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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

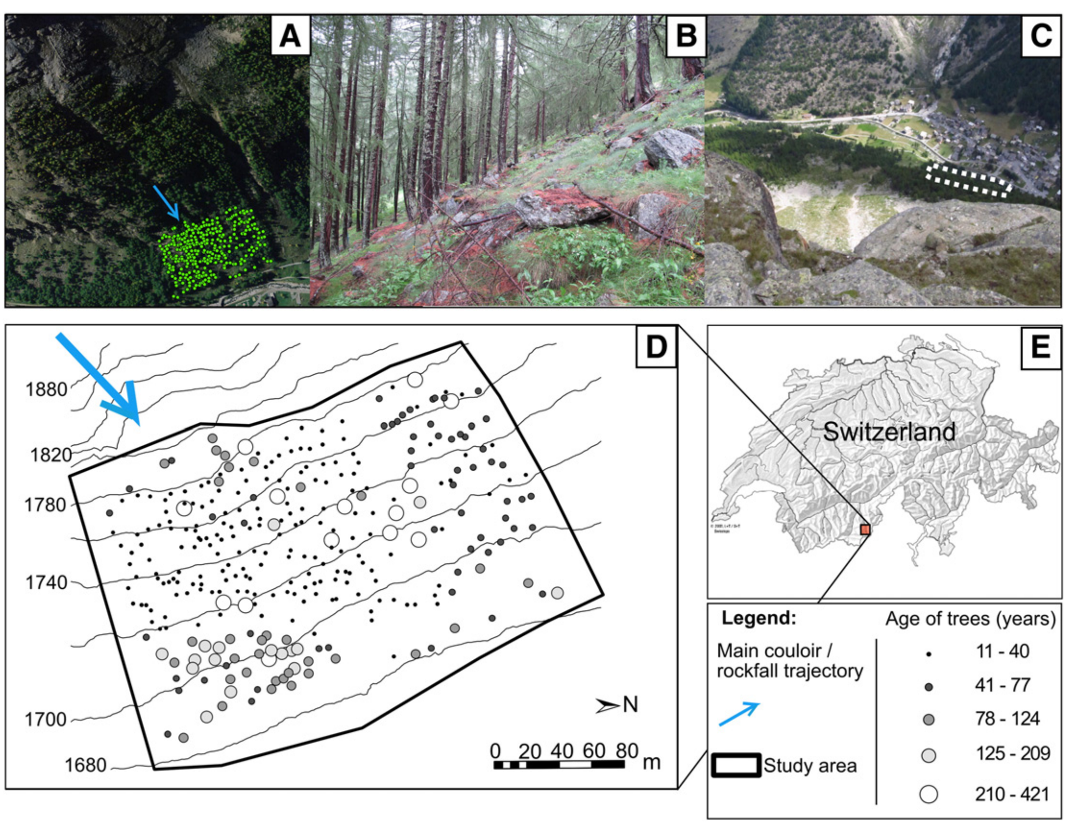

Fig. 1. Overview of the study site. (A) Aerial photograph of the study area and location of sampled trees (green dots); (B) overview of the forest stand; (C) view of the study site from the release areas located at the front of the Plattjen rock glacier towards the study site delimited by dotted box;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

subsamples leading to the best and the worst matching were then used to (iii) investigate the influence of sample size and tree selection on the reconstruction of rockfall chronologies at the site. In a final step, we (iv) compare random extractions (RE) with a stratified sampling strategy based on arbitrary selection (AS) of trees according to a gradient of heterogeneity, the individual level of disturbance, and tree age. This allowed us to propose clear guidelines for the selection of optimal trees in future reconstructions.

3.1. Dendrogeomorphic reconstruction of rockfall activity

In total, 616 increment cores were taken from 314 *L. decidua* trees. Trees were selected according to their position, aiming at a homogeneous distribution and regardless of visible impacts or tree age. This systematic sampling was favored to a preferential selection of visibly impacted trees, as *L. decidua* is known to heal and thus completely hide scars with their thick and peeling bark (Stoffel and Perret, 2006). Sampling was done through the extraction of increment cores 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 on the stem surface, 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. The number of increment cores collected per tree varied from 1 to 8. In general, more cores were taken from trees with larger diameters (and thicker, more structured bark) because more hidden scars can be expected in these as compared to younger trees with smoother bark structures. Trees were sampled every 12 m along transects across the slope, but we excluded trees growing in the fall line (shadow) 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 suppression of tree growth, or growth release. Only strong GD (Stoffel and Corona, 2014) were kept for further analyses. Details on the GD detected in the 314 trees that were used to date past rockfall impacts can be seen in Table 1.

3.2. Testing the optimal sampling strategy for spatial reconstruction

We adapted the routine used in Corona et al. (2013a) designed for snow avalanches, which allows the computation of random extractions (REs) of trees from the dendrogeomorphic data set. The routine is based on the RE of n subsamples for m iterations. The frequency of rockfall activity was computed for each individual tree as follows:

$$f_T = GD_T/A_T \tag{1}$$

where A_T is the age (i.e., of the longest record in years present on the increment cores) of tree T, and GD_T represents the total number of growth disturbances determined in all samples of tree T.

Table 1
Overview on growth disturbances used to date rockfall injuries.

Growth disturbances	Number	%
Traumatic resin ducts	336	90
Callus tissue	20	5
Injuries	6	2
Growth suppression	6	2
Growth release	4	1
All reconstructed events	372	100

A reference map (*Refmap*) was interpolated with the frequency values derived from individual trees of the entire data set (314 *L. decidua* trees) using the inverse distance weighting (IDW) method. Random extraction was performed with 30, 50, 100, 150, 200, 250, and 300 trees from the complete data set. This extraction was repeated 100 times for each threshold. 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 as follows:

$$\delta_i = fRESubmap_{n(i)} - f_{Refmap(i)} \tag{2}$$

$$Mean\ \ RMSE(RESubmap(n)) = \sqrt{\frac{\sum_{Npix}^{i=1} \delta^2_{Npix}}{Npix}} \tag{3}$$

where δ_i represents the discrepancy at pixel i (pixel size: 4 × 4 m), $fREsubmap_{n(i)}$ is the frequency of rockfall interpolated for a submap n at a pixel i, and $f_{Refmap(i)}$ is the frequency of rockfall interpolated at pixel i on the reference map. The *Npix* gives the number of pixels in *Refmap* and *RESubmap(n)*. The RMSE is a measure for the reliability of a given frequency map created by random extraction by quantifying the discrepancy to 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*.

3.3. 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 concept allows a more realistic reconstruction of temporal changes in rockfall activity as it takes account of changing sample and target sizes (in terms of living trees and diameter growth per year). This concept is based on the assumptions that trees with larger diameters are more likely to be hit by rocks and that bigger rocks are more likely to impact trees (Fig. 2). 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.

For each year (y), the RCI as well as the number of possibly missed events (GDM_y) are derived from (i) the sample size and exposed diameter (ED) values, (ii) the total range covered (RC_y) by the trees and from (iii) the portion of the slope that is not covered by the analysis as a result of lacking trees (RNC_y). The exposed diameter is computed as follows:

$$ED_y = \sum_{i=1}^{n} \left(I_y + I_{y-1} \right) \tag{4}$$

where ED_y is the exposed diameter for a given year y, I_y corresponds to the increment rate per year for the selected trees in year y, and where I_{y-1} is the total increment for the year y^{-1}. The ED thus represents the diameter sum of all living trees in year y. Based on the above, the total range covered by trees can therefore be calculated as follows:

$$RC_y = \sum ED_y + SS_y * d \tag{5}$$

where RC_y is the range covered by the forest stand on the slope, ED_y is the exposed diameter per year y, SS_y the sample size (number of sampled trees) for the year y, and d the mean block diameter. The range

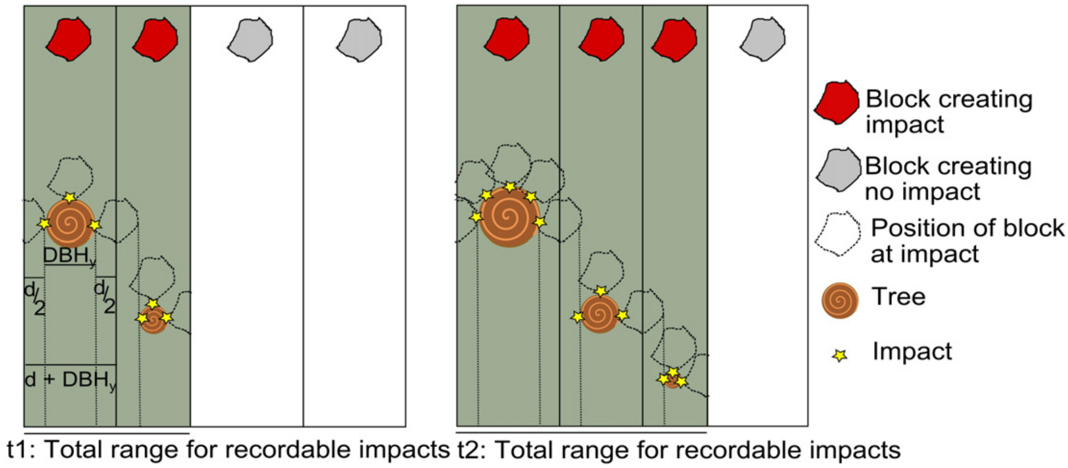

Fig. 2. The RCI concept. (A) Situation at time t. (B) Situation at time $t + 1$. Adapted from Trappmann et al. (2013).

that is not covered by the reconstruction is given by:

$$RNC_y = W - RC_y \tag{6}$$

where RNC_y represents the range not covered, W the slope width, and RC_y the range covered by the reconstruction. We computed the RCI as follows:

$$RCI_y = GD_y * W / RC_y \tag{7}$$

where RCI_y is the RCI per year y, GD_y is the number GD for year y, W is the slope width, and RC_y is the range covered for a given year y. Here the RCI was computed for the best and worst *submap(n)* and compared to one another from 30 to 300 n extractions. The final step estimates the number of missed impacts GDM_y by multiplying a mean number of GD per RC (for the timespan where records are continuous) with the RNC_y.

$$GDM_y = \frac{1}{n} \sum_{i=m}^{n} \frac{GD_i}{RC_i} * RNC_y \tag{8}$$

where m represents the first year with continuous rockfall activity (i.e., constant sequence of years with GD without missing records related to small sample size) and n is the last year of the records. RNC_y is the range not covered for a given year y. The comparison of the GD_y and GDM_y allows more certainty about the reconstruction. The reconstruction is considered as highly reliable as soon as $GD_y > GDM_y$ (i.e., more impacts recorded than presumably missed).

3.4. Stratified sampling strategy based on an arbitrary selection of trees

In a final step, 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, 2008) that calculates the maximum rate of value change from one cell to its neighbors on the reference rockfall frequency map. In a second step, (ii) sample size has been 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 arbitrarily selected as a function of their age (old vs. young trees) and of the number of GD (severely vs. little damaged trees).

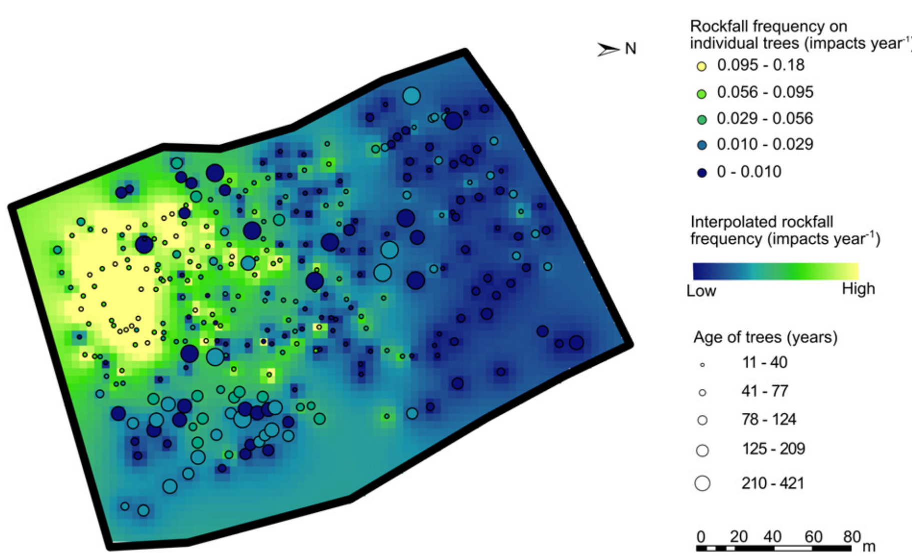

Fig. 3. Reference frequency map (*Refmap*) of rockfall derived from the 314 sampled trees. The interpolation was performed using the inverse distance weighted method.

4. Results

4.1. Event frequency reconstructed with the classical expert approach

The oldest tree sampled at the study site had 421 tree rings at sampling height and was present at the site since at least A.D. 1590, whereas the youngest tree reached sampling height only in A.D. 2000. The mean age of the tree population was 60 years. Based on the analysis of growth disturbances 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 y^{-1}. The reference map is illustrated in Fig. 3 and reflects the channelizing topography. It also shows that the highest activity occurs at the outlet of the rockfall couloir descending from the rock glacier and the steep rockwall (i.e., south-west, and upper part of the study site). The northernmost part of the study site exhibits the lowest activity with a mean frequency of 0.0067 impacts y^{-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.

4.2. Testing optimized random sampling strategy for spatial reconstruction

Using the reference rockfall frequency map, we aimed at defining the best sampling design yielding optimal spatial information with a minimum of noise. For that purpose, we modeled various sample sizes

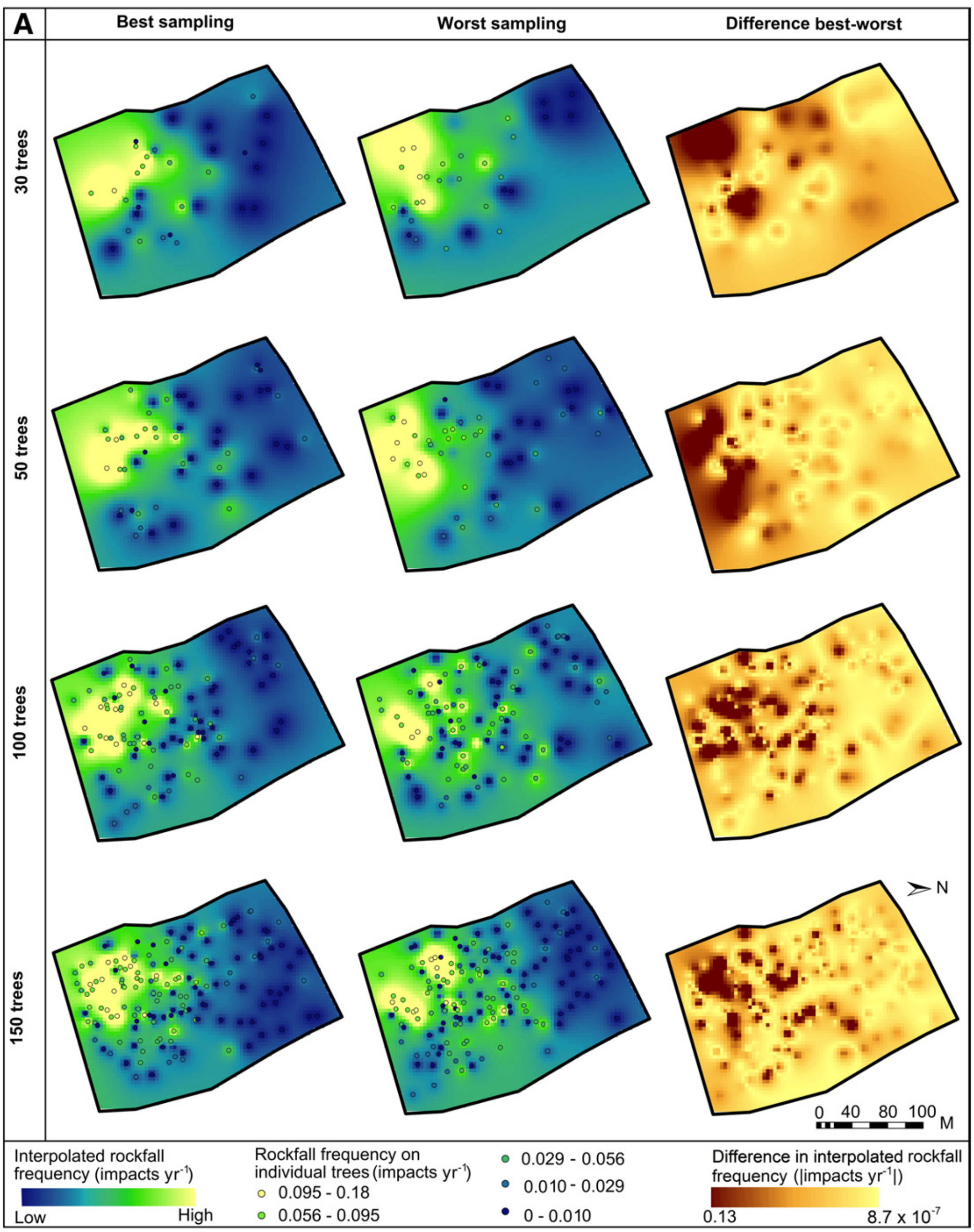

Fig. 4. (A and B) Best (lowest RMSE, left panel) and worst (highest RMSE, central panel) rockfall frequency maps interpolated for each of the 100 subsamples of 30 to 300 randomly extracted trees. Maps on the right panel represent the differences in absolute value between the best and the worst frequency maps computed for each subsample.

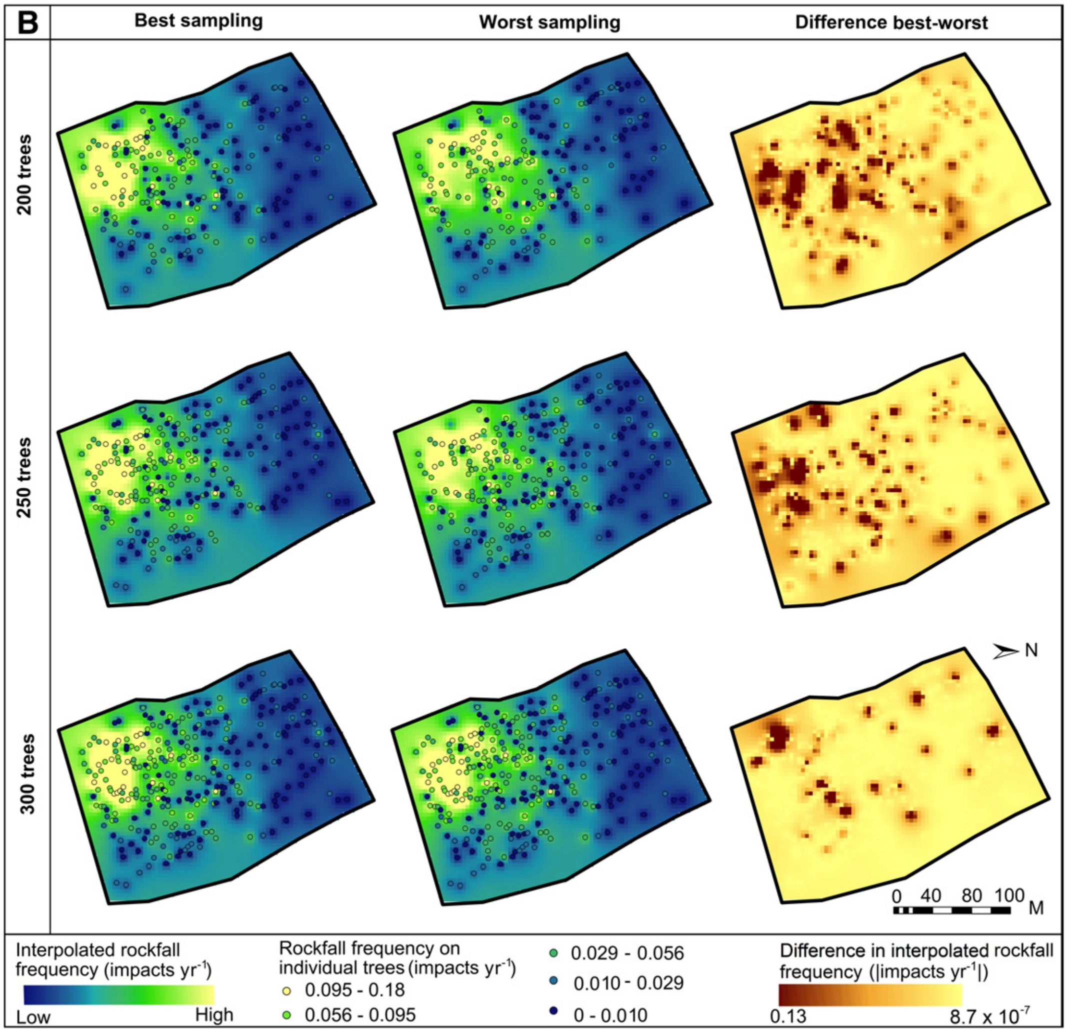

Fig. 4 (*continued*).

varying from 30 to 300 trees to observe differences in the frequency maps of reconstructed events. In order to reduce dependence of results on sampling location, 100 subsets of sample size trees were extracted for each sample size.

Figs. 4–5 illustrate differences between the reference frequency map (*Refmap*), computed with all sampled trees, and the best (i.e., min. *mean RMSE*) and worst (i.e., max. *mean RMSE*) *RESubmaps* obtained for the different RE subsets. Visual comparison of results shown in Fig. 4A and B 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 50) lead to significant under- and overestimations of rockfall frequencies in large compartments (southwesternmost 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.

Fig. 5 illustrates that the *mean RMSE* of *RESubmaps* decreases by >80% with increasing sample size and varies between 0.015 ± 0.01 for *RESubmap30* and 0.005 ± 0.002 impacts y^{-1} for *RESubmap*300. Noteworthy, the best *RESubmap*50 and 100 have an RMSE comparable to the average RMSE obtained for *RESubmaps*100 and 150, respectively.

4.3. Optimized sample size for rockfall chronologies

The rockfall chronologies of the best and worst *RESubmaps* were then analyzed with the RCI concept. As can be seen from Fig. 6A and B, the chronologies obtained show significant differences depending on the number of trees used. A first indicator for the completeness of each reconstruction is the discrepancy between RCI values and the observed GD in the tree-ring series. This discrepancy decreases with increasing sample size, meaning that the confidence in the reconstructions generally increases with larger sample size. Arrows indicate the year at which chronologies become reliable (i.e., the first year with

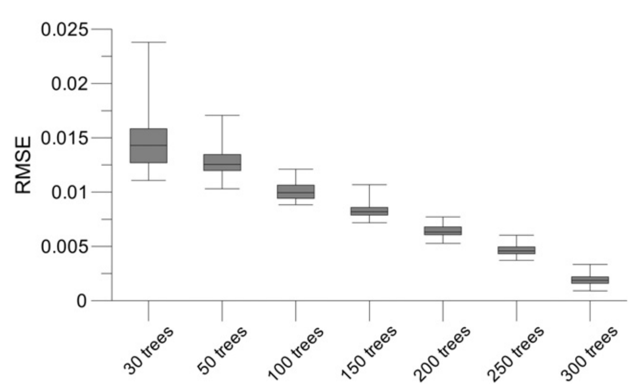

Fig. 5. Boxplots for the root mean square error (RMSE) between the reference frequency map computed from 314 trees and 100 frequency maps computed with 30 to 300 randomly extracted trees. Boxplots show minimum, lower (Q 0.25), median (Q 0.5), upper quantile (Q 0.75), and maximum values for each subsample.

more observed GD than presumably missed ones). Fig. 6 shows that with a sampling size of 30 trees (best and worst sampling) and for 50 trees (worst sampling), not even a short part of the chronologies can be considered as reliable (absence of arrows) because more impacts are assumed to be missed than recorded in the trees. With increasing sample size, the reliable part of the reconstructions can be extended back in time from 1994 (50 trees, best sampling) to 1950 (250 trees, best sampling; 300 best and worst sampling). For a sample size of 30 to 100 trees, the computation of RCI values yields extremely high values, especially for the early years of the reconstructions and a negative exponential downward trend that is related to small sample size rather than to a real trend in rockfall activity. With increasing sample sizes (≥150 trees), RCI chronologies become more stable. According to the considerations mentioned above, Fig. 6A and B suggests a threshold of at least 150–200 trees to obtain short, yet reliable rockfall chronologies. However, sampling more trees will considerably extend the reliable part of the chronologies back in time and will reduce uncertainties.

The phenomenon of chronology reliability is further explored in Fig. 7 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, we again realize that 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

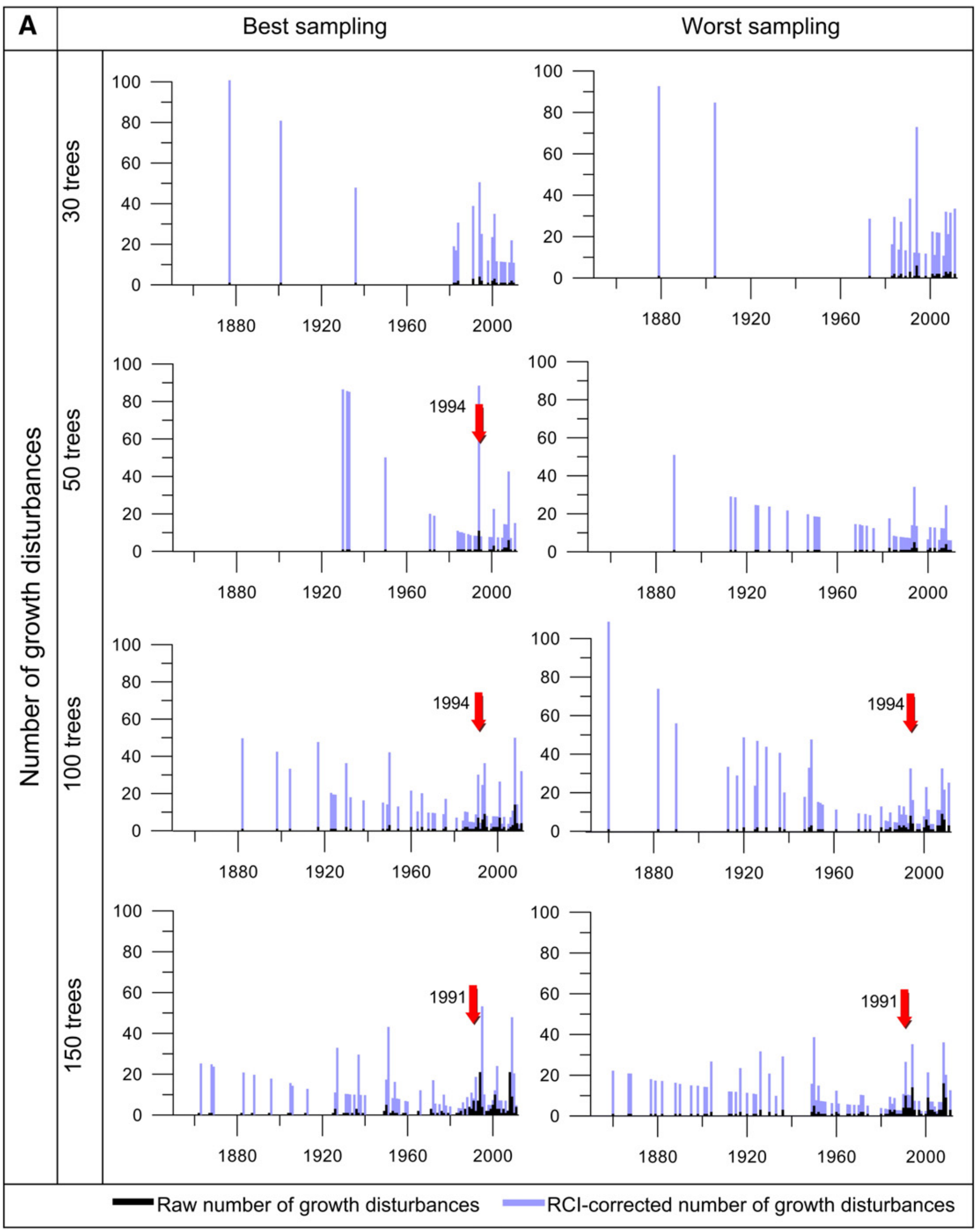

Fig. 6. (A and B) Rockfall chronologies obtained using trees involved in the best and worst submaps for sample sizes ranging from 30 to 300 trees. Red vertical bars indicate the number of recorded growth disturbances (GD); black lines indicate the estimated absolute number of rocks for each year using the range corrected impacts (RCI) concept. Arrows indicate the point from which the reconstructions are considered reliable (i.e., GD recorded > GD presumably missed).

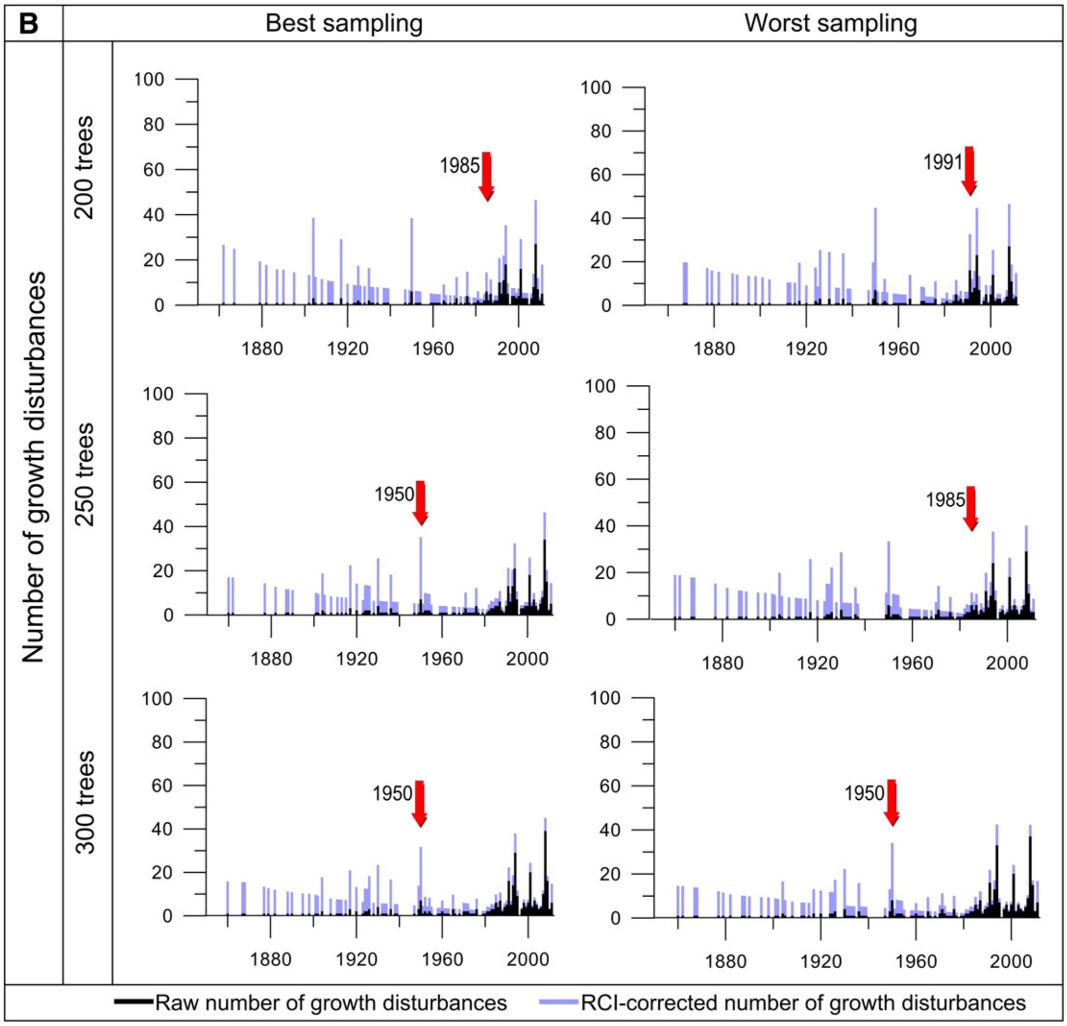

Fig. 6 (*continued*).

worst sampling, respectively) of the event years can be reconstructed. As soon as more than 250 trees are sampled, the rate of reconstructed event years remains stable as well as the confidence interval.

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

The heterogeneity map, shown in Fig. 8, 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 subsamples varying 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 on reconstructed rockfall activity. In each compartment, trees were again arbitrarily selected according to their age and to the number of visible scars. In total, eight different data sets were finally produced (old vs. young, severely vs. lightly injured trees for preferential sampling in areas with homogeneous and heterogeneous activity) for sample size varying from 30 to 200 trees. The characteristics of each data set are summarized in Table 2.

At the spatial scale, the comparison amongst *AS submaps* (Fig. 9) 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 *RE submaps*, 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.

Temporally, Table 2 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).

5. Discussion

In his seminal paper, Shroder (1978) emphasized that sample size may be a moot question unless site selection ensures that all trees are responding to the process under investigation. Site selection has been demonstrated repeatedly to be of key importance (Stoffel and Bollschweiler, 2008), but the question asked by Butler et al. (1987) of how many trees should be sampled for an event to be inferred should be seen as at least equally crucial in the recent context of more frequent inclusion of dendrogeomorphic rockfall records in hazard assessments (Corona et al., 2013b; Trappmann et al., 2014). As the sample density used in this study exceeds that of most previously published work in a quite substantial manner, we attempted to address the influence of sample size and sampling design on rockfall frequency maps and time series. For this purpose, we used various subsets, randomly extracted and arbitrarily selected, of an existing rockfall chronology (314 trees) to model sample sizes varying from 30 to 300 trees.

5.1. Optimal sampling design for spatial reconstructions of rockfalls

Various sampling strategies have been used in the literature to derive interpolations of return periods of rockfalls from tree-ring records. Aiming at exploring the potential of dendrogeomorphic rockfall reconstructions, sampling design was based on vertical and/or horizontal transects and consequently contained large numbers of trees. Stoffel et al. (2005b; 2006) or Schneuwly and Stoffel (2008), for example, developed a sampling design where trees were sampled every *n* meters along horizontal profiles (or transects) to ensure an even distribution of sampled trees and included 135 (6 trees/ha) and 191 (95 trees/ha) in their reconstructions. Moya et al. (2010), on the other hand, performed an exhaustive sampling of 260 trees (40 trees/ha) in 15 to 30 m wide horizontal forest strips located parallel to the contour lines so as to detect all rockfall trajectories. Recent studies stress the importance of tree age (Šilhán et al., 2013), so our initial sampling strategy followed recommendations of Stoffel et al. (2013) aiming at a homogeneous distribution of trees and the inclusion of different tree ages in the reconstruction. While we cannot exclude that the resulting frequency map might also be influenced by tree age, it is quite clear that areas with the highest frequencies correspond well with the area below a couloir, where rockfall activity is channelized and where most rockfall deposits can be found.

We demonstrate that sampling a limited number of only 30 representative trees (6 trees per ha) can result in reliable frequency maps which in turn permits a proper distinction of active from less active

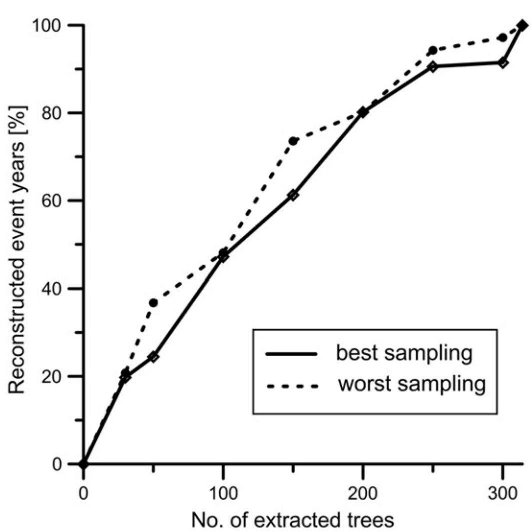

Fig. 7. Percentage of reconstructed event years for the worst and best random extractions as a function of sample sizes.

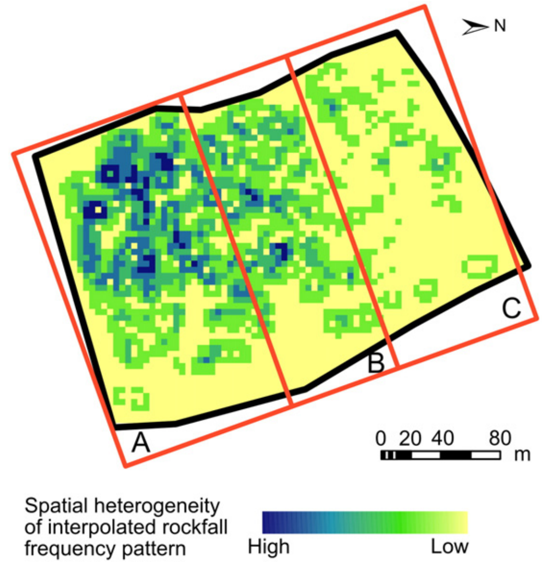

Fig. 8. Heterogeneity map computed from *Refmap* using the ArcGis spatial statistics tool *slope* (ESRI, 2008) that calculates the maximum rate of change in value from one cell to its neighbors. Rectangle delineates the three compartments (A) homogeneous, (B) intermediate, and (C) heterogeneous weighted 0.1, 0.3, and 0.6, respectively, in the stratified sampling strategy.

rockfall zones at the study site. Similarly, Corona et al. (2014) concluded that 50–100 trees may be sufficient to obtain satisfactory results on active landslide bodies. In their study, the authors used a stratified sampling design in which they distributed the most heavily affected trees evenly over the study area. These findings slightly deviate from our conclusions for rockfalls, where a stratified sampling based on the degree of spatial heterogeneity of rockfall activity and the inclusion of old and/or heavily affected trees were the key for a satisfactory reproduction of frequency maps with small subsamples (30–50 trees). On the contrary, sampling trees in areas with rather homogeneous rockfall frequencies or the inclusion of preferential sampling of poorly damaged trees frequently led to major inaccuracies in the resulting rockfall frequency maps. The sampling design that we suggest for rockfall activity is consistent with the results of Schneuwly-Bollschweiler et al. (2013) who demonstrated that maximizing sample size near the cone apex of debris-flow cones — where GD related to avulsion are more likely to occur — would provide better results than would trees cored along the present-day debris-flow channel.

Table 2
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' [a].

	Strategy	Subsample				
		30	50	100	150	200
Arbitrary selection	Trees without visible impact O	NR	NR	2008	1991	1987
	Trees without visible impact E	NR	NR	1981	1981	1986
	Strongly impacted trees E	1993	1993	1986	1984	1984
	Strongly impacted trees O	NR	2008	1985	1985	1985
	Young trees O	NR	NR	1994	1991	1991
	Young trees E	NR	2008	1994	1991	1987
	Old trees E	NR	2009	2007	1981	1981
	Old trees O	NR	2009	1970	1970	1970
Random extraction	Best sampling	NR	1994	1994	1991	1985
	Worst sampling	NR	NR	1994	1991	1991

[a] Annotation: NR: not reliable.

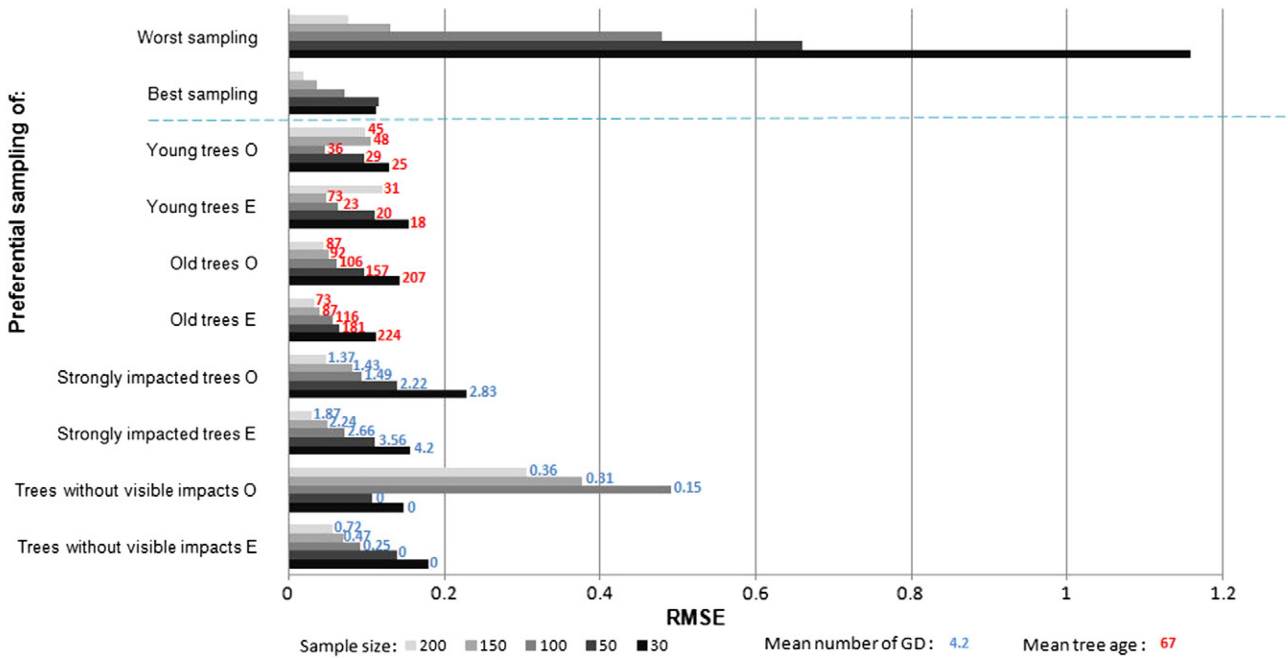

Fig. 9. Root mean square error (RMSE) measuring the deviation of frequency maps generated with different subsets from the reference frequency map. The RMSE is given for various sample sizes of best and worst random extractions as well as for different arbitrary selections. Preferential sampling in areas with heterogeneous rockfall activity is presented by 'E' and in homogeneous by 'O'.

In this study we also illustrate existing methodological difficulties to find a threshold for the interpolated mapping of rockfall frequencies as (i) the best frequency maps are obtained with the largest sample sizes because more sampled trees will increase the diversity in the reference map and as (ii) no clear plateau could be observed in the distribution of RMSEs when compared to sample size. In that sense, our results clearly differ from those for other processes with larger spatial footprints where threshold can be proposed based on the amount of misdated events (noise) in reconstructions.

5.2. Optimal sampling design for temporal reconstructions of rockfalls

The question of how many trees should be sampled to obtain reliable rockfall series was again tested via the quality of results using iterative sampling with different sample sizes. We demonstrate that a small sample size (30 trees) prohibits a reliable reconstruction and that the temporal reliability of the time series will increase proportionally with sample size. At the same time, however, it appears that sampling 250 trees (i.e., 50 trees/ha) will minimize uncertainties while allowing extension of the reliable time series back to A.D. 1950. By comparison, based on the same RCI approach, Trappmann et al. (2013) were able to build reliable rockfall chronologies at nearby sites that date back to 1920 and 1893 with sampling sizes of 97 and 71 trees/ha, respectively. However, sample size is not the only reason for the observed temporal differences in time-series reliability, it is also related to significant differences in the mean age of sampled trees, which reached only 60 years in our case; whereas vegetation was, on average, 115 and 135 years old at the study sites used by Trappmann et al. (2013).

Compared to landslides and debris flows where 80% and 85%, respectively, of all events could be dated with just 5 trees/ha (Schneuwly-Bollschweiler et al., 2013; Corona et al., 2014), a tenfold sampling size (40 trees/ha) is needed to reconstruct 80% of past rockfall event years. We thus confirm the assumption that event chronologies of discrete processes (Perret and Stoffel, 2006) such as rockfalls will need to be sampled with much larger sample sizes than processes with a large spread to come up with comparable accuracy and detail in results.

6. Conclusion

Evaluating the potential of tree-ring analysis on an extensively sampled slope in the Valais region (Swiss Alps) reveals that the optimal sample size and sampling 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 that are quite similar to those obtained with the full data set 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 trees to be investigated 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 sample sizes and sampling design will ultimately facilitate fieldwork and thus render analyses and interpretation more reliable, less time consuming, and will also improve cost–benefit ratios.

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