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Counting scars on tree stems to assess rockfall hazards: A low effort approach, but how reliable?

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ABSTRACT

Rockfall is a widespread and hazardous process in mountain environments, but data on past events are only rarely available. Growth-ring series from trees impacted by rockfall were successfully used in the past to overcome the lack of archival records. Dendrogeomorphic techniques have been demonstrated to allow very accurate dating and reconstruction of spatial and temporal rockfall activity, but the approach has been cited to be labor intensive and time consuming. In this study, we present a simplified method to quantify rockfall processes on forested slopes requiring less time and efforts. The approach is based on a counting of visible scars on the stem surface of Common beech (*Fagus sylvatica* L.). Data are presented from a site in the Inn valley (Austria), where rocks are frequently detached from an ~200-m-high, south-facing limestone cliff. We compare results obtained from (i) the "classical" analysis of growth disturbances in the tree-ring series of 33 Norway spruces (*Picea abies* (L.) Karst.) and (ii) data obtained with a scar count on the stem surface of 50 *F. sylvatica* trees.

A total of 277 rockfall events since A.D. 1819 could be reconstructed from tree-ring records of *P. abies*, whereas 1140 scars were observed on the stem surface of *F. sylvatica*. Absolute numbers of rockfalls (and hence return intervals) vary significantly between the approaches, and the mean number of rockfalls observed on the stem surface of *F. sylvatica* exceeds that of *P. abies* by a factor of 2.7. On the other hand, both methods yield comparable data on the spatial distribution of relative rockfall activity. Differences may be explained by a great portion of masked scars in *P. abies* and the conservation of signs of impacts on the stem of *F. sylvatica*. Besides, data indicate that several scars on the bark of *F. sylvatica* may stem from the same impact and thus lead to an overestimation of rockfall activity.

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1. Introduction

Rockfall is one of the most common geomorphic processes in steep mountain regions and therefore repeatedly threatens inhabited areas and transportation corridors (Stoffel et al., 2006). Several approaches have been developed in the past to determine rockfall hazards at different levels of detail. These range from direct observations of deposited material and inventories of past rockfall events over empirical models to predict maximal runout zones to two- and three-dimensional trajectory models (see Volkwein et al., 2011, for a recent review). However, major efforts are still required to quantify rockfall activity in terms of frequency and magnitude at the local scale, which is crucial for risk assessment, the choice of appropriate mitigation measures and for the validation of output from simulation runs (Stoffel et al., 2006; Dorren et al., 2007; Corona et al., in press).

Dendrogeomorphic techniques (Alestalo, 1971; Stoffel et al., 2010) have been used repeatedly on coniferous trees to provide absolute numbers on past rockfall activity and their spatial distribution (Stoffel et al., 2005a,b; Perret et al., 2006; Stoffel, 2006; Schneuwly and Stoffel, 2008). These studies were based on the identification of growth reactions in the tree-ring series that formed after mechanical disturbance caused by rock impacts. Detection of events was mostly indirect, e.g., through the identification of tangential rows of traumatic resin ducts as a proxy of stem injury (Schneuwly et al., 2009a). This classical approach has been demonstrated to allow very accurate dating of historic events (with up to monthly resolution; Stoffel et al., 2005a), but has not been used widely outside academia as it represents a labor- and time-intensive approach. Broadleaved trees have only been used recently to estimate rockfall activity (Moya et al., 2010; Šilhán et al., 2011), and events have been dated through the identification of growth disturbances within tree-ring series. Proxy indicators of scars inflicted by geomorphic processes have been described only recently for several broadleaved tree species (Arbellay et al., 2010, 2012; Ballesteros et al., 2010), but the complex wood structure has rendered tree-ring analyses of these natural archives challenging so far.

The conservation of scars and anatomical anomalies in the tree-ring record will depend on the tree species. Wood and bark properties cause a different vulnerability of trees, and their wood

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and bark structures may mask scars at different rates and with varying efficiency. Conifers are known to overgrow injuries within years to decades, and the peeling of bark structures can completely blur evidence of injuries (Stoffel and Perret, 2006). Some broadleaved trees are characterized by a thin and fragile bark and can therefore easily be damaged by falling rocks and boulders. Common beech (*Fagus sylvatica* L.) is especially susceptible to injuries as it only builds a relatively thin and soft periderm above comparably hard wood (xylem). Smooth-barked species such as *F. sylvatica* are also known to form a very thin layer of bark (secondary phloem) each year, and the initial cork cambium may persist for the lifetime of the tree without being peeled off (Bowes, 2010). As a consequence, signs of past rockfall impacts can be expected to remain visible for a long time or even for the entire lifespan of the tree.

This study therefore aims at presenting a new method for the quantification of past rockfalls that requires less time and efforts as compared to classical dendrogeomorphic approaches. Analysis is based on the counting of visible scars on the stem surface of *F. sylvatica*. Results are then compared with data obtained with a classical tree-ring approach using Norway spruce (*Picea abies* (L.) Karst.) from the same site. We demonstrate that reliable patterns of rockfall activity can be gathered with both approaches but that absolute numbers of reconstructed rockfalls vary considerably.

2. Study site

The study site selected for analysis is located at the foot of Hechenberg (47°16′11″N., 11°18′18″E.), a mountain close to the city of Innsbruck in the Inn valley (Tyrol, Austria) (Fig. 1). The source area of rockfall is a ~200-m-high, south-facing limestone cliff, followed by a steep (49°), ~200-m-long dolomite ramp with several small depressions that effectively channelize falling rock fragments. The study reach is located directly below the ramp and in the transit area (900–770 masl) with a mean gradient of 40°. The Hechenberg is located within the Austroalpine unit at the southern border of the northern Calcareous Alps (Egger et al., 1999). Main dolomite facies (Oberhauser et al., 1980) with a narrow joint system resulting from tectonic deformation leads to considerable fragmentation and small mean rock sizes, with edge lengths of only a few decimeters. As a result, block sizes of rockfall fragments only rarely exceed 1 m^3 at Hechenberg.

The investigated site has an area of 3 ha and is covered with a mixed forest stand, composed mainly of *P. abies*, *F. sylvatica*, and Scots pine (*Pinus sylvestris* L.). Adjacent to the lower part of the study site, the railway line connecting Innsbruck and Garmisch-Partenkirchen (Germany) crosses the slope. The line is protected by rockfall nets.

The chronicle of the Austrian Federal Railways reports frequent rockfall at Hechenberg, which is supposedly triggered by freeze-thaw processes and heavy precipitation events. Besides rockfall, debris flows have affected the railway line in the past. In the central part of the study reach, a shallow channel shows evidence of sporadic transport of small amounts of accumulated talus by fluvial transport or smaller debris-flow processes. Trees were not selected for analysis in the area affected by debris flows. Avalanches do not occur at the site.

3. Material and methods

In this study, two different approaches and species are used to assess spatial and temporal patterns of past rockfall activity. *P. abies* has been used successfully in the past to reconstruct rockfall activity and therefore serves here for comparison and validation of results obtained with *F. sylvatica*. The study reach was defined such that (i) both species are present at the same site and evenly distributed; (ii) rockfall activity results in numerous visible injuries on trees; and (iii) other processes causing damage to trees (e.g., logging, other geomorphic processes) can be excluded. To avoid systematic errors and bias, trees were selected randomly and regardless of the number of impacts. The *P. abies* trees were selected in three transects, parallel to the contour lines with one tree per 10 m. The *F. sylvatica* trees were selected in a raster of 20 m × 20 m to assure an even distribution of trees. Tree positions were determined with a measuring tape, compass, and inclinometer (scale 1:1000) and transferred into a geographical information system (GIS).

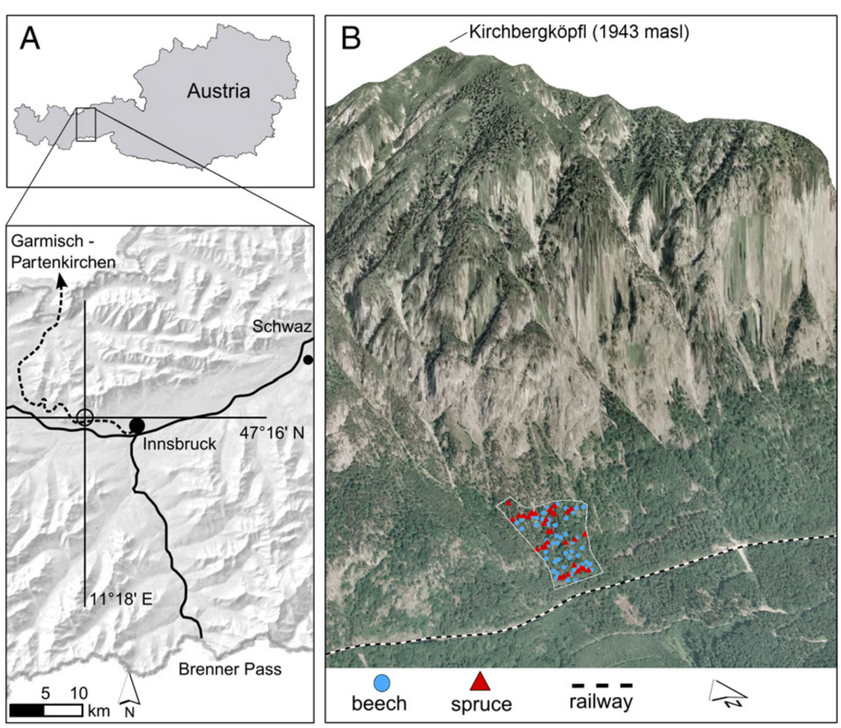

Fig. 1. (A) Location of the study site Hechenberg above the railway line in the Inn valley (Austria), and (B) three-dimensional view of the site with positions of sampled trees.

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