Geomorphology 180–181 (2013) 180–186

Contents lists available at SciVerse ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

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

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A R T I C L E I N F O

Article history:
Received 30 May 2012
Received in revised form 18 September 2012
Accepted 9 October 2012
Available online 17 October 2012

Keywords:
Rockfall
Dendrogeomorphology
Tree ring
Frequency
Scar count

A B S T R A C T

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.

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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0169-555X/$ – see front matter
http://dx.doi.org/10.1016/j.geomorph.2012.10.009

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).

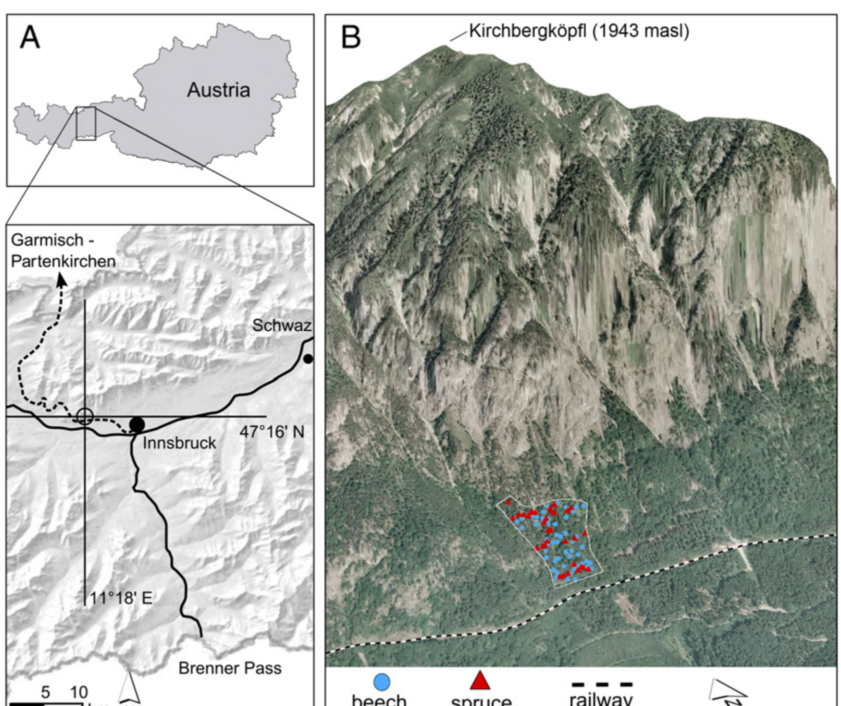

Fig. 1. (A) Location of the study site Hechenberg above the railway line in the Inn valley (Austria), and (B) three-dimensional view of the site with positions of sampled trees.

For all sampled trees, data on stem diameter at breast height (DBH) as well as visible impacts on the stem surface were recorded. Increment cores were taken with an increment borer (max. 40 cm × 0.5 cm). Samples were processed following standard procedures described by Bräker (2002) which included the sanding of samples, counting of tree rings, and measuring of tree-ring widths using a digital LINTAB positioning table connected to a Leica stereo microscope and TSAP 5.0 software (Rinntech, 2012).

In total, 33 *P. abies* and 50 *F. sylvatica* were selected for sampling with a mean DBH of 48 cm for the first and 38 cm for the latter (Table 1). The different sampling procedures resulted in 144 and 50 increment cores for *P. abies* and *F. sylvatica*, respectively.

3.1. Sampling procedure and analysis of P. abies using the classic dendrogeomorphic approach

Conifer species are known to mask injuries effectively, so rockfall events were reconstructed via growth anomalies as observed in the tree-ring record (Stoffel and Bollschweiler, 2008). As *P. abies* has been demonstrated to form tangential rows of traumatic resin ducts (TRD) after mechanical impact by rockfall (Stoffel, 2008), sampling was preferably performed at the level of observed bounce heights (i.e., visible impacts) at the study site (which is usually < 2 m at Hechenberg). As TRD are known to form even at some distance of scars (Schneuwly et al., 2009b), increment cores were extracted at ~0.5, 1.0, and 1.5 m to maximize chances of impact detection in case no injury was visible on the stem surface. One additional core was extracted on the undisturbed downslope side and as close to the ground as possible so as to determine the age of the tree and as a reference for cross-dating purposes. In most cases, visible impacts were observed on the stem of *P. abies* trees, so cores were extracted as close to the injury as possible and following the recommendations of Stoffel and Bollschweiler (2008). In case that more than three injuries were visible on the surface, additional cores were taken; for injuries located close to each other, one increment core was extracted between the scars.

Events in *P. abies* were dated via the identification of typical growth disturbances in the tree-ring record (Stoffel et al., 2005b; Schneuwly et al., 2009a,b). In this study, TRD were the most dominant growth disturbance (89%). In 6% of the cases, rockfall events were identified via the presence of injuries on the increment core. The remaining events were dated via callus tissue (5%) and compression wood (< 1%).

3.2. Sampling procedure and analysis of F. sylvatica using a scar count approach

As a result of the smooth and thin bark, the effects of mechanical impacts remain clearly visible as a scar on the trunk on *F. sylvatica* for a long time. Events were thus reconstructed through a simple count of wounds visible on the stem surface.

Recent rockfall impacts can be identified by their fresh appearance, chipped bark, or injured wood (Fig. 2A). Wounds in the healing process are not yet closed and can be identified by the overgrowing callus tissue and overgrowing wood that is sealing the injuries from the borders toward the center (Fig. 2D). Completely healed injuries stay clearly visible as scars on the stem surface, which are often bulgy and eventually flatten again with increasing age (Fig. 2B, C).

Table 1
Overview of the tree species, extracted increment cores and diameter of the sampled trees.

Species (Analysis method)	*Picea abies* (Tree-ring analysis)	*Fagus sylvatica* (Scar count method)
No. of trees	33	50
No. of cores	144	50
Diameter (DBH) in cm (STDEV)	48 (16)	38 (14)

To avoid misclassifications from other causes of injury (such as woodpecker damage, hail, falling neighboring trees, or branches), we excluded extremely long, vertical injuries as well as very small scars with a height < 3 cm. Furthermore, we excluded branch scars, i.e., typical structures originating from former branches that were removed by self-pruning.

In the case of *F. sylvatica*, only one increment core was extracted on the undisturbed downslope side of the tree as close to the ground as possible so as to determine tree age.

3.3. Calculation of return periods

Return periods were calculated for each individual tree by dividing its age with the number of impacts. As impacts in case of *P. abies* were identified within the timeframe represented on the increment core, the longest tree-ring series of a given tree represents its age. For *F. sylvatica*, we assumed that injuries stay visible on the stem surface over the whole lifespan of the tree. Therefore the real age of trees was reconstructed by adding missing rings in case the pith was missed during sampling: missing rings toward the pith were estimated by tracing the curvature of the inner rings and fitting circles to them (Norton et al., 1987; Duncan, 1989) using a transparent sheet with concentric rings (Bosch and Gutiérrez, 1999). The number of missing rings/years was calculated by dividing the length of the missing radius by the mean growth rate of the five tree rings adjacent to the largest visible arc on the increment core (Rozas, 2003). Additionally, missing rings originating from sampling height above ground level were added (McCarthy et al., 1991). Based on field observations, vertical growth was assumed to be ~10 cm y^{-1} at the study site, meaning that for a core extracted at 30 cm above ground, we added 3 years. Return periods were visualized for individual tree locations and spatially interpolated using the ordinary kriging model provided in ArcMap 9.3 (ESRI, 2001).

3.4. Comparison of the results

As the sampled trees are scattered across the slope, results derived from both approaches were compared on the basis of an error map with raster cells of 40 m × 40 m. Only cells were considered where both species were present. For comparison, a normalized number of impacts $N_{normfagus_i}$ was calculated for each *F. sylvatica* tree (i):

$$N_{normfagus_i} = \frac{\left(N_{fagus_i} * N_{totpicea}\right)}{N_{totfagus}} \tag{1}$$

where N_{fagus_i} represents the number of impacts recorded in *F. sylvatica* tree (i), $N_{totpicea}$ is the total number of impacts derived from the dendrogeomorphic analysis of all *P. abies* ($N_{totpicea} = 277$), and $N_{totfagus}$ the total number of impacts observed in *F. sylvatica* trees ($N_{totfagus} = 1140$).

In a second step, the mean absolute error (MAE_j) was calculated for each raster cell (j). It represents the variation in cell (j) between the mean normalized number of impacts per tree observed on *F. sylvatica* trees $N_{normfagus_i}$ and the mean number of impacts derived from *P. abies* trees N_{picea_i}

where n_{fagus} represents the number of *F. sylvatica* trees and n_{picea} the number of *P. abies* trees per cell:

$$MAE_j = \frac{1}{n_{fagus}} \sum_{i=1}^{n} N_{normfagus_i} - \frac{1}{n_{picea}} \sum_{i=1}^{n} N_{picea_i}. \tag{2}$$

When comparing both approaches, one has to be aware of the small-scale variability of rockfall impacts that can occur in one cell and that may stem from factors that are independent of the different methods applied. These variations in observed numbers of impacts may arise, e.g., from small-scale topographic features, tree locations,

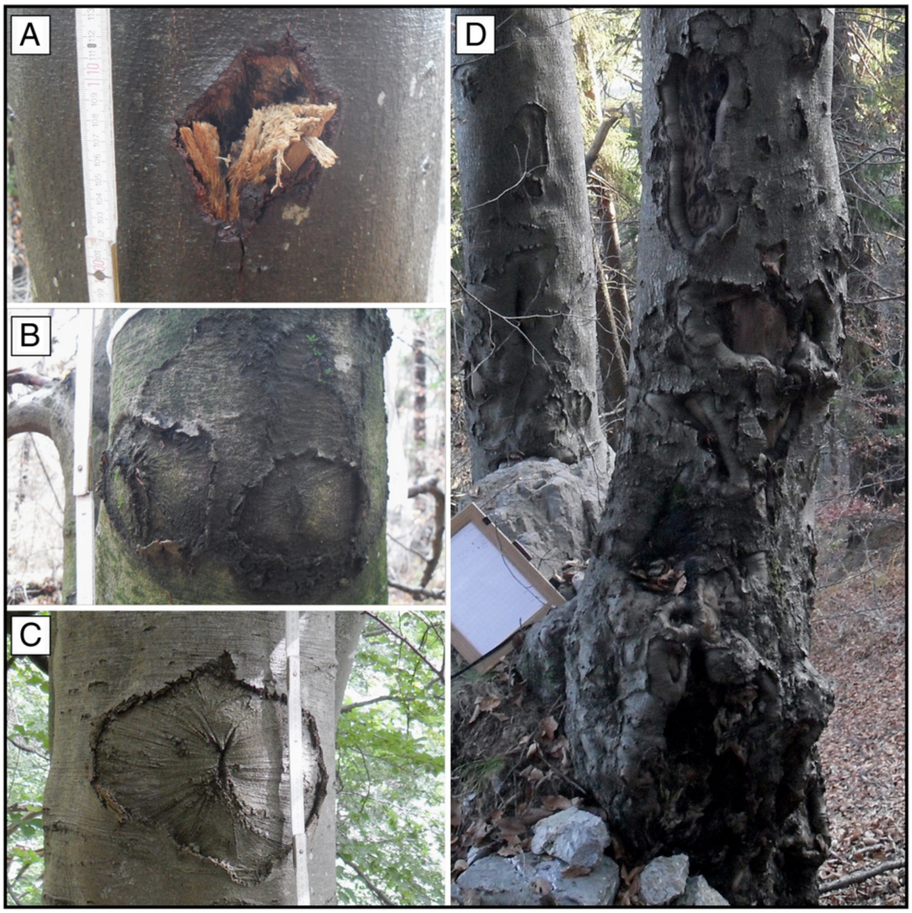

Fig. 2. Typical injuries induced by rockfall on common beech (*Fagus sylvatica*): (A) recent injury with destroyed wood fibers; (B) and (C) completely healed wounds, note the older scar beneath the two younger impacts in (B); (D) heavily disturbed *F. sylvatica* stem with several wounds in the healing process.

tree age, or simply by coincidence. As the results derived from *P. abies* serve as values for the verification of the simplified scar count approach using *F. sylvatica*, the variation in the number of impacts in *P. abies* was seen as a standard for the acceptable variation within the given cell. Similarly, variations between both approaches were seen as acceptable as long as they remained smaller than the variations in the *P. abies* approach itself. For the purpose of verification, we introduced a mean absolute error from the *P. abies* data set (MAE_{picea}) as a reference for an acceptable variation within each cell. The MAE_{picea} was calculated as the mean difference between the highest number of impacts on *P. abies* trees $N_{picea_{max}}$ and the lowest $N_{picea_{min}}$ for all cells (n_j) where more than one *P. abies* was present.

$$MAE_{picea} = \frac{1}{n_j} \sum_{j=1}^{n} \left(N_{picea_{max}} - N_{picea_{min}} \right) \quad (3)$$

Results from Eq. (2) were accepted if MAE_j remained within the range of $\pm MAE_{picea}$ (i.e., ± 5.7 impacts tree^{-1}).

4. Results

4.1. Number of rockfall impacts

The oldest tree-ring record from *P. abies* dates back to A.D. 1761; the oldest *F. sylvatica* had 195 growth rings at sampling height (A.D. 1816). Through the absolute dating of *P. abies* injuries, the oldest rockfall event could be dated to 1819.

Analysis of the increment cores of *P. abies* yielded 277 rockfall events, whereas 1140 rockfall scars were counted on the stem surface of the *F. sylvatica* trees (Table 2). As a consequence, considerable differences exist in the mean numbers of impacts per tree with 8.4 for *P. abies* and 22.8 for *F. sylvatica*. Although the trees selected for analysis grow at comparable locations on the slope, we realize that *F. sylvatica* appears to be affected almost three times more often than *P. abies*.

Despite the huge differences in absolute numbers of impacts, the spatial pattern of rockfall impacts (and hence activity) exhibits similar zones of enhanced and less frequent activity on the slope (Fig. 3): Both series exhibit a decline in the absolute number of impacts from the upper parts of the study reach toward the lower part. The highest activity is recorded for *F. sylvatica* in the upper central part of the site.

4.2. Return periods

The significant difference in absolute numbers of recorded impacts also results in considerably differing mean return periods for both species. Using the classical dendrogeomorphic approach (*P. abies*), an average return period of 18.4 years is obtained, whereas the scar

Table 2
Overview of impacts for different methods, tree age, and calculated return periods.

Species	*P. abies*	*F. sylvatica*
No. of visible impacts	266	1140
No. of impacts from tree-ring analysis	277	–
Sample age in y (STDEV) and tree age [a]	135 (53)	116 (43)/134[a] (44)[a]
Mean number of impacts per tree	8.4	22.8
Mean return period in y	18.4	8.7

[a] Reconstructed age takes account of missing rings.

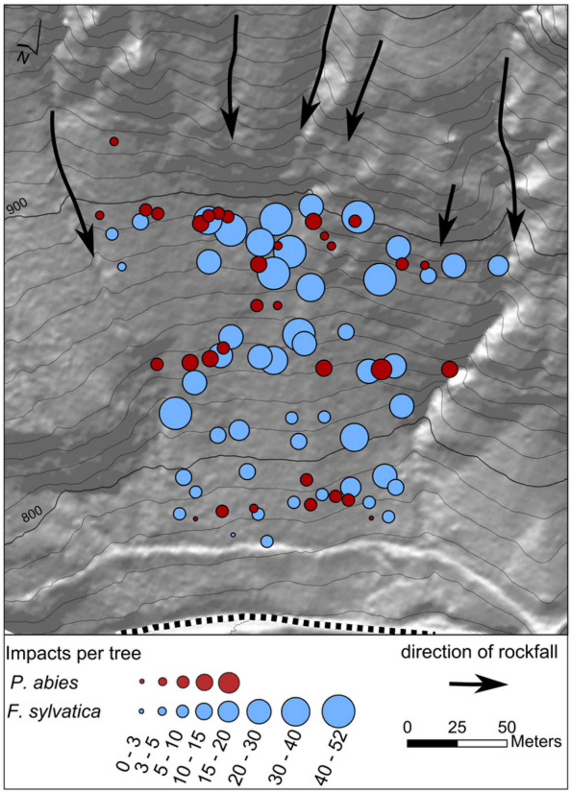

Fig. 3. Absolute numbers of impacts on individual trees at Hechenberg. Although *F. sylvatica* shows much more evidence of rockfall activity as compared to *P. abies*, the distribution of zones strongly and less affected are comparable.

count approach (*F. sylvatica*) results in a mean recurrence interval of 8.7 years. Values differ less drastically but still significantly between the approaches, whereas spatial patterns (Fig. 4) show again certain similarities. Results from both approaches point to more frequently recurring rockfall activity in the upper part of the study reach as well as in its eastern part. However, spatial patterns are more consistent in Fig. 4B (scar count approach), as (i) sectors with differing return periods can be delimited more clearly and as (ii) variations between neighboring trees are less important as compared to *P. abies*.

4.3. Comparison of result

The numbers of scars for individual trees can vary significantly within the same sector as a result of the small-scale variability of rockfall processes. Nevertheless, a comparison of both approaches on the basis of grid cells as presented in Fig. 5 suggests that the variation between both approaches is acceptable in 13 out of the 15 cells analyzed (87%) if absolute numbers of impacts are normalized.

Grid cells where the scar count approach yields slightly higher impact values ($MAE_j > 0$) are located in the upper central part of the slope where the highest rockfall frequencies were reported with both methods and where extensive talus bodies witness numerous rockfalls with preferably small-sized (~2×10^{-4} m^3) clasts.

Major differences in results between the two approaches exist in the cells given in light red in Fig. 5 (central eastern part), where the classical tree-ring reconstruction yields higher numbers of impacts as compared to the scar count. Mean tree age is similar for the trees in these cells (145 years for *P. abies*, 159 years for *F. sylvatica*) and only slightly more cores per tree (4.7) than average (4.4) were extracted. The reasons for the observed variation are therefore not obvious but might be reflective of different tree locations and hence different susceptibilities to rockfall impacts.

5. Discussion

In the study presented here, two approaches were used for the reconstruction of spatial and temporal patterns of rockfall with the aim of testing the validity and quality of a simplified scar count approach. Both approaches yield comparable areas of increased rockfall activity, but huge differences exist in absolute numbers of events and return intervals obtained with the two different techniques. As a result, while yielding absolute dates of events, the classical dendrogeomorphic approach produced almost three times less rockfall impacts as compared to the scar count approach.

The first reason for the differences is the effect of hidden scars. Because coniferous trees mask scars of past events effectively (Stoffel and Perret, 2006), the existence and/or position of old scars can often not be detected on the stem surface, rendering the determination of

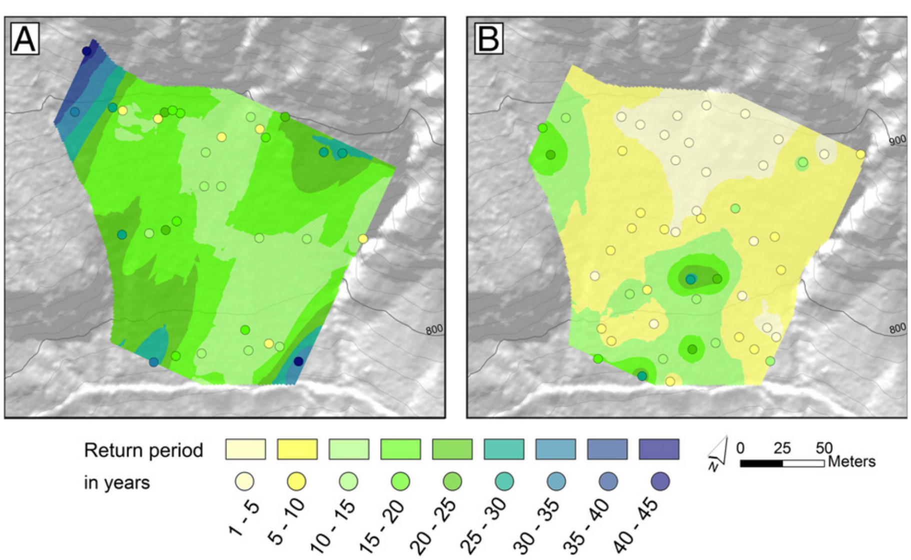

Fig. 4. Return periods calculated for (A) *P. abies* and (B) *F. sylvatica*, illustrated for individual tree locations and spatially interpolated (ordinary kriging).

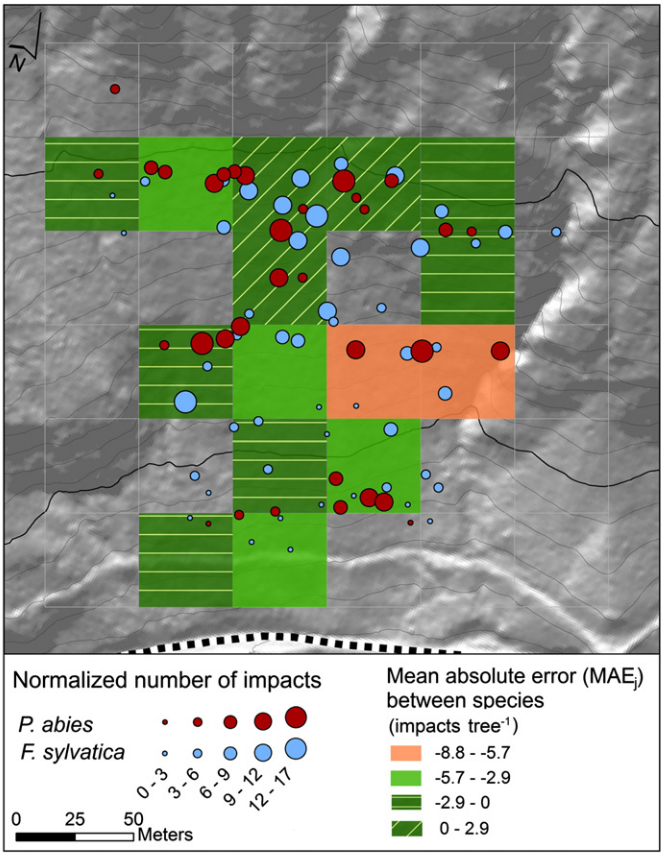

Fig. 5. Spatial distribution of numbers of impacts on *P. abies* (red circles) and *F. sylvatica* (blue circles, normalized); in grid cells with both species present, the variation of the mean number of impacts (MAE_j) between the species are depicted.

suitable sample positions a difficult task. Older events can therefore be missed on increment cores of *P. abies*, and older trees will tend to yield data on fewer impacts relative to their age (Fig. 6), which in turn will result in higher return periods. This assumption is supported by the weak positive correlation between tree age and return period for *P. abies* (Pearson´s linear squared correlation coefficient $R^2 = 0.157$). No such dependence of tree age and return periods could, in contrast, be observed for *F. sylvatica* ($R^2 = 0.004$). Return periods can therefore be derived with high confidence and independently of age in *F. sylvatica*, which is likely the reason for the higher consistency of spatial patterns of return periods in *F. sylvatica* (Fig. 4).

The masking of wounds can be highly variable due to the initial size of the injury, vitality of the tree, its genetic capability to overgrow injuries, bark structure, annual increment rates, or tree age, just to name a few. In general, tree species with a thick and structured bark will mask scars more efficiently than those with thin and smooth bark structures (Stoffel and Perret, 2006). Stoffel (2005), for instance, could identify 75% of all scars by visual interpretation of bark structures on *F. sylvatica*, whereas only 51% of the injuries remained visible on the stem surface of *P. abies*. The correlations between tree age and return periods of our study support these findings, and point to the possibility that almost all scars would remain visible on the stem surface of *F. sylvatica* if they are not blurred by later impacts at positions that have been affected before (Fig. 2D).

A second reason for the difference in results is that one single rock might leave multiple scars on the stem surface of *F. sylvatica*. Using the scar count approach, each injury is considered an individual rockfall which might, however, result in an overestimation of real frequencies. We therefore suggest that scars located very close to each other would not be considered as individual events in future studies. On the other hand, multiple impacts in the same year or events in subsequent years would not necessarily be considered multiple events in *P. abies*, since TRD will tend to form over several years (Schneuwly et al., 2009b). This might, in turn, have resulted in an underestimation of rockfall frequencies at Hechenberg.

Last not least, species-related bark and wood properties may have led to different sensitivities of trees to be injured by mechanical impacts. While the xylem of *F. sylvatica* is comparably hard and covered with a thin bark, the xylem of *P. abies* is softer and coated by a thicker bark. Impacts of smaller rocks with low energy may consequently leave scars on *F. sylvatica*, while the same impact may be buffered by the bark of *P. abies* and not cause any visible growth disturbance in the tree-ring record.

6. Conclusion

Findings of this study indicate quite clearly that an assessment of rockfall activity based on visible tree damage will result in different absolute numbers of past events as compared to dendrogeomorphic approaches. While classical tree-ring studies typically present a minimum frequency of past events and therefore may tend to underestimate rockfall activity, the counting of visible scars on the stem surface of *F. sylvatica* may, in contrast, lead to an overestimation of frequencies.

The scar count method is not meant to substitute classical tree-ring studies, since scars cannot be dated with yearly precision and causes of individual rockfall events cannot be analyzed based on the temporal variation of rockfall activity. Nevertheless, the approach has been shown to represent an efficient and effective method for the spatial assessment of rockfall activity on larger surfaces, as it can be realized with limited temporal and financial efforts, provided that the sampling design and questions of sample depth are optimized and that the issue of masked scars and the role of multiple impacts are addressed in greater detail.

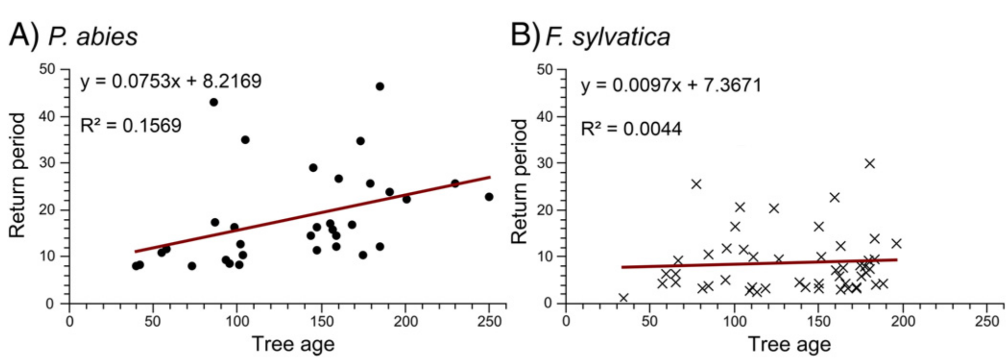

Fig. 6. Correlation between tree age and return period of rockfall events for (A) *P. abies* and (B) *F. sylvatica* and based on different approaches (classical dendrogeomorphology and scar counting).

Acknowledgments

The authors are grateful to Johannes Hübl, Michael Grabner, and Michelle Schneuwly-Bollschweiler for their support and helpful comments. We also acknowledge the Bundesforste AG for coring permissions.

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