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Defining sample size and sampling strategy for dendrogeomorphic rockfall reconstructions

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ABSTRACT

Optimized sampling strategies have been recently proposed for dendrogeomorphic reconstructions of mass movements with a large spatial footprint, such as landslides, snow avalanches, and debris flows. Such guidelines have, by contrast, been largely missing for rockfalls and cannot be transposed owing to the sporadic nature of this process and the occurrence of individual rocks and boulders. Based on a data set of 314 European larch (*Larix decidua* Mill.) trees (i.e., 64 trees/ha), growing on an active rockfall slope, this study bridges this gap and proposes an optimized sampling strategy for the spatial and temporal reconstruction of rockfall activity. Using random extractions of trees, iterative mapping, and a stratified sampling strategy based on an arbitrary selection of trees, we investigate subsets of the full tree-ring data set to define optimal sample size and sampling design for the development of frequency maps of rockfall activity. Spatially, our results demonstrate that the sampling of only 6 representative trees per ha can be sufficient to yield a reasonable mapping of the spatial distribution of rockfall frequencies on a slope, especially if the oldest and most heavily affected individuals are included in the analysis. At the same time, however, sampling such a low number of trees risks causing significant errors especially if nonrepresentative trees are chosen for analysis. An increased number of samples therefore improves the quality of the frequency maps in this case. Temporally, we demonstrate that at least 40 trees/ha are needed to obtain reliable rockfall chronologies. These results will facilitate the design of future studies, decrease the cost–benefit ratio of dendrogeomorphic studies and thus will permit production of reliable reconstructions with reasonable temporal efforts.

1. Introduction

Threatening inhabited areas and traffic lines (Stoffel, 2006), rockfall represents one of the most frequent natural mass movement processes in mountainous areas. Rockfall can be defined as the free falling, bouncing, or rolling of rocks downslope that typically originate from cliffs or rockwalls (Varnes, 1978; Berger et al., 2002). On forested slopes, each rock impact on trees dissipates kinetic energy and may change the rock's trajectory and velocity, thus reducing runout distances as compared to nonforested slopes (Jahn, 1988; Dorren et al., 2005, 2007). Impacts also leave characteristic scars on tree trunks and growth disturbances (GD) in tree-ring series that have been proven to be a reliable, accurate and precise indicator to reconstruct past rockfall activity through dendrogeomorphic analysis (Alestalo, 1971; Stahle et al., 2003; Stoffel et al., 2005a, 2013; Stoffel and Bollschweiler, 2010; Stoffel and Corona, 2014).

Stoffel and Perret (2006) demonstrated that the use of systematic sampling methods — i.e., the coring of trees along linear transects with equal distances between each sampled tree irrespective of the presence of visible scars on its trunk — provides adequate data to derive a reconstruction of past rockfall events. While in the earliest studies a rather limited number of 25–30 samples was used typically for rockfall reconstructions (Gsteiger, 1989; Schweingruber, 1996), later work generally was based on much larger numbers of samples ranging from 135 to 283 trees (e.g., Stoffel et al., 2005b; Moya et al., 2010; Šilhán et al., 2013). Nevertheless, a clear guideline regarding the sample size needed to obtain reliable results still does not exist.

A suite of recent studies concluded that an appropriate sampling design and sample size is a fundamental requirement to improve the reliability of dendrogeomorphic reconstructions (Schneuwly-Bollschweiler et al., 2013; Trappmann et al., 2013). In the case of mass movements with a large spatial footprint, such as snow avalanches (Corona et al., 2012), landslides (Corona et al., 2014), and debris flows (Schneuwly-Bollschweiler et al., 2013), it has been demonstrated that a definition

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of sample size thresholds is possible and that such values permit assessment of realistic event frequencies with optimized cost–benefit ratios. Rockfall, in contrast, does not typically leave a clear spatial footprint as it usually damages a limited number of individual trees along its trajectory (Stoffel and Perret, 2006; Moya et al., 2010). As a consequence, the thresholds established for snow avalanches, landslides, and debris flows cannot be applied in this case as different thresholds and approaches need to be defined to obtain more reliable rockfall reconstructions and better input data for hazard zoning.

In order to fill this gap, this study aims to determine optimal sample sizes and optimal sampling strategy for dendrogeomorphic rockfall studies. Based on an unusually large data set of rockfall induced GD in trees growing on a slope in the Swiss Alps, we (i) test results based on different subsets of trees and (ii) characterize the optimal spatial configuration of trees to be sampled on the slope using random bootstrap extraction of trees from the data set. The same subsets were then used to (iii) explore the effect of sample size and tree selection on the reliability of reconstructed rockfall chronologies. Finally, (iv) the random extractions of trees have been compared with a stratified sampling strategy based on an arbitrary selection of trees so as to propose clear guidelines for the selection of optimal trees (in terms of tree location, age, number of GD, and frequency of GD).

2. Regional setting

The area investigated in this study is located in the Saas valley (Valais, Switzerland, 46° 05′41 N; 7° 57′17 E; Fig. 1) between 1670 and 1800 m asl. The slope under investigation (5 ha) has a north-eastern exposure and slope angles ranging from 14 to 49°. The source area of the rockfall site is formed by an active rock glacier at >2570 m asl. at the lower permafrost boundary as well as by subvertical rock faces downslope on the rock glacier. Based on rockfall deposits on the slope, roughly half of the rockfall deposits originate from the rock glacier (formed by quartzites), whereas the other half (gneisses and schists) is released from the rockwall. The rocks deposited in the study area have mean axes length of 0.57 m and a volume of 0.31 m^3.

The tree stand at the study site is mainly composed of European larch (*Larix decidua* Mill.), intermixed with young Cembran pine (*Pinus cembra* L.) and Norway spruce (*Picea abies* (L.) Karst.). The age distribution of trees (Fig. 1D) shows relatively young individuals (11–40 years) in the upper part of the slope, thus reflecting the influence of former cattle grazing. Rare snow avalanches may potentially have influenced the age distribution on the site as well, especially in the uppermost part where the rockfall couloir opens to form a relatively homogeneous talus slope. Based on geomorphic mapping and tree morphology at the site, however, rockfall is clearly the only relevant process causing damage to the trees sampled in this study. In the lower part of the slope as well as in its northern part, older trees can be found.

3. Material and methods

This study aims at defining optimal sample sizes and optimal sampling strategies for dendrogeomorphic rockfall reconstructions such that over- and undersampling of study sites can be avoided in the future. For the definition of an optimal sample size, we (i) initially carried out a dendrogeomorphic study sampling an unusually large number of trees to establish a virtually complete record of rockfall activity at the site and for the lifespan of the trees. In a next step, we (ii) investigated the effect of sample size and tree selection on reconstructed rockfall activity by randomly extracting subsets of trees with a stepwise increasing number of individuals (30–300) from the complete data set. Based on GD in trees from these subsets, frequency maps were generated and analyzed with respect to their matching with the frequency obtained from the full data set, which serves as a reference. The

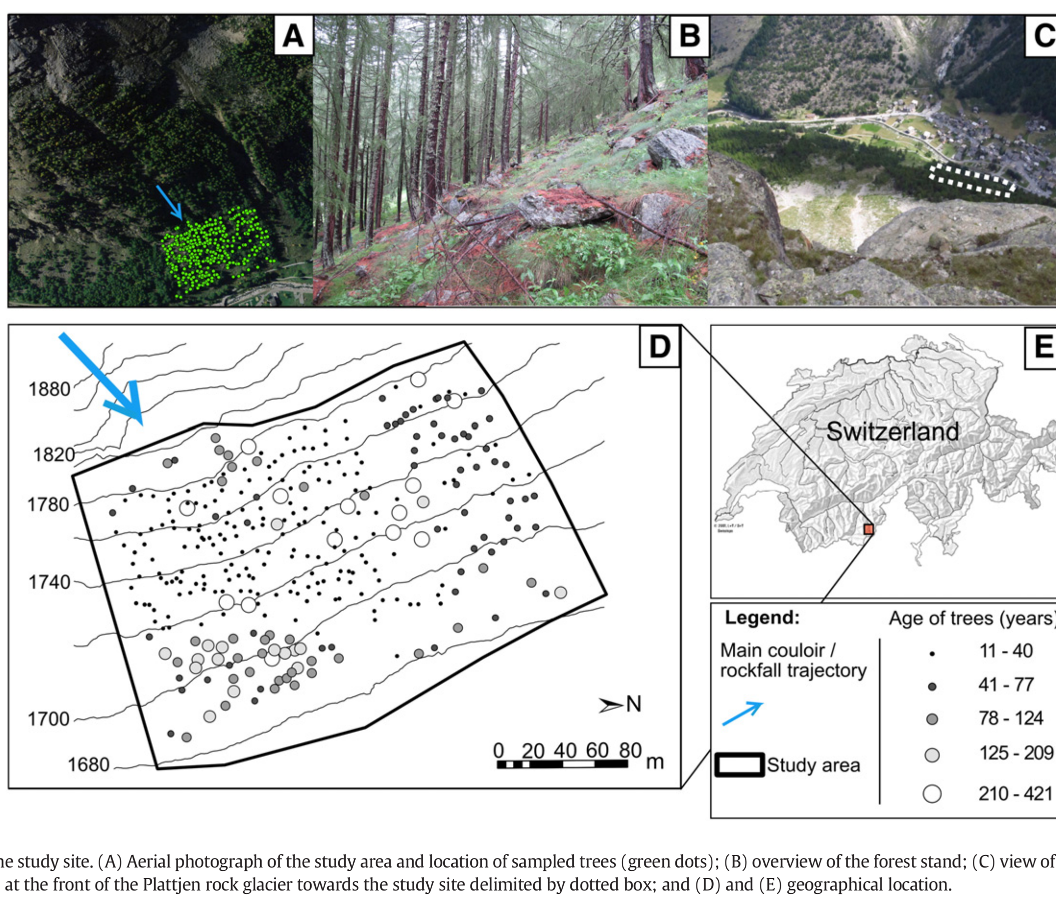

Fig. 1. Overview of the study site. (A) Aerial photograph of the study area and location of sampled trees (green dots); (B) overview of the forest stand; (C) view of the study site from the release areas located at the front of the Plattjen rock glacier towards the study site delimited by dotted box; and (D) and (E) geographical location.