Defining sample size and 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 been 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 dataset of 314 European larch (Larix deciduaMill.) trees (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. Spatially, our results demonstrate that the sampling of only 6 representative trees/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. Temporally, we demonstrate that at least 40 trees/ha are needed to obtain reliable rockfall chronologies.

KEYWORDS

Rockfall, Dendrogeomorphology, Simulation, Frequency, Methodology

INTRODUCTION

Rockfall represents one of the most frequent natural mass movement processes in mountainous areas and 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 non-forested 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 reliable, accurate and precise indicators 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). While in the earliest studies a limited number of 25–30 samples was used for rockfall reconstructions (Gsteiger, 1989; Schweingruber, 1996), laterwork generally was based on much larger numbers of samples (135 - 283 trees; e.g., Stoffel et al., 2005b; Moya et al., 2010; Šilhán et al., 2013). A clear guideline regarding the sample size needed to obtain reliable results still does not exist.

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A suite of recent studies concluded that an appropriate sampling design and 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 of sample size thresholds is possible and that such values permit assessment of realistic event frequencies with optimized cost–benefit ratios. In contrast, rockfall does not typically leave a clear spatial footprint as it damages a limited number of individual trees along its trajectory (Stoffel and Perret, 2006;Moya et al., 2010). Therefore, 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 sampling sizes and strategy for dendrogeomorphic rockfall studies. Based on an unusually large dataset 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 dataset. 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 were 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 and frequency of GD.

REGIONAL SETTINGS

Located in the Saas valley (Valais, Switzerland, 46° 05′41 N; 7° 57′17 E; Fig. 1) between 1670-1800 m asl., the investigated slope (5 ha) has a northeastern exposure and a slope ranging from 14-49°. The rockfall source area is formed by an active rock glacier at >2570m asl. at the lower permafrost boundary as well as by subvertical rock faces downslope of the rock glacier. The rocks deposited in the study area have mean axes lengths of 0.57 m and a volume of 0.31 m³. The tree stand at the site is mainly composed of Larix decidua Mill., intermixed with young Pinus cembra L. and Picea abies L. Karst. The tree age distribution (Fig.1D) shows relatively young individuals (11–40 yr) in the upper part of the slope, thus reflecting the influence of former cattle grazing. Rare 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 sampled trees. In the lower part of the slope and on its northern part, older trees can be found.

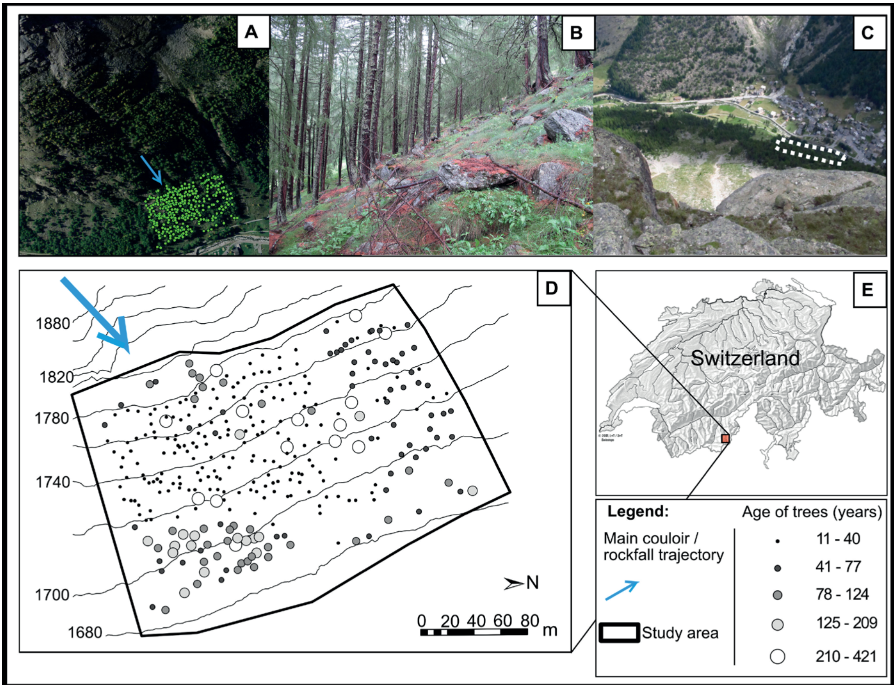

Figure 1: Overview of the study site. (A) Aerial photograph of the study area and location of sampled trees (green dots); (B) overview of the forest stand; C)View of the study site from the release areas located at the front of the Plattjen rock glacier towards the study site delimited by dotted box;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

METHODS

Dendrogeomorphic reconstruction of rockfall activity

In total, 616 increment cores were taken from 314 L. decidua trees. Systematic sampling was favored to a preferential selection of visibly impacted trees as L. decidua is known to heal and completely hide scars (Stoffel and Perret, 2006). Increment cores were extracted as close to the injury as possible, where the vascular cambium remained intact, providing complete tree-ring series and strong signals. In cases where no injury was visible, increment cores were extracted from the upslope side of the stem to maximize chances for impact detection at 0.5, 1 and 1.5 m. More cores were taken from trees with larger diameters (and thicker, more structured bark) because more hidden scars can be expected. Trees were sampled every 12m along transects across the slope, but we excluded trees growing in the fall line of close neighbors.

Standard dendrogeomorphic procedures were used during tree-ring analysis (Stoffel and Bollschweiler, 2008, 2010). Growth disturbances (see Astrade et al. (2012) or Stoffel and Corona (2014) for response typologies) were dated with annual precision. Years with rockfall activity were determined from injuries present on the increment cores, tangential rows of traumatic resin ducts (TRD), the presence of callus tissue, abrupt tree growth suppression or release. Only strong GD (Stoffel and Corona, 2014) were kept for further analyses. Also, when more than one GD is noticed within a year, we only kept the strongest GD for the analyses. Details on the GD detected and kept for the analyses in the 314 trees used to date rockfall impacts can be seen in Table 1.

Testing the optimal sampling strategy for spatial reconstruction

We adapted the routine used in Corona et al. (2013a, see article for a detailed description) designed for snow avalanches, which allows the computation of random extractions (REs) of trees from the dendrogeomorphic dataset. The routine is based on the RE of n subsamples for m iterations. The frequency of rockfall activity was computed for each individual tree.
A reference map (Refmap) was interpolated with the frequency values derived from individual trees of the entire dataset using the Inverse Distance Weighting (IDW) method.
RE was performed with 30, 50, 100, 150, 200, 250, and 300 trees from the complete dataset. This extraction was repeated 100 times for each threshold in order to reduce dependence of results on sampling location. Interpolated frequency raster maps were automatically generated (based on IDW interpolation) for each subsample in the form of 100 "RESubmaps". For each submap the Root Mean Square Error (RMSE) was computed from the reference map to quantify discrepancy between the submap and the reference map.
Maps representing the lowest error (best sampling) and the highest error (worst sampling) for each step of random extraction were plotted and investigated in further detail via comparison with the Refmap.

Testing the optimal sampling strategy for temporal reconstructions

Rockfall time series were derived for the 30-300 tree subsets corresponding to best and worst RESubmaps based on the "range corrected impacts" concept (RCI) (see Trappmann et al., 2013 for a detailed description). The RCI uses impact probability for the forest stand in each year to correct the number of recorded tree impacts. The concept thus includes a range of uncertainty and a quantitative estimation of events missed by dendrogeomorphic analyses. The RCI also permits definition of an adequate sample size, as the approach yields indications on the quality and the reliability of the reconstructed rockfall series.

Stratified sampling strategy based on an arbitrary selection of trees

Frequency maps and chronologies derived from random extractions (REs) were compared with results from the stratified sampling design based on an arbitrary sampling (AS) of trees so as to establish rules for future sampling design. The AS is based on the assumption that fewer samples are needed in areas with trees suggesting similar frequencies, meaning that on a slope segment with identical rockfall frequency, sampling one representative tree could hypothetically yield a reliable rockfall frequency for the sector. For this purpose, (i) heterogeneity maps were computed using the ArcGis spatial statistics tool "slope" (ESRI, 1998) which calculates the maximum rate of value change from one cell to its neighbors on the reference rockfall frequency map. Then, (ii) sample size was weighted in several compartments of the heterogeneity map according to the degree of heterogeneity (i.e. less trees in homogeneous areas). Finally, and for each compartment, (iii) trees were arbitrary selected as a function of their age (old vs. young trees) and of the number of GD (severely vs. little damaged trees).

RESULTS

Event frequency reconstruction

The oldest tree sampled had 421 tree rings at sampling height and was present at the site since at least AD 1590, whereas the youngest tree reached sampling height only in AD 2000. The mean age of the tree population was 60 yr. Based on the analysis of GD in the tree-ring series, a total of 372 rockfall impacts could be detected (Table 1), resulting in a rockfall chronology spanning the last 106 years. The mean frequency of rockfalls at the level of individual trees is 0.031 impacts yr-1. The reference map (Fig.2) reflects the channelizing topography and also shows that the highest activity occurs at the outlet of the rockfall couloir descending from the rock glacier and the steep rockwall (south-west, and upper part of the study site). The northernmost part of the study site exhibits the lowest activity with a mean

Table1: Overview on growth disturbances used to date rockfall injuries.

Growth disturbances	Traumatic resin ducts	Callus tissue	Injuries	Growth suppression	Growth release
Number	336	20	6	6	4
%	90	5	2	2	1

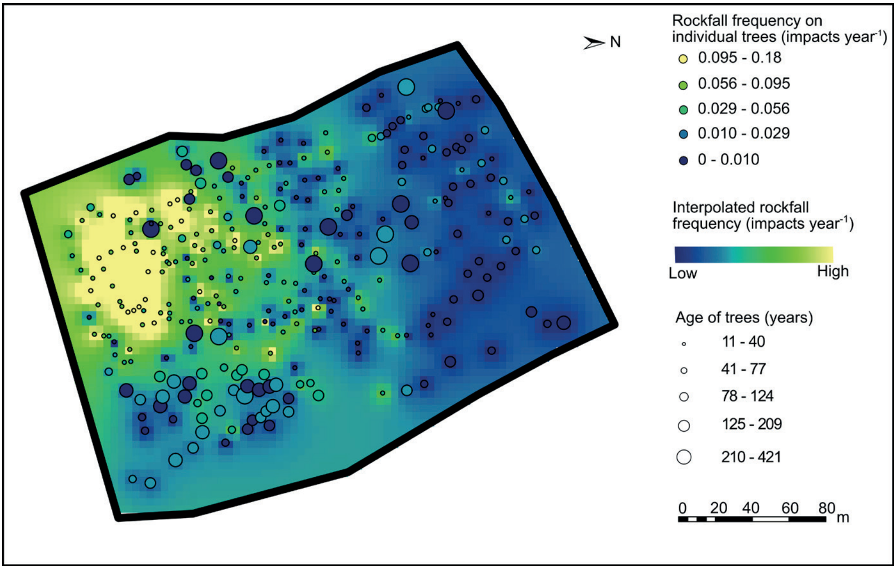

Figure 2: Reference frequency map (Refmap) of rockfall derived from the 314 sampled trees. The interpolation was performed the using inverse distance weighted method.

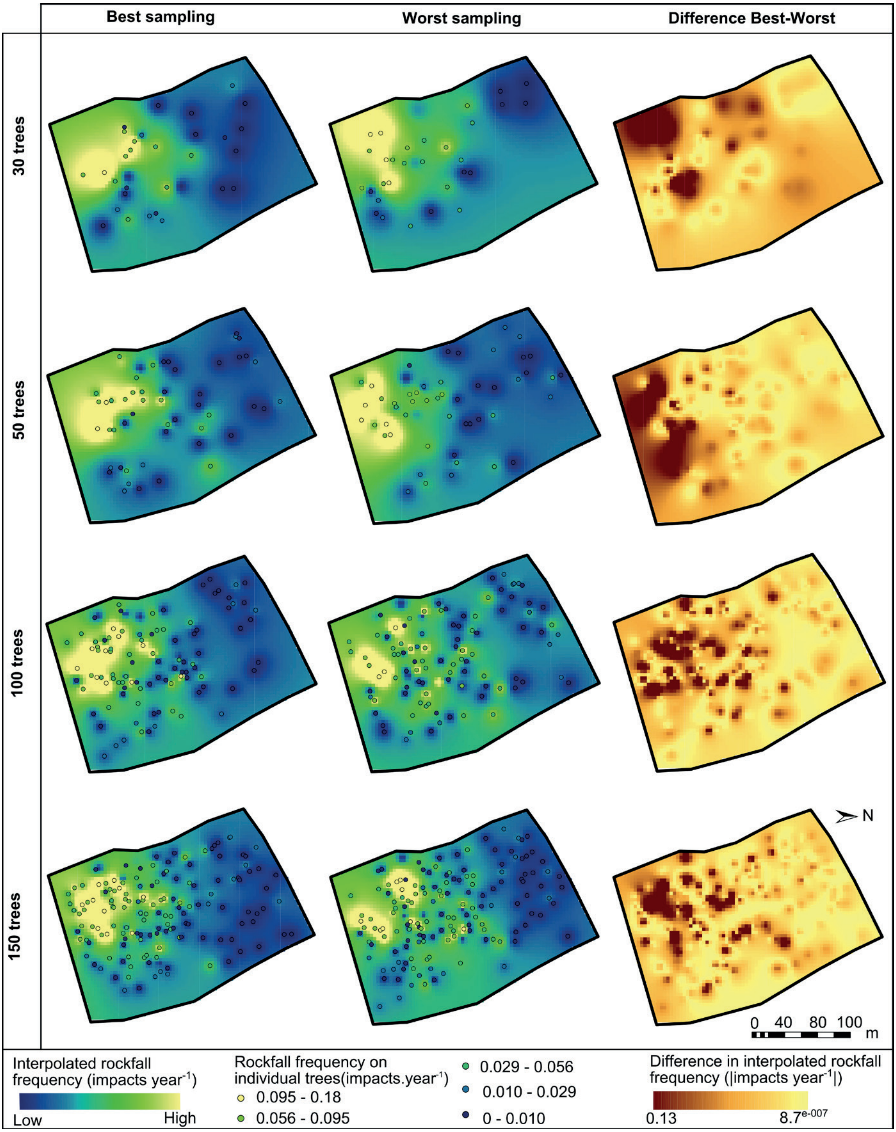

Figure 3.1: Best (lowest RMSE, left panel) and worst (highest RMSE, central panel) rockfall frequency maps interpolated for each of the 100 subsamples of 30 to 150 randomly extracted trees. Maps on the right panel represent the differences in absolute value between the best and the worst frequency maps computed for each subsample.

frequency of 0.0067 impacts yr-1 on individual trees. A downslope decline of rockfall activity also becomes apparent and illustrates the breaking effect of the forest stand on rockfall.
On a temporal scale, the rockfall chronology is reliable after the RCI criterion for the period 1950-2011, earlier years suffer from low numbers of available trees for reconstruction.

Testing optimized random sampling strategy for spatial reconstruction
Figures 3-4 illustrate differences between the reference frequency map (Refmap), computed with all sampled trees, and the best (min. mean RMSE) and worst (max. mean RMSE) RESubmaps obtained for the different RE subsets. Visual comparison of results shown in Fig.3 suggests that the best RESubmaps derived from small sample sizes(30-50 trees) properly reproduce the W-E gradient in rockfall frequency. Conversely, the worst RESubmaps (30 and

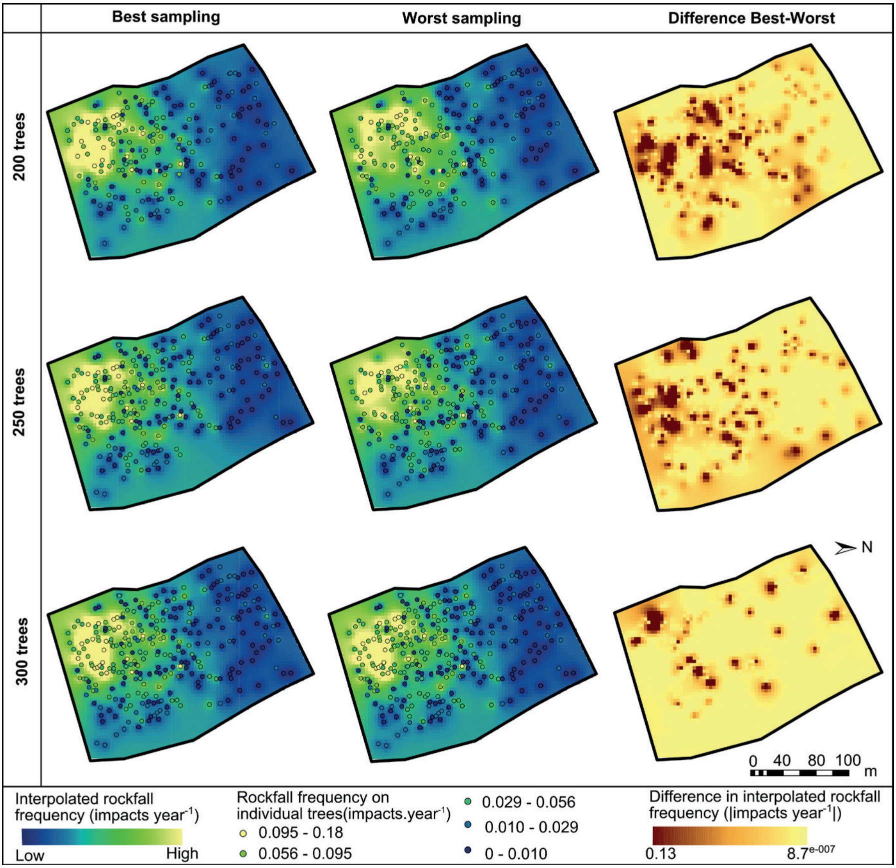

Figure 3.2: Best (lowest RMSE, left panel) and worst (highest RMSE, central panel) rockfall frequency maps interpolated for each of the 100 subsamples of 200 to 300 randomly extracted trees. Maps on the right panel represent the differences in absolute value between the best and the worst frequency maps computed for each subsample.

50) lead to significant under- and overestimations of rockfall frequencies in large compartments (south westernmost and northeastern parts) of the slope where trees were absent in the subset, thereby pointing to clear dependencies between mean RMSE and sampling design, i.e. the spatial distribution of trees selected for the interpolation.
Figure 4 illustrates that the mean RMSE of RESubmaps decreases by >80% with increasing sample size, and varies between 0.015±0.01for RESubmap30 to 0.005±0.002 impacts yr–1 for RESubmap300. Noteworthy, the best RESubmap50 and 100 have a RMSE comparable to the average RMSE obtained for RESubmaps100 and 150, respectively.

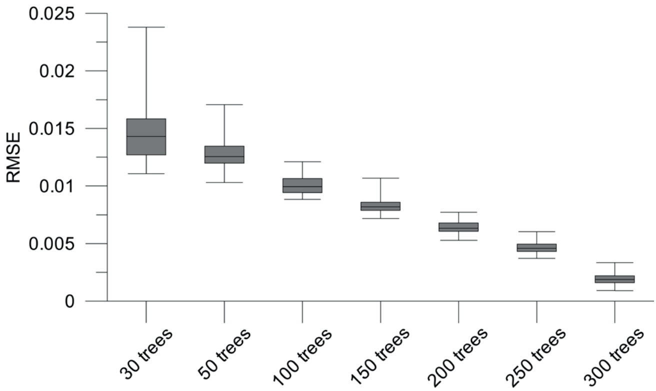

Figure 4: Boxplots for the Root Mean Square Error (RMSE) between the reference frequency map computed from 314 trees and 100 frequency maps computed with 30 to 300 randomly extracted trees. Boxplots show minimum, lower (Q 0.25), median (Q 0.5), upper quantile (Q 0.75) and maximum values for each sub-sample.

Optimized sample size for rockfall chronologies

The rockfall chronologies of the best and worst RESubmaps were then analyzed with the RCI concept. The chronologies obtained show significant differences depending on the number of trees used. Table 2 shows that with a sampling size of 30 trees and for 50 trees (worst sampling), not even a short part of the chronologies can be considered as reliable because more impacts are assumed to be missed in the trees. With increasing sample sizes (≥150 trees), RCI chronologies become more stable. According to the considerations mentioned above, Table 2 suggests a threshold of at least 150-200 trees to obtain short, yet reliable rockfall chronologies.

Table 2: Time period covered by the rockfall time series determined from the Range Corrected Impact (RCI) for best and worst subsamples (30-300 trees). Annotation: NR: Not Reliable

		Subsample						
		30	50	100	150	200	250	300
Random extraction	Best sampling	NR	1994	1994	1991	1985	1950	1950
	Worst sampling	NR	NR	1994	1991	1991	1985	1950

Chronology reliability is further explored in Fig.6 where the proportion of reconstructed event years is illustrated for each best and worst sampling of the RESubmaps. Event years are here defined as years with at least one rockfall impact detected in the given year of the time series. As could be expected, a larger number of sampled trees will lead to a more complete record of event years. However, by using a subset of only 30 (10%) trees, it is possible to reconstruct already 20% of the event years. Starting with 150 sampled trees, more than 50% (61% and 74% for the best and worst sampling, respectively) of the event years can be reconstructed. When over 250 trees are sampled, the rate of reconstructed events years remains stable as well as the confidence interval.

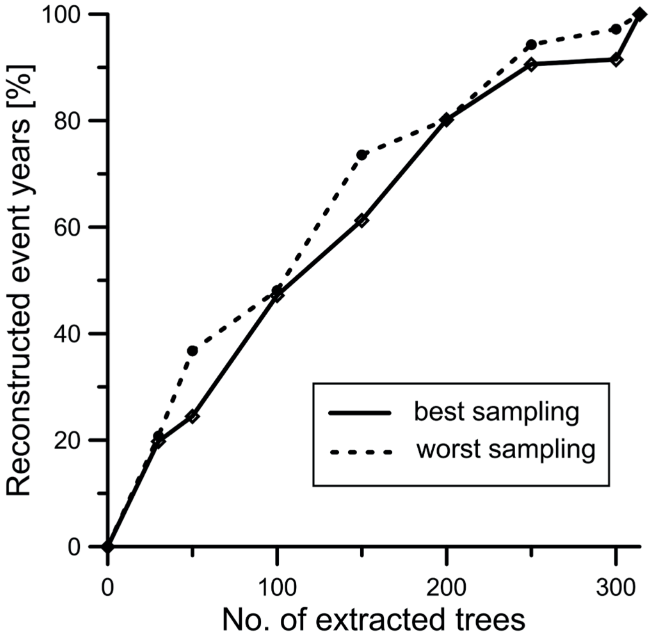

Figure 6: Percentage of reconstructed events for the worst and best random extractions as a function of sample sizes.

Random extraction (RE) vs. arbitrary selection (AS)

The heterogeneity map (Fig.7), reveals three compartments (A, B, C) corresponding to increasing levels of heterogeneity. According to our hypothesis that more sampled trees in areas with heterogeneous activity will yield better reconstructions, weights of 0.1, 0.3, and 0.6 were attributed to each compartment, respectively. In a first test, 10% of trees were selected from homogeneous compartment C, 30% from the transition compartment B and 60% from the heterogeneous compartment A for all subsamples from 30 to 300 trees. In a second test, we inverted the weights of the compartments (A: 0.6; B: 0.3; C: 0.1) to test the influence of stratified sampling. In each compartment, trees were again arbitrarily selected according to their age and to the number of visible scars. In total, eight different datasets were finally produced (old vs. young, severely vs. lightly injured trees for both preferential sampling in areas with homogeneous and heterogeneous activity) for sample size varying from 30-200 trees. The characteristics of each dataset are summarized in Table 3.

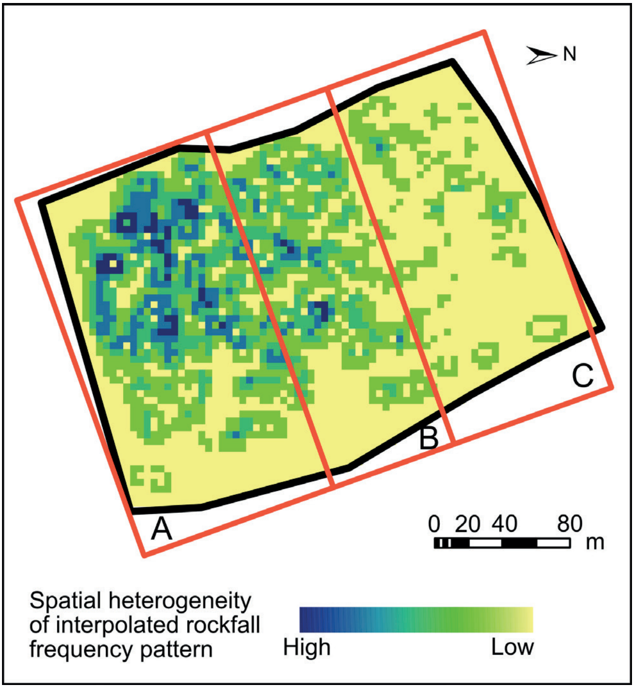

Figure 7: Heterogeneity map computed from Refmap using the ArcGis spatial statistics tool “slope” (ESRI, 1998) that calculates the maximum rate of change in value from one cell to its neighbors. Rectangle delineates the three compartments (A) homogeneous, (B) intermediate and (C) heterogeneous used respectively weighted 0.1, 0.3 and 0.6 in the stratified sampling strategy.

At the spatial scale, the comparison amongst ASsubmaps (Fig.8) clearly demonstrates that lower RMSEs are obtained when trees are sampled preferentially in areas with heterogeneous rockfall activity. Lower errors are also achieved when older trees are selected, and this finding is regardless of sample size. By contrast, 1.3 (30 trees) to 9 times (200 trees) larger discrepancies are observed when trees are selected in homogeneous areas and when trees without visible impact are arbitrarily selected. When comparing the AS and RE submaps, even lower RMSEs can be found for old trees and for a subset <150 trees (i.e. 30 trees/ha), provided that the density of sampled trees is high in the heterogeneous areas. With subsets >150, the best RE results show lower RMSE than any AS reconstruction, even though similarly low levels of RMSE can be achieved if sampling preferentially focuses on older and frequently impacted trees in the heterogeneous areas. By comparing the AS and REsubmaps, it also becomes obvious that preferential sampling of trees without visible impacts results in higher RMSE values. Errors are lower if old trees are preferably sampled, over younger trees.

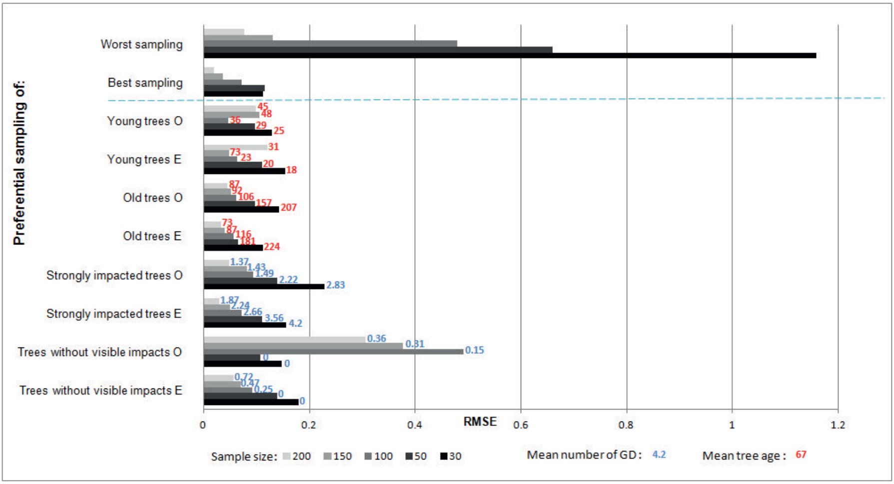

Figure 8: Root Mean Square Error (RMSE) measuring the deviation of frequency maps generated with different subsets from the reference frequency map. RMSE is given for various sample sizes of best and worst random extractions as well as for different arbitrary selections. Preferential sampling in areas with heterogeneous rockfall activity is presented by 'E' and in homogeneous by 'O'.

Temporally, Table 3 demonstrates that in many cases, chronologies from AS are more reliable than those from RE, regardless of the sample size. For sample size <150 trees, the longest reliable reconstructions are obtained when frequently disturbed trees are included in the analyses; they yield reliable periods ranging from 18 (30 trees) to 25 years (100 trees). Interestingly, above this threshold the length of reliable reconstructions only slightly increases to reach 30 years back in time for AS reconstructions involving 150 and 200 old trees (with respective mean ages of 87 and 73 years).

Table3: Time period covered by the rockfall time series determined from the Range Corrected Impact (RCI) for best and worst subsamples (30-200 trees) randomly extracted and for stratified sampling strategies based on arbitrary selections (30-200 trees) function of the age and of the number of impacts. Preferential sampling in areas with heterogeneous rockfall activity indicated by 'E' and in homogeneous by 'O'.
Annotation: NR: Not Reliable

		Random extraction		Arbitrary selection				
	Strategy	Best sampling	Worst sampling	Trees without visible impact O	Trees without visible impact E	Strongly impacted trees E	Strongly impacted trees O	Young trees O
Subsample	30	NR	NR	NR	NR	1993	NR	NR
	50	1994	NR	NR	NR	1993	2008	NR
	100	1994	1994	2008	1981	1986	1985	1994
	150	1991	1991	1991	1981	1984	1985	1991
	200	1985	1991	1987	1986	1984	1985	1991

CONCLUSION

Evaluating the potential of tree-ring analysis on an extensively sampled slope in the Valais region (Swiss Alps) reveals that the optimal sampling size and strategies will depend strongly on the aim of the reconstructions. We demonstrate that for a site with frequent rockfalls composed of individual rocks, as little as 6-10 trees/ha can be sufficient to obtain frequency maps similar to those obtained with the full dataset containing 63 trees/ha. Temporally, results show that 40 trees/ha can be sufficient to reconstruct 80% of past rockfall event years and that the chronologies obtained appear balanced. Although the thresholds provide very valuable indications on optimal sample sizes needed for reliable reconstructions, they should not be seen as absolute values. Instead, sample design and the number of investigated trees will need to remain flexible, as the nature of the process, topography, availability and ability of trees to record events will differ from site to site. In addition, representative trees will need to be selected with great care, even more so in case of small sample sizes. We thus suggest that trees should be selected after a preliminary assessment of process activity at the study site and based on the degree of heterogeneity in rockfall frequency. With respect to the selection of trees, we encourage a balanced choice of different age classes including old and heavily affected trees. Optimized minimum sampling sizes and design will ultimately facilitate fieldwork, and render analyses and interpretation more reliable, less time consuming, and will also improve cost-benefit ratios.

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