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Mass movements and tree rings: A guide to dendrogeomorphic field sampling and dating

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ABSTRACT

Trees affected by mass movements record the evidence of geomorphic disturbance in the growth-ring series, and thereby provide a precise geochronological tool for the reconstruction of past activity of mass movement. The identification of past activity of processes was typically based on the presence of growth anomalies in affected trees and focused on the presence of scars, tilted or buried trunks, as well as on apex decapitation. For the analyses and interpretation of disturbances in tree-ring records, in contrast, clear guidelines have not been established, with largely differing or no thresholds used to distinguish signal from noise. At the same time, processes with a large spatial footprint (e.g., snow avalanches, landslides, or floods) will likely leave growth anomalies in a large number of trees, whereas a falling rock would only cause scars in one or a few trees along its trajectory.

Based on the above considerations, we examine issues relating to the interpretation and dendrogeomorphic dating of mass movements. Particular attention is drawn to sampling in terms of sample distribution across a study site, the actual selection of trees as well as to sample size (i.e., number of trees sampled). Based on case studies from snow avalanche, debris flow, and landslide sites, we demonstrate that thresholds can indeed improve dating quality and, at the same time, minimize noise in time series. We also conclude that different thresholds need to be used for different processes and different periods of the reconstruction, especially for the early stages of the reconstruction when the number of potentially responding trees will be much smaller. This paper seeks to set standards for dendrogeomorphic fieldwork, analysis, and interpretation for different processes of mass movements.

1. Introduction

Trees affected by mass movements record the evidence of geomorphic disturbance in the growth-ring series (Alestalo, 1971; Stoffel et al., 2010a). As a result, they potentially provide a precise geochronological tool for the reconstruction of the activity of past mass movements and, thus, have been used widely to reconstruct time series of various types of geomorphic (e.g., McAuliffe et al., 2006; Stoffel et al., 2008a,b, 2012; Bollschweiler et al., 2009; Lopez Saez et al., 2012a; Osterkamp et al., 2012), hydrological (St. George and Nielsen, 2002; Ballesteros et al., 2011a,b; Stoffel and Wilford, 2012), and geological (Jacoby et al., 1988; Stoffel et al., 2005a; Salzer and Hughes, 2007; Baillie, 2008; Bekker, 2010; Corona et al., in press—a) processes. The identification of past processes typically was based on the presence of growth anomalies in affected trees and, thereby, focused on the presence of scars, tilted or buried trunks, as well as on apex decapitation.

Trees record mechanical disturbance (i.e., impact, loading, burial or erosion; see Stoffel and Bollschweiler (2008) and references therein for details) to the year and even to the season under ideal circumstances (Bollschweiler et al., 2008a; Schneuwly and Stoffel, 2008a,b; Stoffel et al., 2008a; Schneuwly et al., 2009a,b), but typically fail to provide information on the nature of the process that caused the disturbance. Exceptionally, the nature of the mass movement can be reconstructed from the growth-ring record of affected trees based on the timing of the reaction. This is the case for snow avalanches occurring before the tree starts to form a new increment ring (with a reaction at the boundary of two rings) and high elevation debris flows in summer (i.e., somewhere between the earlywood and the latewood of the growth ring; Stoffel et al., 2006a). In addition, a distinction of processes can also be based on a wood-anatomical analysis of reactions induced by processes occurring at the same time of the year (e.g., rockfall and snow avalanches; Stoffel and Hitz, 2008). In any case, however, trees should only be sampled after careful evaluation of the study site

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and a detailed comprehension of processes occurring at the site under investigation.

Another critical issue in dendrogeomorphic investigations has been the interpretation of signals in the tree-ring record, for which clear guidance and guidelines have yet to be established. As a result, largely differing thresholds have been used in the past to distinguish signal from noise. Some studies have dated mass movement based on a single growth disturbance (GD) in just one tree, whereas other authors only added events to their reconstructed time series as soon as 40% of all trees sampled showed reactions in a specific year (Butler et al., 1987; Butler and Sawyer, 2008). As a consequence, these differences in thresholds have given rise to repeated and contentious discussions on the value, accuracy and completeness of dendrogeomorphic dating and, therefore, call for the definition of more objective standards and guidelines.

At the same time, evidence left in trunks, as well as the nature and extent of damage in trees, will ultimately be dictated by the nature of the mass movement itself (Stoffel and Perret, 2006; Stoffel et al., 2010a), implying that different thresholds should be defined for different types of mass movements. For processes with a large spatial footprint (such as landslides, floods, or snow avalanches), GD will likely be visible in a large number of trees; whereas an individual rockfall would only leave scars in one or a few trees along the fall line of the rock (Stoffel and Perret, 2006).

Based on the above considerations, this paper aims at (i) providing guidelines for the selection and dendrogeomorphic sampling of trees in the field and at (ii) examining issues relating to the interpretation and dating of mass movements based on information contained in growth-ring records. Particular attention is drawn to sampling in terms of the distribution of sampled trees across the study site, the actual selection of trees in the field as well as to sample size (i.e., number of trees sampled). Based on selected examples from snow avalanche, debris flow, and landslide sites in the European Alps, we demonstrate that the definition of thresholds is indeed needed to improve the quality of dating and to reduce faulty dating (noise) of events. In addition, we illustrate that different thresholds have to be defined for different types of mass movements and for different periods covered by the reconstruction, especially for the early (i.e., the oldest) stages of the time series for which the number of potentially responding trees will be much smaller than for the recent past. This paper, thus, seeks to establish a coherent set of standards for dendrogeomorphic fieldwork, analysis, and interpretation for different types of mass movement processes.

2. How and where to sample trees in the field

A careful dendrogeomorphic study typically starts with a detailed assessment and delineation of mass movement processes and anthropogenic activities in the field. This work should also involve analysis of diachronic time series of aerial photographs or satellite imagery. The initial assessment should then be complemented with a detailed geomorphic reconnaissance in the field and the mapping of geomorphic features and deposits at a scale appropriate for the purpose of the study. In the case of landslides, debris flows, lahars, and other torrential processes, mapping should be done at the finest scale possible (e.g., 1:1000), whereas a coarser scale and the identification of deposition or flooding areas might be sufficient for the analysis of snow avalanches, rockfall activity, or floods.

Best results are usually obtained when complex sectors of the study site, with geomorphic forms shaped by different mass movement processes, are excluded from analysis, as the nature of the damage normally will not allow identification of the causative process (Stoffel et al., 2006a; Stoffel and Hitz, 2008). The same holds true for doubtful damage (e.g., trees located close to roads or walking paths, possible influence of felling activity, scars induced by ungulate browsing) that should be excluded from analysis, as they tend to add noise to the reconstruction.

For those areas of the study site for which anomalies in tree morphology can be unambiguously attributed to the mass movement process under investigation, we would like to address some possible limitations and drawbacks of trees as recorders of past process activity to develop a series of criteria and guidelines for the best possible sampling in the field.

Trees with visible growth defects, be it in the morphology or in the form of visible scars, will tend to provide data on the more recent past, but not necessarily inform the researcher about the activity of mass movement in former times and, thereby, lead to an overestimation of the more recent activity. This is especially true for scars in conifers with ample and peeling bark, such as is the case of *Larix*, *Picea*, or *Pinus*, where damage has been demonstrated to be blurred fully after just a few decades (Stoffel and Perret, 2006).

Older trees, on the other hand, will produce decreasing ring widths with increasing tree age (as they have to allocate their resources to a steadily growing stem and branch surface) and thereby become less suitable and less sensitive recorders of mass movements, especially of events that occurred in the recent past. These trees will likely underestimate recent activity but will still represent excellent candidates for the reconstructions of events farther back in time (Stoffel and Beniston, 2006; Corona et al., in press—b).

Broadleaved trees do not normally live as long as conifers and, therefore, tend to be of limited help in the reconstruction of long time series. At the same time, however, they will be excellent recorders of recent activity (Arbellay et al., 2010b, 2012a,b; Moya et al., 2010; Ballesteros et al., 2011a,b), as many broadleaved species are characterized by relatively thin and smooth bark structures that will tend to record impacts of larger and smaller (or less energetic) events (Trappmann and Stoffel, 2013).

Based on the above considerations, we call for a balanced sampling of older and younger trees as well as for a mixture of conifer and broadleaved species. Trees selected for analysis should be distributed evenly across the study site and sampled in a systematic way. No preference should be given to trees with visible growth defects, but rather samples should be obtained (i) along vertical and/or horizontal transects on snow avalanche, landslide or rockfall sites or (ii) within a distance from the channel (defined by process at the site); and (iii) at specific radial distances from fan and cone apices (Schneuwly-Bollschweiler et al., in review) in the case of torrential and fluvial processes (e.g., floods, debris floods, debris flows, or lahars). The distance between each sampled tree, along the transect or between transects, will again be dictated by the nature of the process; detailed examples are provided in Section 4.

3. Features typically used to date past mass movements

Dendrogeomorphic investigations of mass movement processes typically focus on the occurrence of a limited number of specific GD in tree-ring records to date the occurrence of past events (see Stoffel and Corona (in review) for a detailed overview on tree reactions).

Among the GD used for the reconstruction of mass movement processes, scars (injuries; see Fig. 1A) are certainly one of the most frequently used indicators to infer mass movement. In addition to being the clearest evidence of past impacts, scars have also been demonstrated to allow annual dating and up to monthly resolution (e.g., Stoffel et al., 2005b, 2008a,b, 2011; Arbellay et al., 2010a; Schneuwly-Bollschweiler and Stoffel, 2012).

Certain conifer species — among others, the genus fir *(Abies)*, larch *(Larix)*, spruce *(Picea)*, and Douglas-fir (*Pseudotsuga*; Bannan, 1936; Stoffel, 2008), but not pine (*Pinus*; Ballesteros et al., 2010a) — will produce resin and associated tangential rows of traumatic resin ducts (TRD; Fig. 1B) around scars (Stoffel, 2008; Schneuwly et al., 2009a, b) so as to protect the unaffected wood from attacks by wood-decaying pathogens. The presence of TRD has, thus, been considered a valuable indicator for the dating of mechanical damage — even in the absence of visible wounds.