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ORIGINAL PAPER

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Inventory and analysis of tree injuries in a rockfall-damaged forest stand

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Abstract Rockfall is a major threat to settlements and transportation routes in many places. Consequently, the protective function of mountain forests has recently gained particular interest. However, much is still unknown about the ideal properties of protective forest stands. Therefore the present paper discusses a method for the inventory and analysis of tree injuries in a rockfall-damaged forest stand. With this method, the interrelation between stand geometry and rockfall injuries in a subalpine *Polygalo chamaebuxi-Piceetum* was examined. The study site of 0.3 Ha is located in the transit zone of frequently passing, small rockfall fragments (~10 cm in diameter) causing healable tree injuries. Tree and injury parameters were recorded and analysed as to injury number, height and size. The spatial distribution of the 157 trees (diameter at breast height dbh > 5 cm) in the stand as well as of the 1,704 identified rockfall injuries showed a very uneven pattern. As expected, number, height and size of the injuries generally declined with increasing distance from the cliff as well as due to higher stem densities. In contrast, results indicated that the dbh of trees has no significant influence on the number of injuries per tree. However, this study showed a clear interrelation between tree and injury distribution: in general, large trees close to the cliff and smaller trees with a high density further down the slope seem to be favourable for good protection. At least an uneven-aged, multilayered stand should be sustained. Overall, the combined analysis of stand geometry and injury parameters provides information on the spatial distribution of rockfall and on the influence of tree arrangements.

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Introduction

While in many countries economic demands on mountain forests have recently decreased, their protective function has gained particular importance (Berger et al. 2002). The reason for this is that natural hazards, such as rockfall, are major threats to settlements and traffic routes in large parts of the Alps and other mountainous regions (Varnes 1978; Hutchinson 1988; Hungr et al. 1999; Erismann and Abele 2001; Budetta 2004). Appropriate measures have to be taken for public protection. For this purpose the adequate management of protective forest stands might well be the most sustainable method with which to optimise protection and to minimise costs at the same time (Berger and Rey 2004; Dorren et al. 2004). However, mountain forests are also highly sensitive to natural and anthropogenic disturbances. Hence, for a better understanding of cause—effect relationships between major processes in mountain ecosystems, there is a need for observation and inventory activities, combined with experimental studies (Kräuchi et al. 2000; Naylor et al. 2002). Such investigations at the same time form the basis for hazard analysis and risk assessment (Kienholz 1995; Kienholz et al. 2002).

The general protective function of mountain forest against rockfall—the natural hazard that is under consideration here—is not questioned nowadays (Jahn 1988; Mani and Kläy 1992; Gsteiger 1993; Berger and Rey 2004). However, little is known about the ideal properties of a forest stand that provides maximum protection. The following facts are given so far (BUWAL 1996; NaiS 2003, Thormann and Schwitter 2004): in the transit zone of rockfall, the contact with trees can decelerate rocks and blocks or stop them temporarily. With deceleration, the jump height of rocks is also reduced. The effect of a tree contact mainly depends on tree diameter and rock size. Depending on the energy of a rock impact, trees can be tilted, injured or broken. Consequently, the velocity and energy of the rocks are substantially reduced. The forest effect against very large blocks is limited. In addition to tree diameters, stem densities are also very important: a high stem number normally results in a high number of rock—tree impacts. However, the maximum stem number in a given forest stand is limited depending on the tree species, age distribution of the trees and other environmental factors.

In general, the protective effect of a specific forest stand is dependent on several influencing factors: (1) on the geometry of the stand (stem number, diameters and arrangement); (2) on the size, velocity and energy of the falling rocks; (3) on the vulnerability of trees as well as on the rock—tree interaction and (4) on the influence of the ground surface and subsurface. Some of these different aspects of the interaction between rockfall and forest were already investigated by Jahn (1988), Zinggeler et al. (1991), Mani and Kläy (1992), Gsteiger (1993), Dorren and Seijmonsbergen (2003), Perret et al. (2004) and Stoffel et al. (2005), mostly on a local scale. However, studies on the scale of single trees are so far lacking.

The present paper discusses a simple but detailed method for the inventory and analysis of tree injuries in a rockfall-damaged forest stand. The objective of the study was to examine the interrelation between stand geometry (spatial distribution of trees and tree diameters) and rockfall injuries (number, height and size) in a subalpine *Polygalo chamaebuxi-Piceetum* stand with an important protective function. The investigated stand is located at the foot of a high cliff in the transit zone of frequently passing, rather small rockfall fragments (mean diameter about 10 cm) causing mainly small, healable tree injuries. Analyses of all rockfall injuries visible on the stem surfaces (i.e. recent and old injuries at any stage of healing) were performed so as to investigate their significance for the assessment of the protective effect of a stand. Thus, the study provides a contribution to the interdisciplinary problem on how to assess the protective effect of a specific forest stand against rockfall.

Methods

Study site

The inventory method for rockfall-damaged forest stands was developed on a study site in Diemtigtal in the Swiss Prealps (Canton of Berne, 7°33′E, 46°36′N, 1,240 m a.s.l.). Fig. 1 shows the approximately 400-m high Triassic limestone cliff of Schwarzenberg, at the foot of which a deep, southeast exposed talus slope with a slope angle of about 40° is located. This talus slope with a relatively homogenous topography is forested with a *P. chamaebuxi-Piceetum*. According to Ott et al. (1997) this forest type is usually found in montane to subalpine environments in the northern limestone Alps on dry, alkaline, steep and south-facing sites; stand structure is rather open and trees mainly grow on elevated sites and in clumps. The study was performed within the indicated stand of about 0.3 Ha (cf. Fig. 1), situated in the transit zone of frequently falling rock fragments, which only have a mean diameter of about 10 cm.

Recording of tree and injury parameters

As stand geometry is an important factor when assessing the protective effect of a specific forest stand (Bebi et al. 2001), the first step of the inventory was the *recording of tree parameters*: the spatial distribution of the single trees was determined by means of aerial photogrammetry (e.g. Uuttera et al. 1998; Miller et al. 2000), which provided coordinates of the clearly visible over-storey trees. The remaining trees were measured manually in the field, by determining the horizontal distance and the azimuth to one or two over-storey trees. Thereafter tree species, dbh (at the upslope side of the stem), storey, growth-shape and vitality were recorded for every tree, following Stierlin et al. (1994). There was no lower diameter limit for the recording of a tree, but every tree reaching the height of at least 1.3 m was measured.

The second step of the inventory comprised the *recording of injury parameters*, which provide information on the spatial distribution of rockfall, on rock sizes and jump heights. The method for the recording of rockfall injuries is based on propositions made by Gsteiger (1993) and Mattheck and Breloer (1994). First,

Fig. 1 Study area at the foot of Schwarzenberg in Diemtigtal, Switzerland (location see Fig. 4)

every rockfall injury was given an identification number. As in the investigated area no other geomorphic processes such as landslides, debris flows or snow avalanches are found, in general, every tree injury should result from a rockfall. However, to make sure that only rockfall injuries were recorded, injuries on the downslope side of a stem as well as injuries located considerably higher on a stem than most other injuries in the area were neglected. Also injuries much larger than the other injuries or injuries looking very different from the injuries caused by a rock impact were excluded. Finally, as close to roads or in areas with former thinning man-induced injuries are frequent, such areas were omitted.

The recording of every rockfall injury then included two steps: first the injury was characterised by assigning an *injury type* as listed in Table 1. Fig. 2 shows a typical injury of type 2 "injury to bark and wood". A single injury can also be described by more than one type—for example by types 2 and 6 if it is a fresh "injury to bark and wood" with "resin flow". Besides injury type, parameters such as injury height, size, position on the stem and stage of healing are also of interest. Therefore, in a second step, the *injury geometry* (cf. Fig. 3) was assessed by means of five quantitative parameters as described in Table 2.

Table 1 Frequency of the ten different injury types

	Injury type	Frequency
1	Injury to the bark	1,460
2	Injury to bark and wood	220
3	Open rot cave starting from rockfall injury	9
4	Buckle over rockfall injury	159
5	Buckle over rot cave starting from rockfall injury	25
6	Resin flow (fresh and transparent to bright yellow)	198
7	Resin burls (old and yellow to dark brown)	360
8	Radial crack starting from rockfall injury	14
9	Rib starting from rockfall injury (healed radial crack)	2
10	Inclusion of a rock	6

On average every rockfall injury (total number 1,704) was described by one or two injury types. Type 1 (injury to the bark) is including injuries with resin burls or callus margins occluding the underlying wood

Fig. 2 Injury to bark and wood (*P. abies*)

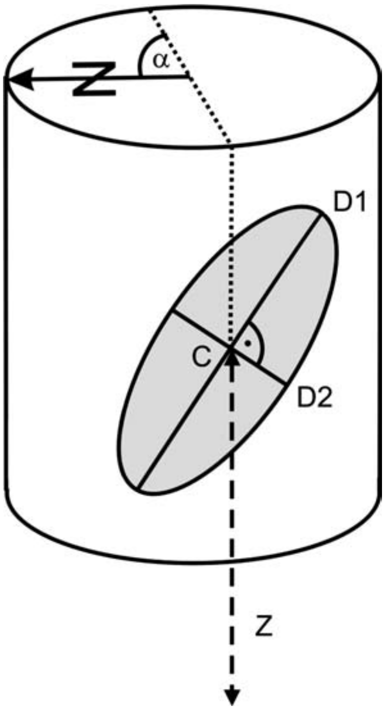

Fig. 3 Injury model (description of injury parameters see Table 2)

Statistical and spatial analyses

Data analysis was performed as to assess the interrelation between stand geometry and tree injuries. Tree and injury parameters were visualised as well as analysed statistically and spatially. Besides analyses for the whole stand, different parts of the stand were examined separately, for detailed comparisons: on the one hand, the middle part was divided into two subareas (S1 and S2) along the fall line (420 m^2 each), which have an almost identical dbh distribution but a different stem arrangement and density. Both subareas also show the same tree species distribution. On the other hand, the stand was divided into an upper, a middle and a lower part, which are similar in size but differ in stem number and arrangement as well as in dbh and tree species distribution.

Statistical analyses (all performed with *SPSS 11.5.1* by SPSS Inc. 2005) comprised the calculation of stand parameters such as stem density per hectare, dominant dbh, basal area and basal area mean diameter of the stand. Furthermore, injury parameters such as mean injury number, height, diameter and area per tree as well as their standard deviations (SD) were calculated. Pro-

Table 2 Five parameters for the description of the injury geometry

	Injury geometry	Description of the parameter	Use of the parameter
1	Height *Z* (cm)	Height above ground (upslope side of the stem) of the injury centre C	Reconstruction of the injury height
2	Diameters *D* (cm)	*D*1 max. injury diameter (incl. callus margins), *D*2 max. diameter vertical to *D*1	Reconstruction of the original injury size
3	Shape	Assignment of an ideal geometrical shape: circle, ellipse, square, rectangle or triangle	Reconstruction of the injury area
4	Azimuth α (°)	Azimuth angle of the injury centre C	Reconstruction of the radial injury position
5	Callus margin	Size of the callus margin in percent of the whole injury area: 0, <10, >50 or 100%	Reconstruction of the stage of injury healing

portions of injury types, stages of healing and radial positions on the stem were also examined. In addition, between different parts of the stand comparisons of means were performed for the number, height and area of injuries per tree. As the number of injuries per tree showed a normal distribution (graphical test with histogram and QQ plot) comparisons were performed with a *t*-test for independent samples with inhomogeneous variances. The mean injury heights and areas per tree were compared using the nonparametric Mann–Whitney test for independent samples with inhomogeneous variances. The means compared were considered to be significantly different at $P < 0.05$.

Furthermore, bivariate correlation analyses were used in order to explore any relationship (1) between the number of injuries per tree and the dbh of every tree and (2) between the number of injuries per tree and the distance to the cliff of every tree. For all correlations, the nonparametric Spearman-Rho Correlation Coefficient (r_s) was calculated and correlations were considered to be significant at $P < 0.05$. Moreover, so as to further explore the relationship between the number of injuries per tree (dependent) and the dbh as well as the distance to the cliff of every single tree (predictors), a simple multiple linear regression model was tested: number of injuries per tree $= f$ (dbh, distance to cliff).

For spatial analyses of features such as number, height and size of the injuries, data were edited with *ArcView GIS 3.2* by ESRI (2005). As tree coordinates were known, trees could easily be placed in the GIS as geo-objects and the related attributes were linked with the trees. By performing spatial linear interpolations with ten neighbouring trees and a grid size of 1 m, the distribution of injury parameters was visualised. Furthermore, stand geometry was characterised qualitatively as well as via the "mean tree-free distance" (MTFD), a concept proposed by Gsteiger (1993). This parameter indicates the mean distance a falling rock in a given stand can move along the fall line between two tree impacts. The MTFD, as given in Fig. 4, is depending on stem number, mean dbh (m) and mean rock diameter (m) in a given area (m^2):

$$\mathrm{MTFD} = \frac{\mathrm{area}}{\mathrm{stem\,number(mean\,dbh + mean\,rock\,diameter)}}.$$

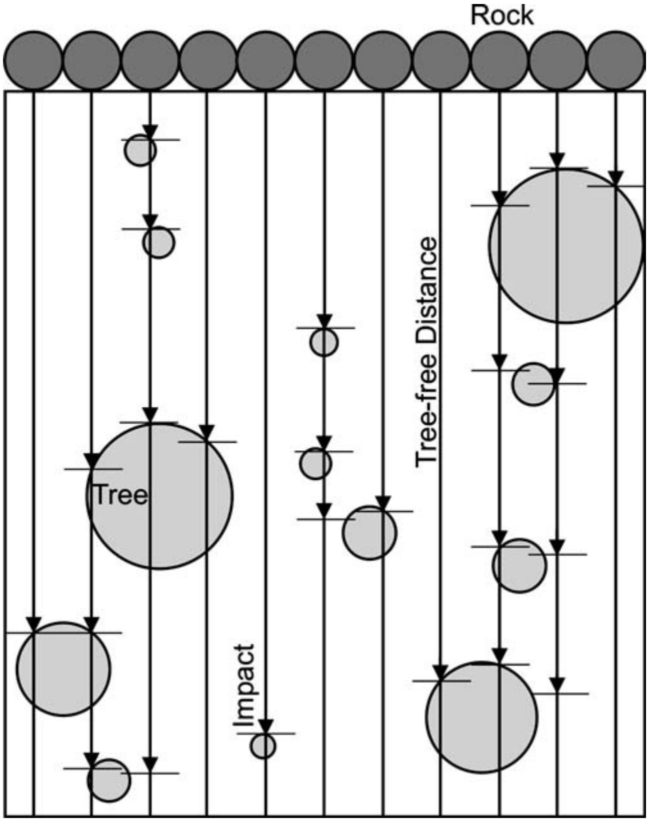

Fig. 4 Concept of the "mean tree-free distance" (MTFD) along the fall line. This parameter indicates the mean distance a falling rock in a given stand can move along the fall line between two tree impacts

Due to the steep terrain, the slope distance was used for the calculation of the area.

Results

Stand characteristics

The investigated stand covers an area of about 0.3 Ha (25 m × 120 m slope distance) and consists of 221 trees, but only 157 trees have a dbh larger than 5 cm. For these 157 trees, a mean density of 520 stems/Ha is calculated. The dominant dbh (mean of the 30 largest stems

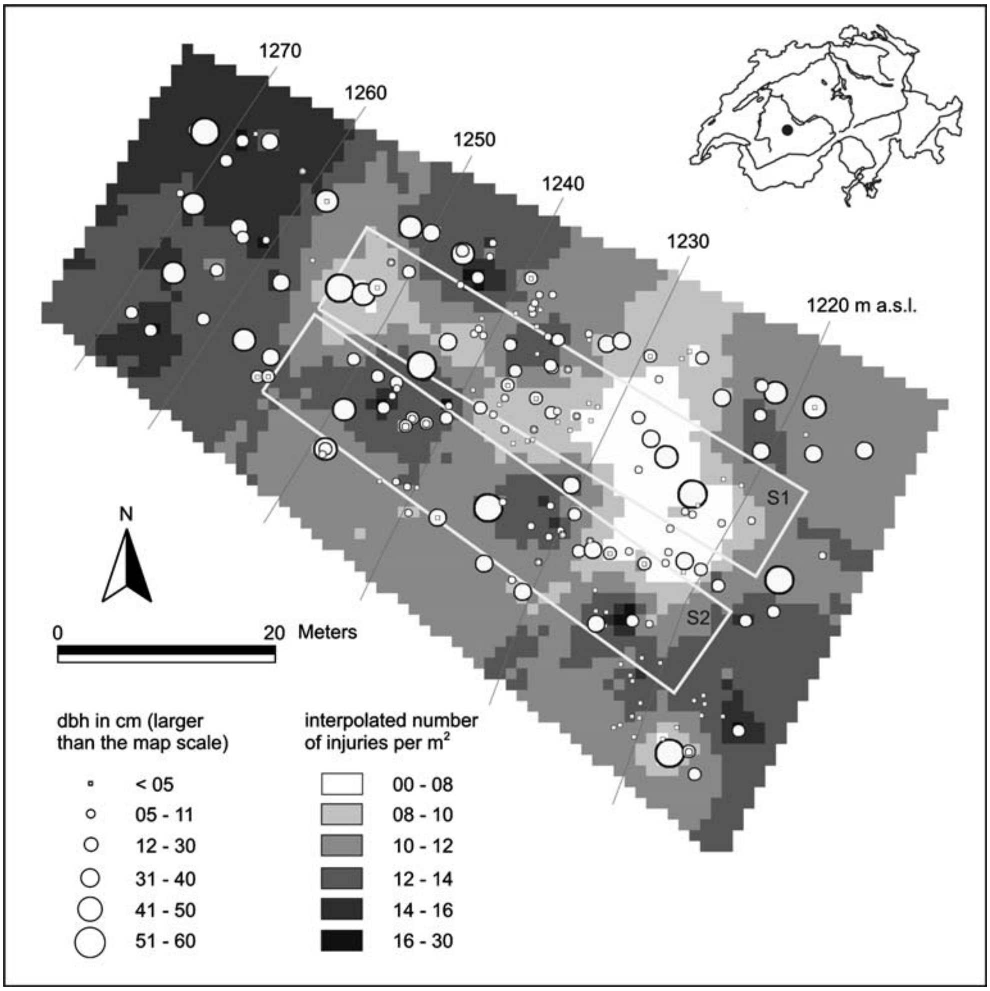

Fig. 5 Stem and dbh distribution as well as interpolated number of tree injuries per m^2 in the study area in Diemtigtal, Switzerland (location see map in the right upper corner); *S1* subarea 1, *S2* subarea 2

per 0.3 Ha) amounts to 44.7 cm (SD = 6.9), which according to Stierlin et al. (1994) corresponds to a level of development of a “mean high forest”. The stand basal area for the 157 trees is 25.8 m^2/Ha and the basal area mean diameter therefore amounts to 25.1 cm. Consequently, the dbh of dominant trees is considerably larger than the basal area mean diameter, which indicates that a high number of thin trees is found in the stand. The predominating tree species is *Picea abies* (L.) Karst with 121 individuals. *Sorbus aria* (L.) Crantz and *Sorbus aucuparia* L. are represented by 65 individuals and *Acer pseudoplatanus* L. by 25 individuals.

In Fig. 5, a map of the stand under investigation is given; the foot of the rock cliff borders on the stand in the north-west. The map shows the exact location of all 221 trees with the according dbh classes as well as the interpolated number of rockfall injuries. Both the stems and stem diameters show an uneven spatial distribution: close to the cliff, where low stem densities are found, large stem diameters clearly predominate and there is almost no regeneration in this area. The lack of light, soil material and water hinder regeneration; the unstable, sharp-edged debris fragments on the ground surface damage every growing shoot. The highest stem density is found in the middle of the stand, where mainly trees with small diameters grow. When comparing the two subareas, it is evident that in S1, there are some thick trees in the upper part, and several thin trees forming a dense thicket below. In contrast, trees are more scattered in S2 and they are growing in clumps. Overall stem density is higher for S1 (830 stems/Ha) than for S2 (760 stems/Ha).

‘The MTFD for the investigated stand was calculated as follows: taking into account the 157 trees (dbh > 5 cm) with a mean diameter of 0.21 m in the 3,000 m^2 area, and assuming a mean rock diameter of 0.08 m (estimated on the basis of the rock fragments on the ground), the MTFD amounts to 66 m. Thus, theoretically a small rock can easily cross half of the stand (120 m slope distance) without hitting any tree. However, as most of the 64 trees with a dbh ≤ 5 cm also show rockfall injuries, thin stems must as well have a considerable influence on rockfall processes. In fact, taking into account all 221 trees, the MTFD is reduced by 9 m down to 57 m. Because of the uneven tree distribution, not only does the stem density vary on a small scale, but also the MTFD: as shown in Table 3, the MTFD is somewhat shorter for subarea

Table 3 "Mean tree-free distance" (MFTD) for the whole stand as well as for subareas S1 and S2

Area	MFTD (m) for trees > 5 cm dbh	MFTD (m) for all trees
Whole stand	66	57
Subarea 1	43	27
Subarea 2	46	40

S1 than for subarea S2. Taking all trees into account, the MTFD is also reduced considerably and for S1 it only amounts to 27 m.

Rockfall injuries

For the 157 trees with a dbh > 5 cm, a total number of 1,704 rockfall injuries was registered, which is a mean number of 11 injuries per tree (SD = 5.1). As expected, analysis of the *azimuth* α revealed a clear maximum of the number of injuries at the upslope side of the trees: 63% of all injuries were located within a 90° sector around the fall line. Furthermore, on average, every rockfall injury was described by one or two injury types. As seen in Table 1, the predominant injury type was "injury to the bark", whereas "injury to bark and wood" occurred much less. However, as injuries with resin burls or closed callus margins that occlude the underlying wood were also classified with "injury to the bark", this category probably was mentioned too frequently. For all these injuries it is no more possible to define whether the impact affected the bark and wood–except by means of dendroecological methods (Schweingruber 1996; Stoffel 2005). Because of the large number of *P. abies*, which generally produce plenty of resin, a high number of recent "resin flow" and old "resin burls" were also encountered. Moreover, analysis of the *callus margin* classes showed that almost 80% of all injuries were completely healed. With 13% of the wounds, the healing was advanced, while only 7% formed no or virtually no callus margin yet.

Besides the tree arrangement, the map in Fig. 5 also shows the spatial distribution of the *number of injuries*: the darker the pattern, the more the injuries. Obviously, not only trees but also injuries are unevenly distributed. In the upper part of the stand, there are clearly more injuries in the northern than in the western corner. Possibly rocks are channelled in the cliff and therefore enter the stand more frequently in the northern part. Moreover, there is a general decrease in the number of injuries from top to bottom as well as a distinct small-scale variability. This is also given in Table 4, which provides the total and mean number of injuries per tree for different areas: in subarea S1, a total number of 314 injuries, concentrated mainly in the upper part, was found, whereas in subarea S2, 452 injuries, distributed along the whole slope were counted. Furthermore, it is obvious that the highest mean number of injuries per tree is found in the upper part of the stand, whereas it is significantly lower in the middle and lower part of the stand. As given in Table 5, the comparison of means showed that the mean number of injuries per tree was significantly different for most parts of the stand. However, between the middle and the lower part, the comparison showed no significant difference ($P = 0.125$).

As also provided in Table 4, the overall mean *injury height* in the investigated forest stand was 84.6 cm above ground (with a very high SD of 63.4), whereas for subareas S1 and S2 significantly lower mean heights were calculated. Between S1 and S2, however, the comparison of means (Table 5) showed no significant difference ($P = 0.377$). All other mean injury heights compared were significantly different. Table 4 also shows a clear decline of mean injury heights from the upper to the middle and the lower part of the stand. The maximum injury heights (up to about 4 m) were found just below the cliff where falling rocks may jump at the trees directly out of the wall. Further down, high jumps only occurred where terrain steps in microtopography are found.

The *injury size* was described by means of the *injury diameters* and the *injury area* (cf. Table 2): for the whole stand the mean diameter $D1$ was 10.6 cm (SD = 7.4); the mean diameter $D2$ was 7.1 cm (SD = 4.7); the mean injury area, calculated via the injury shapes, amounted to 76.2 cm^2 (SD = 126.2). As given in Table 4 for subarea S2, these values are about the same, whereas for subarea S1, the mean $D1$ as well as the mean area are significantly smaller. Moreover, it is evident that the largest

Table 4 Total and mean number of rockfall injuries per tree as well as mean injury height, diameter ($D1$) and area for the whole stand and for different parts of the stand (*SD* standard deviation)

Area	Total number of injuries	Mean number of injuries per tree	SD	Mean injury height (cm)	SD	Mean injury diameter (cm)	SD	Mean injury area (cm^2)	SD
Whole stand, 157 trees	1,704	11	5.1	84.6	63.4	10.6	7.4	76.2	126.2
Subarea 1, 36 trees	314	9	3.4	73.1	55.2	9.4	6.0	59.7	75.4
Subarea 2, 38 trees	452	12	6.0	76.1	55.0	10.6	8.5	76.2	132.3
Upper part, 25 trees	334	13	3.9	115.2	70.5	13.4	11.6	127.7	276.2
Middle part, 79 trees	869	11	4.5	80.0	59.1	10.0	8.0	68.7	121.9
Lower part, 53 trees	501	10	6.3	72.0	59.0	11.0	7.7	85.3	140.5

Table 5 Comparison of means between different parts of the stand for the mean number of injuries per tree as well as for the mean injury height and area. Statistically significant differences ($P < 0.05$) are marked in bold (the *t*-test was used for the comparison of the number of injuries; the Mann–Whitney test was applied for the comparison of injury heights and areas)

Compared areas	Mean number of injuries per tree (*P*)	Mean injury height (*P*)	Mean injury area (*P*)
Subarea 1 versus rest of the stand	**0.000**	**0.002**	**0.001**
Subarea 2 versus rest of the stand	0.346	**0.016**	0.257
Subarea 1 versus subarea 2	**0.007**	0.377	0.106
Upper part versus rest of the stand	**0.005**	**0.000**	**0.000**
Middle part versus rest of the stand	0.928	**0.022**	**0.000**
Lower part versus rest of the stand	**0.008**	**0.000**	0.168
Upper versus middle part	**0.014**	**0.000**	**0.000**
Upper versus lower part	**0.001**	**0.000**	**0.004**
Middle versus lower part	0.125	**0.005**	**0.001**

injuries are found in the upper part of the stand. On the other hand, the smallest injuries are located in the middle part, where mainly thin trees grow. This fact indicates that injury size is clearly depending on the dbh as thick trees can have larger injuries than thin trees.

Finally, as given in Fig. 6a, no statistically significant correlation ($r_s = 0.007$, $P = 0.932$) between the number of injuries per tree and the dbh was found. Even if different parts of the stand (subareas S1 and S2, upper, middle and lower parts) are analysed separately no correlation exists. In contrast, a significant correlation ($r_s = -0.273$, $P = 0.001$) between the number of injuries per tree and the slope distance to the cliff was detected (Fig. 6b). The slightly negative correlation coefficient indicates that trees growing closer to the cliff in general show more injuries than trees growing further away from the cliff. As provided in Table 6, the result of the multiple linear regression performed also shows that the distance to the cliff has a larger influence on the number of injuries than the dbh. Although the overall model for the dependent “total number of injuries per tree” and the predictors “dbh” and “distance to cliff” is significant ($P = 0.007$), the proportion of the explained variance only amounts to 6% ($r^2 = 0.063$). Furthermore, the dbh has no significant influence on the number of injuries per tree ($P = 0.454$), whereas the distance to the cliff seems to be a significant factor ($P = 0.002$).

Discussion

The objective of the investigation presented was to develop a method for the inventory and analysis of tree injuries in a rockfall-damaged forest stand. With this method, the interrelation between stand geometry and rockfall injuries was studied so as to assess the protective effect of a *P. chamaebuxi-Piceetum* stand against rockfall. The study site is located in the transit zone of frequently passing, small rockfall fragments (mean diameter about 10 cm).

As mentioned, stems, stem diameters and injury parameters show an uneven spatial distribution in the investigated stand: for the middle part of the stand, the question has to be raised, how the uneven spatial distribution of the number of injuries in the two subareas selected can be explained. Apparently, an interrelation between the spatial tree distribution and the number of injuries must be assumed. Although tree density is higher in S1 than in S2, there are less injuries (in total and per tree) within S1. The influence of the thicket in the middle is rather evident; below this zone, only few injuries are found, as probably many rocks are strongly decelerated or even stopped within the thicket. On the other hand, in subarea S2, there is no thicket, which means rocks travel further down, causing injuries on a

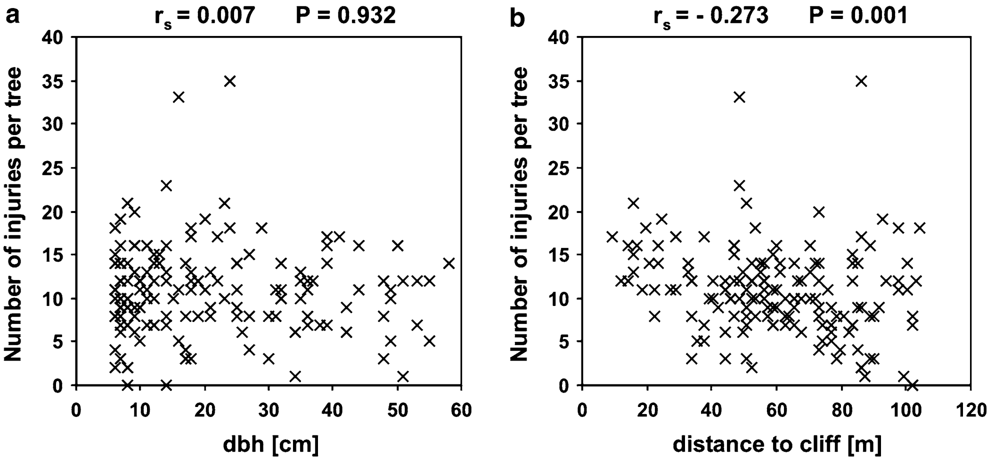

Fig. 6 **a** Statistically not significant correlation between the number of injuries per tree and the dbh; **b** statistically significant correlation between the number of injuries per tree and the slope distance to the cliff of every tree (Spearman-Rho correlation coefficients)

Table 6 Results of the multiple linear regression for the "total number of injuries per tree" as the dependent variable and the predictors "dbh" (tree diameter at breast height) and "distance to cliff" (slope distance tree–cliff)

Dependent: total number of injuries per tree ($r^2 = 0.063$, $F = 5.201$, $P = 0.007$)	Coefficient value B	SE	Standardised coefficient value β	T	P
Constant	14.633	1.316		11.120	0.000
dbh	−2.157	2.871	−0.059	−0.751	0.454
Distance to cliff	−0.056	0.017	−0.251	−3.198	0.002

longer stretch. Presumably, they cannot normally be stopped, but only slightly slowed within the area investigated. Furthermore, due to the higher number of injuries in the upper northern corner of the stand, it is also possible that rocks are entering S1 with lower velocity than S2. They already had more tree contacts, and thus less injuries are caused within S1. In general, it seems to be favourable to have thicker and homogeneously distributed stems in the upper part of the stand, where velocity of falling rocks is still high. Below this zone, rocks normally fall with lower velocity, as they have already bounced against trees or on the ground. Therefore, in this zone, a large number of thin stems or a dense thicket appears to be good to decelerate rocks even more. However, in practice, a forest stand consisting of large trees close to the cliff and of small trees with a high density far from the cliff can normally not permanently be sustained. Nevertheless, it can be concluded that sufficient regeneration in a stand is important, and that an uneven multilayered stand with a mosaic of all tree sizes and age classes provides ideal protection against rockfall, which confirms the findings by Dorren et al. (2004).

Considering the MTFD, the following pattern emerges: although there is a very high number of rockfall injuries in the investigated stand, the MTFD for the whole stand and for a small rock is quite long. This indicates that the stand overall has a rather low retention capacity and therefore its protective effect is only moderate. However, the MTFD is considerably reduced when calculated separately for the two subareas. There are also different patterns between the subareas: as shown, the MTFD is shorter for S1 than for S2, which means the retention capacity for falling rocks is higher within S1 than within S2. Also the substantial influence of thin trees is clearly seen, as the MTFD is again reduced if all trees are taken into account. However, as in S1 there are less injuries but also a shorter MTFD than in S2, a contradiction emerges: according to the concept (Gsteiger 1993), a shorter MTFD is expected to coincide with more injuries. Again a possible explanation for this contradiction is that—due to the short distance between tree impacts—velocity and thus also energy of falling rocks are quickly reduced. Therefore, after a short distance, many rocks can no more injure any trees. Thus the MTFD only provides limited information about the actual impact frequency of falling rocks. However, it is a measure that allows a direct comparison of different forest stands: the shorter the MTFD, the higher the potential retention capacity of the stand.

The hypothesis, that rock velocities and energies are lower in some areas than in others, is also supported by considering injury heights and sizes: as expected, injury height as well as injury size generally show decreasing values with increasing distance from the cliff, which clearly indicates lower rock velocities and energies further down the slope. Furthermore, mean injury heights are slightly lower and injury sizes smaller in subarea S1 than in S2. Presumably, this is again a result of the higher stem density in S1, which may considerably reduce the kinetic energy of falling rock fragments. Apparently, for the whole stand, as well as for the two subareas, there is also a clear interrelation between the MTFD and the mean injury height: the shorter the MTFD, the lower the mean impact height. This fact also underlines the assumption that rock velocity is reduced in areas with a shorter MTFD, and thus with a higher stem density.

Finally, results of the bivariate correlation analysis as well as of the multiple linear regression showed that in the investigated stand, the number of injuries per tree cannot be sufficiently explained with the variables "dbh" and "distance to cliff", although the distance to the cliff of a tree proved to have a significant influence on the number of injuries. In contrast, the dbh showed no statistically significant influence on the number of rockfall injuries per tree, which is astonishing as thicker stems provide a larger surface to the falling rocks, and therefore should be hit with a higher probability than thin stems. In reality, rocks normally neither enter nor cross the forest stand homogeneously distributed, and thus trees are possibly exposed to different rockfall frequencies. Moreover, the probability of a rock impact is also influenced by the number, size and distribution of the trees above every single tree. However, the influence of such stand parameters cannot easily be assessed and can only be analysed qualitatively. Another possible explanation for the small dependency of the number of injuries per tree on the dbh is that trees that are hit very frequently (e.g. due to their position in the terrain) and therefore become heavily injured, cannot grow to large diameters. Furthermore, it is also assumed that trees with a large dbh in general have a thicker bark than trees with a small dbh. Thus, with thicker trees some impacts by small rocks possibly caused injuries to the bark, only visible over a short time period, and consequently some of these injuries might no more be detected at the time of the field inventory. In addition, besides rockfall distribution, stand and single tree parameters, terrain properties such as microtopography, roughness of the surface and damping of the subsurface also considerably influence the motion of falling rocks and thus the number of tree impacts. However, again these influencing factors cannot easily be quantified and inserted in a regression model.

Conclusion

This study has taken a step in the direction of confirming common assumptions on the protective effect of a forest stand against rockfall (e.g. Jahn 1988; Mani and Kläy 1992; Gsteiger 1993; BUWAL 1996; NaiS 2003; Berger and Rey 2004). With increasing distance from the cliff, injury number, height and size clearly decline, indicating a deceleration of rocks due to several tree impacts. Moreover, injury number and height are also reduced due to areas with high stem densities and thus with a short MTFD. On the other hand, results showed that the dbh of the trees has no significant influence on the number of injuries per tree. Consequently, stem number and spatial distribution of stems are very important within rockfall areas, as these parameters mainly influence the number of tree impacts. Overall, this study showed a clear interrelation between tree and injury distribution, and it indicated that injury number and height are good parameters as to analyse this connection. Unlike injury size, injury height is not dependent on tree diameter. In general, it seems to be favourable to have large trees close to the cliff and smaller trees with a high density further down the slope, or at least an uneven and multilayered stand with a mixture of all tree sizes and age classes should be sustained.

Overall, the method presented provides a tool for a detailed inventory and analysis of rockfall injuries in connection with the actual state of a stand. Moreover, it supplements existing methods such as the MTFD concept by Gsteiger (1993) and it forms a basis for further research, e.g. for modelling works. The combined analysis of stand geometry and injury parameters mainly provides information on the spatial distribution of rockfall as well as on the influence of tree arrangements in a specific stand. For a more comprehensive assessment of the protective effect, this method should be supplemented for example with dendroecological methods, as to assess the temporal rockfall distribution as well.

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