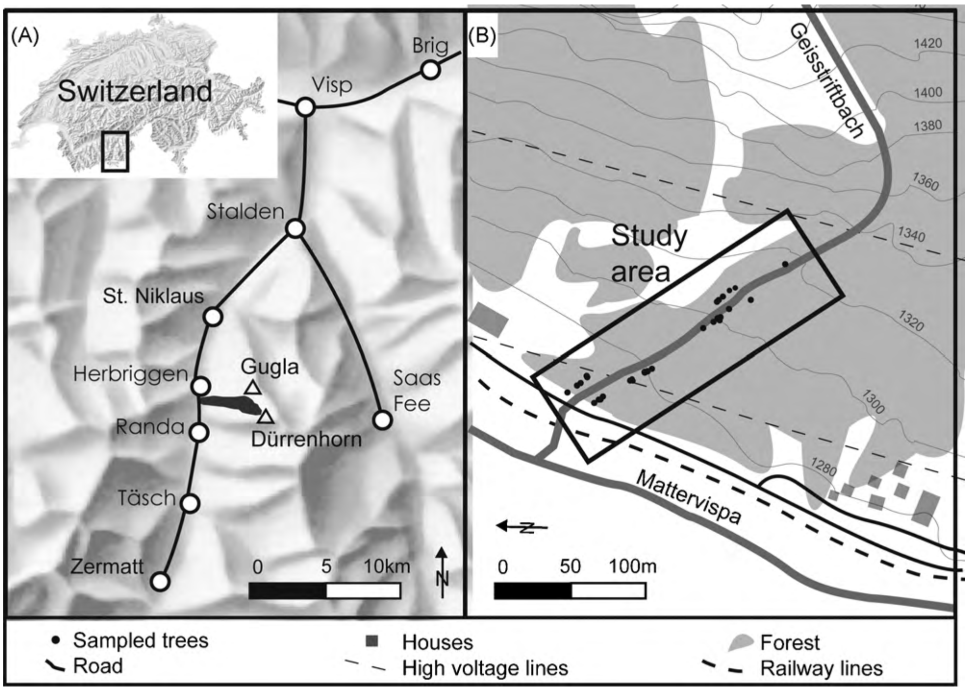

Fig. 1. (A) The catchment area of the Geisstriftbach torrent is located in the southern Swiss Alps (Valais) between the settlements of Herbriggen and Randa. (B) Sketch map of the study area and position of trees sampled along the channel of the Geisstriftbach.

derivation of appropriate management regimes for protective forests are thus issues that are of key interest both scientifically and practically.

For a long time, forest dynamics have been viewed as being determined mainly by intrinsic processes such as growth and competition (Bormann and Likens, 1979). In recent years, a shift has occurred towards a view that explicitly acknowledges the importance of external, large-scale disturbances such as fires, insect attacks or windthrow. Data characterizing the natural disturbance regime in forest ecosystems at the regional scale originate mainly from tree-ring reconstructions (Swetnam and Lynch, 1993; Barton et al., 2001). As a consequence, the detection of growth disturbances of trees has become a central and widely applied method for reconstructing the disturbance history of forests (Bergeron et al., 2002; Rubino and McCarthyz, 2004).

Small-scale disturbances affecting individual stands can, in contrast, also be caused by geomorphic activity (Frelich, 2002; Schumacher, 2004), with debris flows representing one of the predominant mass-movement processes on mountain slopes (Blijenberg, 1998; Jakob and Hungr, 2005). The spatial extent, frequency and intensity of debris flows can strongly determine mountain forest dynamics, as single trees or entire stands can be injured, buried or even removed by debris-flow activity (Jackson, 1987; Jackson et al., 1989; Wilkerson and Schmid, 2003). In Switzerland alone, damage on infrastructure caused by geomorphic processes exceeds US$ 300 million year^{-1} (BAFU, 2008).

Similar to large-scale disturbance events, the activity of various geological and geomorphic processes has repeatedly been reconstructed with dendrochronological methods (Alestalo, 1971; Stoffel et al., 2010). In debris-flow research, tree-ring reconstructions allow for the determination of the frequency (Stoffel et al., 2008), magnitude (Stoffel, 2010), spatial patterns (Bollschweiler et al., 2007), meteorological triggers (Pelfini and Santilli, 2008; Bollschweiler and Stoffel, in press) or seasonality of debris flows (Stoffel and Beniston, 2006). In a similar way, the assessment of germination dates of trees colonizing debris-flow deposits provides evidence regarding the timing of the last event (Baumann and Kaiser, 1999; Bollschweiler et al., 2008a).

While previous research using tree-ring series for the analysis of past geomorphic activity has focused primarily on process dynamics and land-forming processes, the impact of geomorphic activity on tree germination has been widely neglected to date. In this sense, data on the effect of mass-wasting disturbance appears to be crucial for the understanding of the implications on the forest ecosystem (Wells et al., 1998), but this aspect has not been addressed for sites affected by geomorphic processes so far.

Thus, the goals of this preliminary study are (i) to date the timing of colonization of surfaces cleared by former debris-flow activity, (ii) to assess the nature of growth disturbances in trees that are regularly affected by debris flows, and (iii) to reconstruct the frequency and spatial impact of disturbance events on trees, using a debris-flow channel in the Swiss Alps as a case study.

Study site

The study was conducted along the debris-flow channel of the Geisstriftbach torrent, located on the west-facing slope of the Mattertal Valley (Valais, Switzerland, 46°07′N/7°47′E; Fig. 1). The catchment area of the Geisstriftbach totals 5 km^2 and extends from the Gugla (3377 m a.s.l.) and Dürrenhorn summits (4035 m a.s.l.) to its confluence with the Mattervispa river at 1260 m a.s.l. The considerable gradient between the source area and the cone results in steep torrent topography. The upper part of the catchment is dominated by gneissic rocks belonging to the crystalline Mischabel unit (Labhart, 1998), while in the lower part, debris originating from various gravitational processes such as rockslides and rockfall covers bedrock. A major part of the upper catchment is located above tree line and is characterized by steep slopes with scarce vegetation.

The debris-flow cone extends from 1270 to 1350 m a.s.l. and is covered by a forest composed primarily of pioneer trees. In the upper part of the cone, European rowan (*Sorbus aucuparia* L.) and silver birch (*Betula pendula* Roth.) cover the debris-flow material, whereas in the lower part, conifers such as European larch (*Larix decidua* Mill.) and Norway spruce (*Picea abies* (L.) Karst.) are dominant. Most trees on the cone show morphological evidence of past debris-flow activity.

Anthropogenic influence on the cone is most pronounced in its northern part today, where the land is used as pasture, but it can be assumed that pasture activity was much more intense and widespread in the last decades. The main road and railway line connecting Zermatt to Visp is located on the lowermost part of the debris-flow cone, where the Geisstriftbach torrent merges into the Mattervispa river.

Data on past debris-flow activity in the Geisstriftbach is scarce and covers the past three decades only (1978, 1993 and 1997; SRCE, 2007). During the event in 1997, more than 30,000 m^3 of debris were mobilised from the periglacial departure zone.

Materials and methods

Geomorphic mapping and sampling design

In a first analytical step, all geomorphic features and deposits associated with past debris-flow events originating from the active channel of the Geisstriftbach were mapped at a scale of 1:1000. The map was based on detailed measurements using compass, measuring tape and inclinometer.

Along the currently active debris-flow channel, *L. decidua* and *P. abies* trees disturbed by previous debris-flow events were cored using increment borers or cross-cut with a chainsaw. Within this study, we selected trees showing scars, candelabra growth, exposed root systems as well as buried or tilted trunks that resulted from the impact of past debris flows. As a rule, two cores per tree were extracted, one in the flow direction, the other on the opposite side of the trunk. Sampling height was chosen according to trunk morphology. Tilted or injured trees were sampled at the height of the disturbance, whereas topped or buried trees were cored as close to the ground as possible to gather a maximum of information. Only trees with a diameter at breast height above 10 cm and with no apparent signs of impacts other than debris flows (e.g., snow avalanches, human activity) were selected (Jakob et al., 2005; Stoffel and Bollschweiler, 2008, 2009). In total, 28 heavily affected *L. decidua* (26 trees) and *P. abies* (2 trees) were sampled (54 cores and 7 cross-sections). The position of the sampled trees was indicated on the geomorphic map, and the characteristics of sampled trees were noted to support the further analysis.

Dendrochronological analysis

In the laboratory, trees were analyzed following standard dendrochronological procedures (Bräker, 2002; Stoffel and Bollschweiler, 2008). Individual steps included surface preparation, counting of tree rings, measuring of tree-ring widths using a LINTAB measuring table and TSAP 4.63 (Heidelberg, Germany). Growth curves of trees were then cross-dated with a reference chronology from a neighboring torrent (Bollschweiler et al., 2008a) so as to separate abrupt growth changes resulting from larch budmoth outbreaks or climatic extremes from growth anomalies induced by debris flows (Cook and Kairiukstis, 1990; Vaganov et al., 2006).

Minimum age dating and recolonization

Minimum age of geomorphic forms can be retrieved from cross-dated tree-ring series with relatively high accuracy, if sampling height and ecesis corrections are taken into account (Desloges and Ryder, 1990; McCarthy et al., 1991; Lewis and Smith, 2004; Koch, 2009). We assumed that trees at our study site successfully germinate within a few years after a debris-flow event (personal observations and L. Jörger, *verbatim*). Tree germination rates on geomorphic forms are best determined by counting the annual growth rings in a cross-section taken at the germination level (McCarthy et al., 1991). However, stem burial, branches, obstacles or rot did not normally allow sampling at germination level. In this study, sampling positions ranged from 0.2 to 1.1 m above ground level, to which an average of 0.5 m was added to account for the burial height (DesRochers and Gagnon, 1997). To compensate for the time elapsed from germination until a tree reached sampling height, we added an age correction factor. Age at sampling height was estimated in comparison to nearby *L. decidua* with according heights, for which the age could be easily determined by counting branch whorls. Whenever the pith was not present on the core, we estimated the number of missing rings using a transparent sheet with concentric rings (Bosch and Gutierrez, 1999).

Assessment of growth disturbances and reconstruction of events

Tree-ring series were analyzed visually so as to identify growth disturbances caused by past debris-flow events. The analysis of ring-width series as well as the visual inspection of samples was used to determine abrupt growth suppression after topping, stem burial or root exposure as well as sudden growth releases in survivor trees after the elimination of competitors (Butler, 1979). Similar to Nowacki and Abrams (1997), abrupt growth changes were taken into account if the difference in ring width following an event trespassed a certain threshold as compared to growth before the disturbance. In the present study, increment had to be (i) >50% below or >200% above the pre-event values and (ii) the change had to last for at least four years.

Changes in anatomy were investigated to obtain further evidence of debris-flow activity. This procedure included the identification of compression wood after stem tilting (Giardino et al., 1984; Fantucci and Sorriso-Valvo, 1999) as well as tangential rows of resin ducts (Bollschweiler et al., 2008b; Stoffel, 2008; Stoffel and Hitz, 2008) and callus tissue bordering the injuries (Schneuwly and Stoffel, 2008; Schneuwly et al., 2009a,b). If resin ducts were formed in early earlywood, we considered them to be a consequence of avalanche activity and did not account for them.

The identification of past debris flows was based on the number of sampled trees that simultaneously showed growth reactions. We further took into account the spatial distribution of the affected trees along the channel. Strong and abrupt growth reactions were assumed to reflect a debris-flow event as soon as they were clearly present in at least five trees.

Results

Recolonization of levees and age structure of tree population

All sampled trees colonized the two levees (i.e. lateral deposits bordering a debris-flow channel) of the Geisstriftbach torrent after AD 1880. The mean age of trees standing along the channel amounts to 80 years (STDEV: 28.3 years), with the oldest specimen germinating in the 1880s and the youngest individual establishing on the debris-flow deposits – from those thicker than 10 cm in 2006 – in the 1960s. Germination dates are given in Fig. 2, indicating that most trees established at the turn of the nineteenth and twentieth century.

Fig. 2 illustrates that trees tend to be older with increasing distance from the cone apex. While all trees sampled in the lower part of the channel germinated before 1920, it is noteworthy that the trees currently present in the upper section established on the debris-flow deposits after 1930 only.

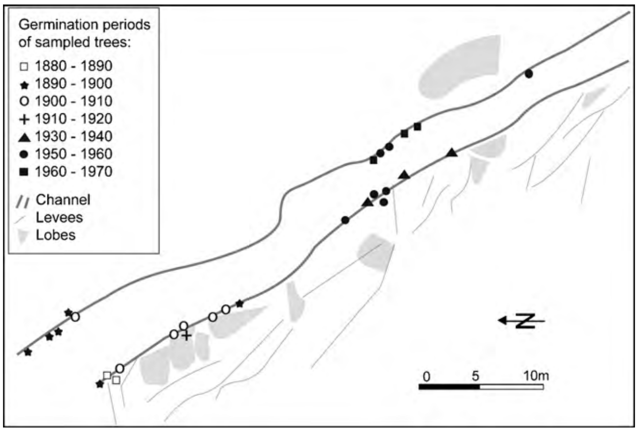

Fig. 2. Tree ages along the Geisstriftbach torrents. Trees in the lower part of the channel germinated between 1880 and 1920, trees in the upper part between 1930 and 1970.

Growth reactions of trees to debris flows

As only disturbed trees were selected for analysis, they all show clear signs of former debris-flow activity. In total, 69 visible growth defects were observed in the 28 trees sampled (Table 1). All trees chosen for analysis were tilted, presumably due to (i) the strong forces exerted by passing surges, (ii) the deposition of debris-flow material or (iii) the destabilization of trees growing at the channel banks. Other defects that were observed regularly in the trees included trunk burial (16 trees) and injuries (14 trees), which clearly resulted from debris-flow events. In addition, six trees had part of their roots exposed, and two specimens were found topped, leading to a tree morphology known as “candelabra growth”. Partly decomposed stumps found in the vicinity of three trees further indicate that competitor trees have been eliminated by former debris-flow activity.

Trees reacted to past debris-flow activity with anomalous growth and specific anatomical features. Table 1 shows that tangential rows of traumatic resin ducts are the most common growth reaction of *L. decidua* and *P. abies* to geomorphic disturbance; they represent more than one-third of the 200 debris-flow signatures identified in the tree-ring series. The presence of compression wood and abrupt growth suppressions were two other important features that each constituted one-fifth of all reactions. Abrupt growth releases resulting from the elimination of competitor trees were observed in 13% of the trees, and the formation of callus tissue amounted to 4% of growth reactions.

Fig. 3 provides an example of a *L. decidua* tree sampled in the lower part of the channel. A visual analysis of the cross-section as well as ring-width measurements clearly revealed signs of past debris-flow activity. During a debris-flow event in 1957, this tree was injured and tilted. As a result, the wound was closed on the upslope side, and the tree formed compression wood on the downslope side of the trunk.

Table 1. Former debris-flow activity left 69 visible growth defects and caused 200 growth reactions in 28 trees sampled along the Geisstriftbach torrent.

Event (visible defects)	Trees affected	% of visible defects
Tilting	28	41
Stem burial	16	23
Injury	14	20
Exposure of roots	6	9
Elimination of competitors	3	4
Topped trees	2	3
Total	69	100
Response (growth reactions)	**Trees affected**	**% of total responses**
Tangential rows of traumatic resin ducts	74	37
Compression wood	41	20
Growth suppression	42	21
Growth release	25	13
Injury	10	5
Callus tissue	8	4
Total	200	100

Debris-flow frequency and sectors affected by events

We reconstructed 13 debris-flow events for the period AD 1913–2006 based on 69 visible growth defects and 200 growth disturbances observed in the 28 trees sampled. Table 2 and Fig. 3 clearly illustrate that individual debris-flow events may induce multiple reactions in a single tree, resulting in 5–38 growth reactions identified per debris-flow event. At the same time, it becomes obvious that not all trees were equally affected by any given event. On average, 31% of the trees were showing growth reactions after debris-flow activity.

It also appears from the data that debris flows did not equally affect the trees selected for analysis, and that differences exist depending on the elevation (i.e. lower vs. upper part of the channel) and on tree position (i.e. southern vs. northern channel levee). Those trees sampled in the lowermost part of the channel showed repeated signs of debris-flow activity since the beginning of the tree-ring-based reconstruction in 1913. Trees located in the upper part of the channel were considerably younger and debris flows occurring before the mid-twentieth century were therefore not recorded by these trees. Taking into account their shorter lifespan, these trees show more signs of geomorphic activity than trees in the lower part. Our data indicate that the trees growing on the southern levee in the lower part of the channel (1280 m a.s.l.) were disturbed by 11 out of 13 debris-flow events. Other trees growing in the lower part (1300 m a.s.l.), but on the northern levee show growth anomalies for five out of six debris flows after 1970.

Disturbance events caused by individual debris flows can be categorized into different spatial patterns, with subsequent events regularly affecting the same group of trees. Fig. 4A demonstrates that a debris-flow event in 1957 left signs only in 6 out of 18 trees growing in the southern levee, but did not apparently cause growth defects to trees standing

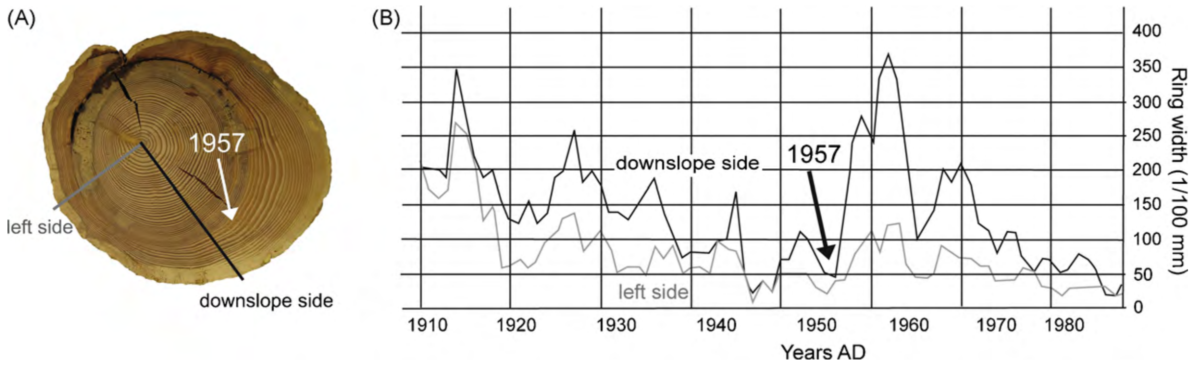

Fig. 3. (A) Cross-section and (B) growth curves of a heavily affected *Larix decidua* Mill. During a debris-flow event in 1957, the tree was injured and tilted by a debris-flow event. As a result, the wound was closed on the upslope side and the tree formed compression wood on the downslope side of the trunk. The growth reduction in 1966 originates from a larch budmoth year.

Table 2. The reconstruction of debris-flow events along the Geisstriftbach torrent covers the period AD 1913–2006 and was based on the dating of growth disturbances in 28 trees (26 *Larix decidua* Mill. and 2 *Picea abies* (L.) Karst.). Growth disturbances identified on increment cores and cross-sections included tangential rows of traumatic resin ducts (TRD), injuries (i), compression wood (cw), growth suppression (gs), growth release (gr) and callus tissue (ct).

Event	Sample depth	Trees affected	% of trees affected	Nature of growth disturbances						
				TRD	i	cw	gs	gr	ct	Total
2002	28	9	32	3		1	6			10
1997	28	12	43	5		4	1	5		15
1992	28	14	50	18	3	4	4	5	4	38
1991	28	5	18	3	1	2		1		7
1978	28	10	36	3	1	7	2	3		16
1971	28	14	50	3		7	7	1	2	20
1968	27	6	22	3		1	1	3		8
1960	18	9	50	9	2	2	4	1	2	20
1957	18	6	33	4	1	1	3	3		12
1945	16	7	44	1	1	3	2			7
1935	15	6	40	5		1	1	2		9
1920	14	3	21	3		1	1			5
1919	14	7	50	3		4	7			14

in the northern levee of the channel. A similar distribution of disturbed trees was reconstructed for the previous and subsequent events (1945 and 1960). During a debris-flow event in 1997, in contrast, 12 out of 28 trees in all parts along both levees of the channel were affected (Fig. 4B). Although being present since the 1950s, the isolated tree sampled in the uppermost part of the channel reacted to the 1997 event only, and not to the others reconstructed for the last 50 years.

Discussion

In this study, we report on a tree-ring-based reconstruction of geomorphic events and implications for tree germination along a debris-flow torrent in the Valais Alps (Switzerland). Based on a rather limited number of trees (26 *Larix decidua* Mill., 2 *Picea abies* (L.) Karst.), we (i) approximated tree ages, (ii) assessed reactions of trees affected by debris flows and (iii) reconstructed the frequency and spatial impact of debris flows in the stand. Being able to survive repeated debris-flow activity, *L. decidua* is an important tree species in protection forests.

Many tree species are suitable for dendrochronological purposes (e.g., Astrade and Begin, 1997; Stoffel et al., 2010), but *L. decidua* features some outstanding characteristics. Like other conifers, *L. decidua* forms tangential rows of traumatic resin ducts following mechanical disturbance, allowing for the exact dating of former debris-flow events (Stoffel, 2008). Its thick bark and the rapid closure of wounds (Stoffel and Perret, 2006) increase the resistance to exogenic geomorphic disturbances, so that *L. decidua* is able to survive repeated debris-flow activity over a long period.

Germination dates were assessed from tree-ring series of individuals colonizing the two levees. Taking into account the

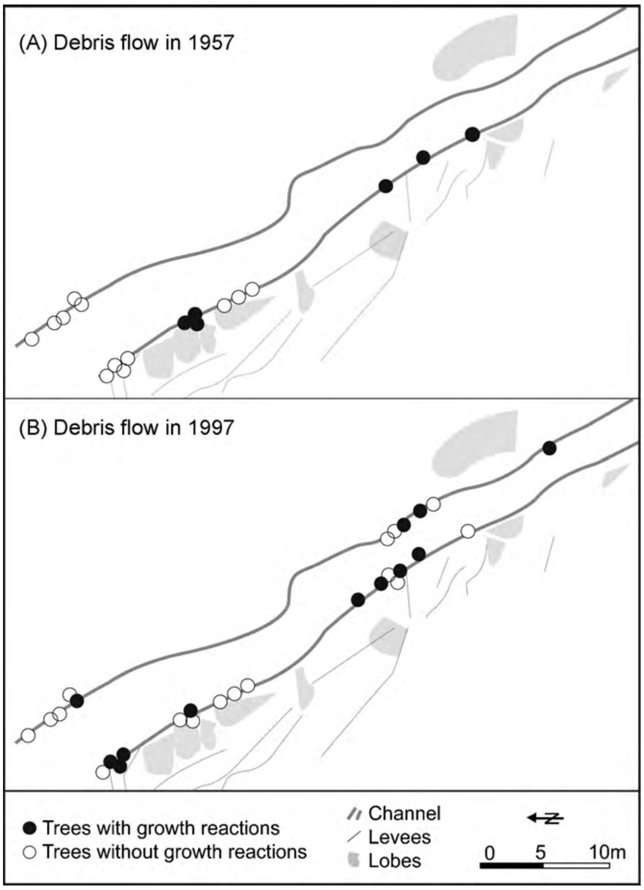

Fig. 4. Spatial patterns of debris-flow events in 1957 and 1997. (A) In 1957, only trees on the left side of the channel showed growth reactions to the debris-flow event. (B) In 1997, trees on both sides all along the channel have been affected.

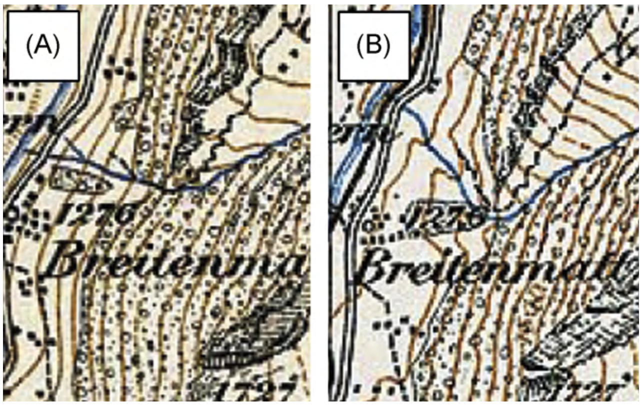

Fig. 5. Germination dates of the sampled trees suggest that a devastating debris-flow event in the 1880s had cleared the surface and scoured the currently active channel. This interpretation is supported by topographical maps from 1881 to 1891, which show a dislocation of the channel (Swisstopo, 2006).

time elapsed between tree germination and the time needed for the trees to reach sampling height, we added a locally observed average tree age at sampling height, thus respecting accelerated juvenile growth.

The time elapsing between the deposition of material by a debris flow and the actual colonization of the bare surfaces by tree seedlings varies between a single year and several years up to decades (Yoshida et al., 1997; Koch, 2009). This uncertainty cannot be reduced further, as it is an inherent element of the methodology. At our study site, there is clear observational evidence that recently cleared surfaces are recolonized by pioneer species such as *L. decidua* and *Betula pendula* Roth. within only a few years after geomorphic events (personal observations and L. Jörger, *verbatim*). This rather short germination lag time (ecesis) is most likely due to favourable climatic and soil conditions such as low elevation and substantial input of fine-textured material, but it is also the result of abundant seed sources in nearby forests.

Based on the germination dates of the oldest trees sampled along the channel, we suggest that a devastating debris flow must have occurred in the early 1880s, eliminating the former stand in the area of the current channel. This interpretation is supported by two topographical maps dating back to 1881 and 1891 (Fig. 5, Swisstopo, 2006), where a dislocation of the debris-flow channel on the cone is evident, changing its course from an east–west to the current southeast–northwest direction. Such drastic changes in the flow direction are often associated with major debris-flow activity, which apparently occurred in the Geisstriftbach torrent sometimes between 1881 and 1891.

In addition, debris flows strongly determine individual tree growth and stand dynamics. For trees along the Geisstriftbach torrent, we propose that succession is hampered repeatedly by debris flows in the upper part of the channel, and that trees are fairly easily removed by incidents. In contrast, debris-flow activity appears to have a less devastating and disturbing effect on trees with increasing distance from the cone apex, where slope gradients are considerably smaller and the impacts of individual debris-flow surges less severe. Besides the fact that trees are much younger in the upper part with germination dates between 1930 and 1970, they have also been disturbed more frequently. Close to the cone apex, only a few *L. decidua* were able to colonize and broadleaved pioneer trees such as *Sorbus aucuparuia* L. and *B. pendula* are dominant today. Thus, the assessment of tree germination dates provides – with all limitations involved due to the rather limited sample size – an independent line of evidence supporting a causal basis for the correlation of higher tree age with increasing distance from the source of debris-flow activity (Bollschweiler et al., 2008b).

The age structure of trees sampled along the Geisstriftbach torrent also indicates that trees are initially growing up in cohorts, but that only single trees manage to outgrow competitors. This growth pattern is one of the reasons for the clumped distribution of even-aged trees along the channel. Typical succession in the sub-alpine area with predominance of conifers usually begins with fast-establishing *L. decidua* on raw soil (Frehner et al., 2005). Protected from gliding and sliding snow, *P. abies* then begins to regenerate and gradually replaces *L. decidua* if growth conditions are stable (Frehner et al., 2005). However, this change of tree species only partially occurs along Geisstriftbach torrent as succession is repeatedly thrown back to the initial stages after devastating debris-flow events. Under such unsteady growth conditions, *L. decidua* should be promoted actively, as it is a tree species highly adapted to external disturbances (Frehner et al., 2005).

The analysis of the growth disturbances of 26 heavily affected *L. decidua* and 2 *P. abies* allowed for an identification of 13 debris flows along the Geisstriftbach torrent for the period AD 1913–2006. But we need to bear in mind that the debris-flow frequency provided in this study only represents the minimum number of events that have occurred in the Geisstriftbach torrent in the period investigated, because (i) the number of trees selected is rather small, (ii) because we exclusively sampled trees along the torrent and thus may have overlooked part of the events and as (iii) individual events may have been contained within the channel, i.e. without disturbing any trees in the levees and on the cone. Similarly, the time elapsed between individual events is quite regular and does not provide any clear evidence for an increase or decrease in debris-flow frequency, although such changes have been put forward as an early indicator of global change (Jomelli et al., 2004; Stoffel and Beniston, 2006; Bollschweiler and Stoffel, in press). Due to the restricted sample depth, implications for forest dynamics are limited.

Lastly, the position of repeatedly disturbed trees provides evidence regarding preferential breakout locations of debris flows along the torrent. For example, due to frequent disturbances reconstructed in the trees sampled at ∼1280 m a.s.l. along the southern levee, this area can be considered to be such a preferential breakout location. Even though disturbance intensity is higher near the cone apex, trees in the lower part along the Geisstriftbach torrent have also been repeatedly and recently affected by debris flows. The road connecting Zermatt to Visp has several times been harmed during debris-flow events (SRCE, 2007), which reinforces the need to further study the frequency and magnitude of debris-flow events in the Geisstriftbach torrent.

Conclusion

Dendrogeomorphic methods allowed for a dating of the recolonization of surfaces cleared by a major debris-flow event in the 1880s and for a reconstruction of 13 debris flows following this devastating event. In combination with geomorphic and topographic maps, the methods applied proved to be suitable for investigating (i) disturbance effects on trees after minor debris-flow events as well as (ii) patterns of tree recolonization after major geomorphic disturbances.

Surviving repeated debris-flow activity, *L. decidua* shows once more to be highly adapted to environments that are regularly affected by geomorphic disturbance events. It should therefore be promoted in protection forests to maximize the persistence and sustainability of the stand structure. Further investigations are, however, needed to quantify the protective effect of *L. decidua* stands against debris flows.

Through the combined analysis of growth defects in trees with minimum age dating of deposits, we were able to determine debris-flow events with a spatially limited impact on trees as well as devastating activity eliminating parts of the stand. We thus suggest that the approach applied here is highly suitable for investigating the impacts of debris flows on forest dynamics and for reconstructing the minimum frequency of debris-flow activity along a torrent.

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References

Alestalo, J., 1971. Dendrochronological interpretation of geomorphic processes. Fennia 105, 1–139.

Astrade, L., Begin, Y., 1997. Tree-ring response of *Populus tremula* L and *Quercus robur* L to recent spring floods of the Saone River, France. Ecoscience 4, 232–239.

BAFU, 2008. Schäden durch Hochwasser, Murgänge, Erdrutsche. http://www.bafu.admin.ch.

Barton, A.M., Swetnam, T.W., Baisan, C.H., 2001. Arizona pine (*Pinus arizonica*) stand dynamics: local and regional factors in a fire-prone madrean gallery forest of Southeast, Arizona, USA. Landscape Ecology 16, 351–369.

Baumann, F., Kaiser, K.F., 1999. The Multetta debris fan, Eastern Swiss Alps: a 500-year debris flow chronology. Arctic, Antarctic, and Alpine Research 31, 128–134.

Bergeron, Y., Denneler, B., Charron, D., Girardin, M.-P., 2002. Using dendrochronology to reconstruct disturbance and forest dynamics around Lake Duparquet, northwestern Quebec. Dendrochronologia 20, 175–189.

Blijenberg, H.M., 1998. Rolling stones? Triggering and frequency of hillslope debris flows in the Bachelard Valley, southern French Alps. PhD Thesis. University of Utrecht.

Bollschweiler, M., Stoffel, M., in press. Changes and trends in debris-flow frequency since A.D. 1850 – results from the Swiss Alps. The Holocene.

Bollschweiler, M., Stoffel, M., Ehmisch, M., Monbaron, M., 2007. Reconstructing spatio-temporal patterns of debris-flow activity using dendrogeomorphological methods. Geomorphology 87, 337–351.

Bollschweiler, M., Stoffel, M., Schneuwly, D.M., 2008a. Dynamics in debris-flow activity on a forested cone – a case study using different dendroecological approaches. Catena 72, 67–78.

Bollschweiler, M., Stoffel, M., Schneuwly, D.M., Bourqui, K., 2008b. Traumatic resin ducts in *Larix decidua* trees impacted by debris flows. Tree Physiology 28, 255–263.

Bormann, F.H., Likens, G.E., 1979. Catastrophic disturbance and the steady state in northern hardwood forests. American Scientist 67, 660–669.

Bosch, O., Gutierrez, E., 1999. La sucésion en los bosques de *Pinus uncinata* del Pirineo. De los anillos de crecimiento a la historia del bosque. Ecologia 13, 133–171.

Bräker, O.U., 2002. Measuring and data processing in tree-ring research – a methodological introduction. Dendrochronologia 20, 203–216.

Butler, D.R., 1979. Snow avalanche path terrain and vegetation, Glacier National Park, Montana. Arctic and Alpine Research 11, 17–32.

Cook, E.R., Kairiukstis, L.A., 1990. Methods of Dendrochronology – Applications in the Environmental Sciences. Kluwer, London, 414 pp.

Desloges, J.R., Ryder, J.M., 1990. Neoglacial history of the Coast Mountains near Bella-Coola, British-Columbia. Canadian Journal of Earth Sciences 27, 281–290.

DesRochers, A., Gagnon, R., 1997. Is ring count at ground level a good estimation of black spruce age? Canadian Journal of Forest Research 27, 1263–1267.

Fantucci, R., Sorriso-Valvo, M., 1999. Dendrogeomorpholigical analysis of a slope near Lago, Calabria (Italy). Geomorphology 30, 165–174.

Frehner, M., Wasser, B., Schwitter, R., 2005. Nachhaltigkeit und Erfolgskontrolle im Schutzwald. Wegleitung für Pflegemassnahmen in Wäldern mit Schutzfunktion. Vollzug Umwelt, Bern, 564 pp.

Frelich, L.E., 2002. Forest Dynamics and Disturbance Regimes: Studies from Temperate Evergreen–Deciduous Forests. Cambridge University Press, Cambridge, 266 pp.

Giardino, J.R., Shroder, J.F., Lawson, M.P., 1984. Tree-ring analysis of movement of a rock-glacier complex on Mount Mestas, Colorado, USA. Arctic and Alpine Research 16, 299–309.

Huber, U.M., Bugmann, H.K.M., Reasoner, M.A. (Eds.), 2005. Global Change and Mountain Regions: An Overview of Current Knowledge. Springer, Berlin, Heidelberg, New York, 650 pp.

Jackson, J.L., 1987. Debris flow hazard in the Canadian Rocky Mountains. Geological Survey of Canada 86, 1–20.

Jackson, L.E., Hungr, O., Gardner, J.S., Mackay, C., 1989. Cathedral Mountain debris flows, Canada. Bulletin of Engineering Geology and the Environment 40, 35–54.

Jakob, M., Bovis, M., Oden, M., 2005. The significance of channel recharge rates for estimating debris-flow magnitude and frequency. Earth Surface Processes and Landforms 30, 755–766.

Jakob, M., Hungr, O., 2005. Debris-flow Hazards and Related Phenomena. Springer, Berlin, Heidelberg, New York, 739 pp.

Jomelli, V., Pech, V.P., Chochillon, C., Brunstein, D., 2004. Geomorphic variations of debris flows and recent climatic change in the French Alps. Climatic Change 64, 77–102.

Koch, J., 2009. Improving age estimates for late Holocene glacial landforms using dendrochronology – some examples from Garibaldi Provincial Park, British Columbia. Quaternary Geochronology 4, 130–139.

Körner, C., 2003. Alpine Plant Life – Functional Plant Ecology of High Mountain Ecosystems. Springer, Berlin, Heidelberg, New York, 374 pp.

Labhart, T.P., 1998. Geologie der Schweiz. Ott Verlag, Thun, 211 pp.

Lewis, D., Smith, D., 2004. Dendrochronological mass balance reconstruction, Strathcona Provincial Park, Vancouver Island, British Columbia, Canada. Arctic, Antarctic and Alpine Research 36, 598–606.

McCarthy, D.P., Luckman, B.H., Kelly, P.E., 1991. Sampling height–age error correction for spruce seedlings in glacial forefields, Canadian Cordillera. Arctic and Alpine Research 23, 451–455.

Nowacki, G.J., Abrams, M.D., 1997. Radial-growth averaging criteria for reconstructing disturbance histories from presettlement-origin oaks. Ecological Monographs 67, 225–249.

Ott, E., Frehner, M., Frey, H.U., Lüscher, P.U., 1997. Gebirgsnadelwälder. Ein praxisorientierter Leitfaden für eine standortgerechte Waldbehandlung. Paul Haupt, Bern, Stuttgart, Wien, 287 pp.

Pelfini, M., Santilli, M., 2008. Frequency of debris flows and their relation with precipitation: a case study in the Central Alps, Italy. Geomorphology 101, 721–730.

Rubino, D.L., McCarthyz, B.C., 2004. Comparative analysis of dendroecological methods used to assess disturbance events. Dendrochronologia 21, 97–115.

Schneuwly, D.M., Stoffel, M., 2008. Spatial analysis of rockfall activity, bounce heights and geomorphic changes over the last 50 years – a case study using dendrogeomorphology. Geomorphology 102, 522–531.

Schneuwly, D.M., Stoffel, M., Bollschweiler, M., 2009a. Formation and spread of callus tissue and tangential rows of resin ducts in *Larix decidua* and *Picea abies* following rockfall impacts. Tree Physiology 29, 281–289.

Schneuwly, D.M., Stoffel, M., Dorren, L.K.A., Berger, F., 2009b. Three-dimensional analysis of the anatomical growth response of European conifers to mechanical disturbance. Tree Physiology 29, 1247–1257.

Schumacher, S., 2004. The role of large-scale disturbances and climate for the dynamics of forested landscapes in the European Alps. PhD Thesis. Swiss Federal Institute of Technology, Zürich.

SRCE, 2007. Base de données des événements du Canton du Valais. Service des Routes et des Cours d'Eau, Sion.

Stoffel, M., 2008. Dating past geomorphic processes with tangential rows of traumatic resin ducts. Dendrochronologia 26, 53–60.

Stoffel, M., 2010. Magnitude–frequency relationships of debris flows – a case study based on field survey and tree-ring records. Geomorphology 116, 67–76.

Stoffel, M., Beniston, M., 2006. On the incidence of debris flows from the early Little Ice Age to a future greenhouse climate: a case study from the Swiss Alps. Geophysical Research Letters 33, L16404.

Stoffel, M., Bollschweiler, M., 2008. Tree-ring analysis in natural hazards research – an overview. Natural Hazards and Earth System Sciences 8, 187–202.

Stoffel, M., Bollschweiler, M., 2009. What tree rings can tell about earth-surface processes: teaching the principles of dendrogeomorphology. Geography Compass 3, 1013–1037.

Stoffel, M., Hitz, O.M., 2008. Rockfall and snow avalanche impacts leave different anatomical signatures in tree rings of juvenile *Larix decidua*. Tree Physiology 28, 1713–1720.

Stoffel, M., Perret, S., 2006. Reconstructing past rockfall activity with tree rings: some methodological considerations. Dendrochronologia 24, 1–15.

Stoffel, M., Bollschweiler, M., Butler, D.R., Luckman, B.H. (Eds.), 2010. Tree Rings and Natural Hazards: A State-of-the-Art. Springer, Berlin, Heidelberg, New York, 505 pp.

Stoffel, M., Conus, D., Grichting, M.A., Lièvre, I., Maître, G., 2008. Unraveling the patterns of late Holocene debris-flow activity on a cone in the Swiss Alps: chronology, environment and implications for the future. Global and Planetary Change 60, 222–234.

Swetnam, T.W., Lynch, A.M., 1993. Multicentury, ragional-scale patterns of western spruce budworm outbreaks. Ecological Monographs 63, 399–424.

Swisstopo, 2006. Mischabel (533). B.f. Landestopographie, Sigfriedkarten 1:50 000.

Vaganov, E.A., Hughes, M.K., Shashkin, A.V., 2006. Growth Dynamics of Conifer Tree Rings. Images of Past and Future Environments. Springer, Berlin, Heidelberg, New York, 354 pp.

Wells, A., Duncan, R., Stewart, G., 1998. Forest dynamics in Westland, New Zealand: the importance of large, infrequent earthquake-induced disturbance. Journal of Ecology 89, 1006–1018.

Wilkerson, F.D., Schmid, G.L., 2003. Debris flows in Glacier National Park, Montana: geomorphology and hazards. Geomorphology 55, 317–328.

Yoshida, K., Kikuchi, S., Nakamura, F., Noda, M., 1997. Dendrochronological analysis of debris flow disturbance on Rishiri Island. Geomorphology 20, 135–145.