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Implications of coppice stand characteristics on the rockfall protection function

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ABSTRACT

Coppice forest stands can play a key protective role on active rockfall slopes in mountainous regions. This paper aims at quantifying their protection function and at explaining the role of different stand parameters in this function. To achieve these objectives we first made field inventories focussing on the dendrometric and spatial characteristics of 13 coppice stands. Then, we developed a 2D simulation model, called RockCop, to quantify their protective function against rockfall. The simulations show that the predominant size of the falling rocks conditions which of the dendrometric stand parameters mainly determine the protective function of a coppice stand. In the case of small rocks (20 cm Ø), we conclude that a higher stand density improves the protective function. Thus, for those rocks, young stands are most adequate. An acceptable level of protection against medium-sized rocks (50 cm Ø) is only fulfilled by few coppice stands and determined by specific combinations of stand density, stem diameters, basal area and species composition. None of the investigated stands offer sufficient protection against large rocks (1 m Ø).

1. Introduction

In mountainous areas, forests play an important role for the protection of infrastructure and settlements against rockfall (MCPFE, 2007; Schönenberger, 2000). In this article, we define rockfall as the removal and rapid downslope movement of individual rocks up to 1 m^3. However, rockfall models that account for the mitigating effect of trees are scarce (*e.g.* Cattiau et al., 1995; Dorren and Seijmonsbergen, 2003; Dorren et al., 2006; Le Hir, 2005; Liniger, 2000; Stoffel et al., 2006; Woltjer et al., 2008; Zinggeler, 1990). These models could allow for a quantification of the protective role of forests and a consequent optimisation of investments in expensive civil engineering measures. The latter might guarantee more cost-efficient and sustainable rockfall protection (Kienholz and Mani, 1994; Motta and Haudemand, 2000).

All these rockfall models focus mainly on the properties of adult high forests, which are characterised by single trees of different age and a random spatial distribution of stems. At lower altitudes (≤1200 m a.s.l.) in many temperate mountainous regions like for example the French Alps, however, a good portion of forests can be classified as deciduous coppice (IFN, 1998; UNECE/FAO, 2000). These are normally man-made forests that regenerate vegetatively from tree stools (living stumps) following clearcuts (Mayer, 1992). Unlike adult high forests, such stands are generally younger and characterised by a clustered spatial stem distribution. This is due to multi-stemmed trees, hereinafter called clumps that have evolved from coppice shoots.

The protective role of coppice stands against rockfall is referred to in guidelines on silvicultural measures (Gauquelin et al., 2006; Gsteiger, 1993; Schwitter, 1998; Wasser and Frehner, 1996), but their effective protective function has never been quantitatively evaluated. Furthermore, there are uncertainties about their growth dynamics and the change of the protective role in time. In this context, we noted that among forest officials in the western Alps there is a prevalent concern that coppice stands will sooner or later collapse if they are left unmanaged. Gerber and Elsener (1998), for example, recommend silvicultural measures to anticipate broad stand collapses. However, scientific evidence for those worries is lacking and needs to be investigated more thoroughly in future studies.

To increase the understanding of the protective function of different coppice stands and the influence of their stand characteristics the two specific objectives of this study are:

(1) to quantify the protective function against rockfall by applying a 2D simulation model to the data of detailed coppice inventories;

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Table 1
Properties of all plots.

Plot no.	Plot mean age [a] (SD)	Mean stem diam. [cm]	Stand density [stems ha^{-1}]	Basal area [m^2 ha^{-1}]	Species composition[a] (at least 70%) [%]	Surface [m^2]	Altitude [m]	Slope [°]	Exposition [°]
1	18 (1.8)	4.1	9644	13.9	Ac: 23; Fa: 22 La: 21; So: 12	225	820	35	ESE
2	22 (1.8)	5.4	9156	26.6	Ac: 43; So: 20 Qu: 20	225	840	34	ESE
3	24 (4.0)	5.2	7689	19.5	Fa: 25; Co: 25 Ac: 16; So: 16	225	790	33	ENE
4	26 (4.7)	5.9	5620	20.5	Fa: 50; Ac: 32	500	760	34	NNE
5	28 (3.7)	5.6	8844	28.7	Co: 44; Ac: 22 So: 14	225	800	32	WNW
6	39 (12.9)	7.2	2872	21.0	Co: 25; Ac: 17 So: 16; Qu: 12	390	570	31	SSW
7	42 (1.8)	8.4	4442	33.6	Fa: 48; Ac: 15 Ul: 12	448	1160	40	ESE
8	42 (2.5)	8.6	4400	35.9	Fa: 43; Fr. 22 Ac: 15	500	1150	28	ESE
9	44 (1.3)	9.1	2918	28.1	Fa: 37; Ac: 33	425	780	36	ENE
10	58 (4.2)	10.7	2714	38.8	Fa: 68; Ac: 14	630	750	29	ENE
11	63 (3.3)	11.3	2133	30.1	Ti: 44; So:15 Qu:14	750	435	33	WNW
12	64 (19.9)	10.8	1937	29.0	Co: 41; Ac: 26 Ti: 15	630	430	38	W
13	66 (8.6)	11.0	1852	30.1	Co: 22; Ro: 22 So: 19; Qu: 9	729	390	16	WNW

[a] Species abbreviations: Ac: *Acer* spp., Ca: *Carpinus betulus* L., Cn: *Cornus mas* L., Co: *Corylus avellana* L., Fa: *Fagus sylvatica* L., Fr: *Fraxinus excelsior* L., La: *Laburnum anagyroides* Medik., Pr: *Prunus avium* L., *Qu*: *Quercus pubescens* Willd., Ro: *Robina pseudoacacia* L., So: *Sorbus aria* L., Ti: *Tilia cordata* Mill., Ul: *Ulmus glabra* Huds.

(2) to assess, for different stages of growth, the stand characteristics that principally determine the rockfall protective capacity.

2. Material and methods

2.1. Study sites

Thirteen plots have been set up in coppice stands in the area between Grenoble and Annecy in the northern French Alps. The main species were *Fagus sylvatica* L., *Acer spp*., *Corylus avellana* L., *Sorbus aria* L., *Tilia cordata* Mill. and *Fraxinus excelsior* L. All stands were even-aged and situated on regular slopes varying from 16° to 40°. We established a rectangular inventory plot with an area ranging from 225 to 750 m^2 in the most homogenous part of every stand. The higher the stand density, the smaller the plot surface was. For all plots, we checked that there were no leftover standards from previous stands, neither conifers nor plants dominating in the understorey (*e.g. Buxus sempervirens* L.). Mainly due to differences in exposition, soil properties, forest management practices and stand age and history, the species compositions varied considerably. Therefore it was not possible to find stands of consecutive ages with similar species compositions. Ten stands had emerged from clearcuts of the previous stand, two had developed on abandoned farmland and for one stand the origin was not clear.

2.2. Dendrometric measurements

The simulations required detailed information on every individual stem of each plot. Therefore, we measured each standing tree and sprout with a diameter at breast height (DBH; measured at 1.3 m height at the upslope side of the stem) larger than 2.5 cm. Tree species and DBH were registered and all stems were mapped by recording absolute X and Y distances from a defined GPS point using a simple theodolite and an ultrasound distance measuring device.

Furthermore, we noted whether the stems were part of a clump or individual trees and if trees were alive or dead. Clumps were defined as collectives of the same species consisting of at least two stems with a DBH larger than 2.5 cm. Single trees were regarded as individual trees neglecting the possibility of originating from stool- or root-sprouting.

Stand age was determined by counting the tree rings on increment cores taken at breast height from the ten thickest trees in a plot. Thereby, we always included several different species. A summary of the plot data is presented in Table 1.

2.3. Analysis of the horizontal spatial stand structure

The spatial stem distribution was analysed with Ripley's K(d)-function (Ripley, 1977), using an ADS 1.2-6 application (Pelissier and Goreaud, 2007) in "R" software (R-Project; free software environment for statistical computing: http://www.r-project.org). This function analyses all point-to-point distances of individuals i and j in a plot by calculating the number of individuals within the distance d following Eq. (1):

$$\hat{K}(d) = \frac{1}{\hat{\lambda} \cdot N} \sum_{i=1}^{N} \sum_{j \neq i} k_{ij} \tag{1}$$

where $\hat{\lambda}$ is stand density: N/A (number of stems per plot/area of the plot), i,j: represent position of individuals relative to the distance d, and k_{ij}: boolean variable. N is the number of stems in the plot with the surface A and $\hat{\lambda}$ the density following $\hat{\lambda} = N/A$. For all distances shorter than d, k_{ij} is 1. For all distances longer than d, k_{ij} is 0. A high value of $\hat{K}(d)$ indicates clustering, resulting from a higher stem density for a certain d. To test the null hypothesis of spatial randomness, confidence envelopes of 95% were simulated using the Monte Carlo method described by Ripley (1981). In this way, stem aggregation is statistically validated for $\hat{K}(d)$ larger than the higher confidence limit. Edge effects were considered by using the weighted edge correction method proposed by Ripley (1977).

2.4. RockCop, 2D rockfall simulations in coppice

We developed a simple 2D rockfall simulation model, named RockCop, that allows quantifying the protective function of coppice stands. Then, we tested nine different rockfall scenarios in which we compared each time the performance of the different stands in the same conditions.

RockCop, assumes the rockfall process to occur as follows: blocks of different size detach from a cliff face, rebound on the scree slope at the foot of the cliff and move further downwards transiting a forest stand. Passing through the forest, the rocks loose kinetic energy by impacting trees.

The model is simplified and neglects the influence of rock shape, rebound heights and terrain surface. For the simulations in this study we fixed the initial fall height from the cliff at 10 m and the length of the non-forested slope between the cliff and the forest stand at 20 m. All 13 coppice stands had the same size, a width of 30 m and a length of 50 m (measured down the slope). In varying the slope angle (32°, 35° and 38°) and the rock diameter (20 cm, 50 cm and 1 m), we tested nine different scenarios for every stand with 10,000 rocks per simulation run.

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The forest data were taken from the sample plots and include (1) the exact X and Y position, (2) the species name and (3) the stem diameter at breast height (DBH) of every living and dead standing tree with a DBH larger than 2.5 cm. For the simulations equally sized plots are required. However, since the inventory plots had different sizes, we copied all *X* and *Y* coordinates into an area of 30 m × 50 m.

To simulate rockfall in a coppice stand in a meaningful way, we developed a model that accounts for:

- the trajectory of every rock;
- the kinetic energy of every rock;
- the amount of energy dissipated by impacted trees.

The trajectory of every rock is defined by a straight line from the release point of the virtual cliff down the slope, with a maximum lateral deviation of 10 degrees to both sides (Fig. 1a). Uniformly distributed random release point and direction of every rock guarantee the consistent implication of the whole stand. The total width of the trajectory is defined as two thirds of the rock diameter (Fig. 1b). This can be seen as an interceptor zone that is equally wide at both sides of the straight line. The neglected third accounts for the fact that scratch impacts hardly dissipate energy (Dorren and Berger, 2006). The rock mass *m* [kg] is obtained by multiplying the density $\rho = 2500$ kg/m^3 with the rock volume *V* [m^3] = diameter^3.

The calculation of the kinetic energy of a falling rock at any point of its trajectory is based on the energy line principle as described by Gerber (1998), Heim (1932), Meißl (1998) and Toppe (1987). The basic idea of this principle is a notional line between the release point of the rock and the maximum stopping position on a non-forested slope (Fig. 2). The energy line angle β is fixed at 31° following the findings of Berger and Dorren (2007). It is assumed that the kinetic energy of a falling rock at a given point *n* on the slope equals the potential energy it has following Eq. (2):

$$E_{pot\,n} = m \cdot g \cdot h_n \quad (2)$$

Here, *m* [kg] is its mass, *g* (9.81 m s^{-2}) is the acceleration due to gravity and h_n [m] is the height difference between the energy line and the given point *n*. The influence of rock shape, rebound heights and terrain surface cannot be taken into account in a simplified model like RockCop. Therefore, to prevent from overestimation of the stand's energy dissipative capacity, in this model the rock energy at any point of its trajectory corresponds always to the maximal energy at the end of the slope. Its calculation is based on Eq. (2) using the height difference at the slope edge h_0 instead of h_n (Fig. 2).

In the model, the position of every tree is represented by an *X* and *Y* coordinate. The calculation of the tree's mechanical resistance is based on its specific mechanical properties and on

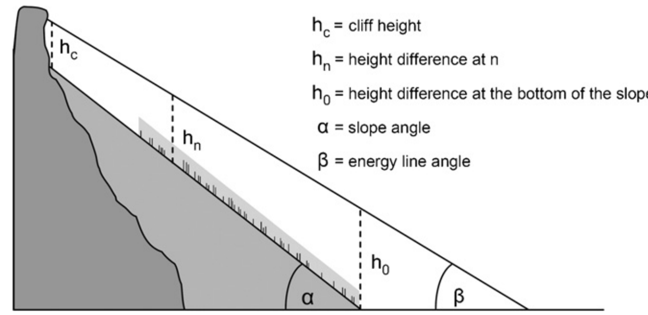

Fig. 2. The energy line principle (modified from Meißl, 1998).

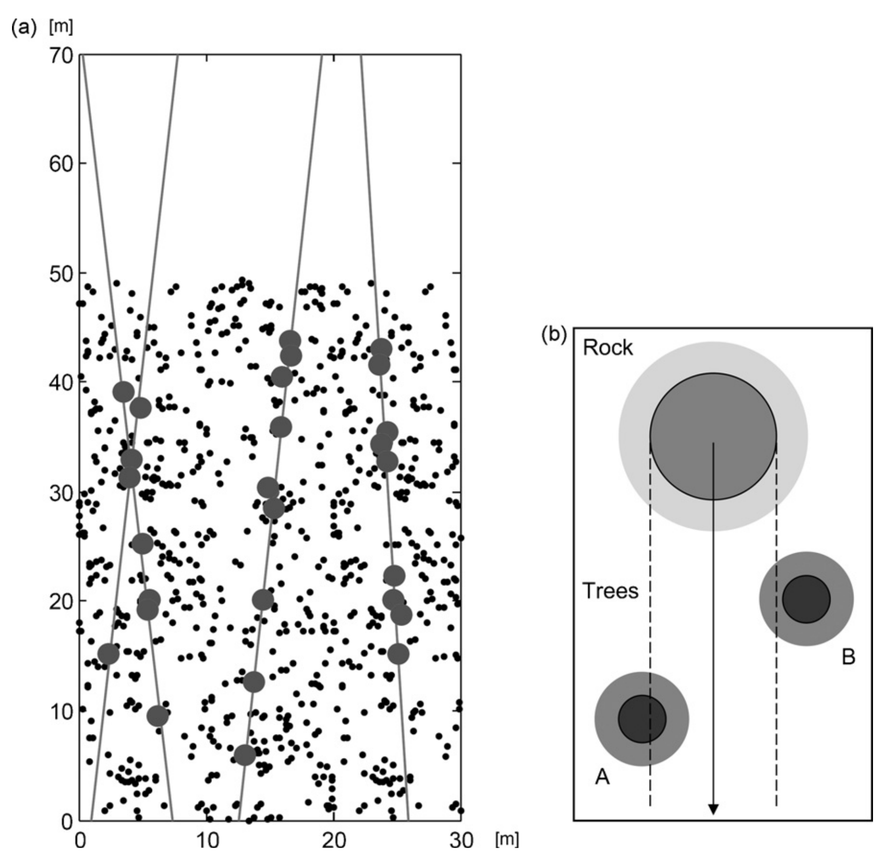

Fig. 1. (a) 4 examples of trajectory lines and impacted trees (larger dots on the lines) in a coppice stand. (b) Trajectory with interceptor zone of rock and trees. Tree A counts for an impact; tree B is not impacted.

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Table 2
Ratio of impact toughness to *Abies alba* expressed as TF (Tree Factor, cp. Eq. (3); the TF values for dead trees and hardwoods are assumed).

Tree species	Mean impact toughness [kJ m^{-2}] (after Sell, 1987)	Ratio to *Abies alba* TF
Dead trees	–	0.1
Hardwoods (without data on toughness)	–	1.1
Sorbus aria	47	0.9
Tilia cordata	50	1.0
Abies alba	51	1.0
Ulmus glabra	60	1.2
Acer spp	63	1.2
Quercus pubescens	67	1.3
Fraxinus excelsior	68	1.3
Carpinus betulus	80	1.6
Fagus sylvatica	100	2.0
Robina pseudoacacia	130	2.5

the DBH. To consider again the above-mentioned fact that scratch impacts hardly dissipate energy, only half of the tree diameter counts for an obstacle against falling rocks (Dorren and Berger, 2006) (Fig. 1b).

As we did not find any data on the amount of impact energy that can be dissipated by clumps, the model used energy dissipation data of single trees that were obtained during real-size rockfall experiments in high forests by Dorren and Berger (2006). They found an exponential relationship between the maximum amount of energy that can be dissipated by *Abies alba* Mill. ($E_{diss,max}$) and its DBH, expressed by the Eq. (3):

$$E_{diss,\max} = \mathrm{TF} \cdot 38.7 \cdot \mathrm{DBH}^{2.31} \quad (3)$$

where TF is the ratio of dry wood impact toughness of any species to *A. alba* (Table 2). Dorren and Berger (2006) showed that the ratio of $E_{diss,max}$ between different tree species is similar to the ratio of the impact toughness between literature values for dry wood of these species. Therefore, TF allows to account for the coppice species. For certain species, literature data on impact toughness were not available, because they are never used for timber due to too small diameters (*e.g. C. avellana* L.). As the wood density of these species is significantly higher than that of *A. alba* and a high wood density is the most determining factor for high impact toughness (Niemz, 1993), we assumed a general TF of 1.1 for these hardwoods. Standing dead trees pose an obstacle to falling rocks, but the mechanical resistance of these trees depends mostly on their state of decay. As there was no data available we assumed a general TF of 0.1.

If the trajectory of the falling rock, with the total width of two thirds of the rock diameter, intersects with the inner half of the stem diameter of a tree, the model calculates a tree impact. The amount of kinetic energy dissipated by the tree in that case equals to $E_{diss,max}$ (Fig. 1a and b). If the cumulative dissipated energy equals $E_{pot\ 0}$, the rock is assumed to be stopped. If only a part of the kinetic energy is dissipated, the residual rock energy is calculated as follows (Eq. (4)):

$$E_{res} = E_{pot\,0} - \sum E_{diss,\max} \quad (4)$$

To check the influence of the spatial stem distribution on the protective capacity of the stand, we first tested the coppice stands with the spatial stem distributions that were recorded in the field (i.e. clustered stem distribution). In addition, we repeated all simulations in coppice stands with uniform, random stem distributions. To create these stands, we changed the *X* and *Y* coordinates of all the trees present in every stand at random (random stem distribution).

To assess the protective role of a coppice stand we used two simulation output values that we considered most decisive. Firstly, the percentage of rocks that pass through the complete coppice stand, expressed as Residual Rockfall Hazard (RRH). Secondly, the ratio between the mean energy of these rocks and the energy of rocks at the bottom of a non-forested slope with an identical gradient ($E_{pot\ 0}$), expressed as Rock Energy Reduction (RER). In contrast to other output values expressed in physical units, RRH and RER are percentages that allow a direct comparison of the rockfall hazard below a forested and a non-forested slope. To facilitate further interpretation of the obtained results we converted RRH and RER into integer values (RRH_R and RER_R) between 1 and 5 according to Fig. 3. Then we combined these two factors to a final Rockfall Protection Index (RPI), ranging from best protection (=1) to least protection (=5) following Eq. (5):

$$\mathrm{RPI} = \mathrm{RRH_R} \cdot 0.7 + \mathrm{RER_R} \cdot 0.3 \quad (5)$$

where RRH_R and RER_R = 1, 2, 3, 4 or 5 according to ranking (Fig. 3).

This equation permits to weight the impact of RRH and RER on the RPI. For this study, we chose a RRH–RER-ratio of 7:3, because we considered the reduction of the number of rocks that exit the stand (RRH) being most decisive for its protective function. By including the energy reduction of these rocks (RER), a second decisive element is incorporated into the assessment. For the interpretation of the RPI values we suggest 4 categories as shown in Fig. 3. This approach implicates several qualitative elements of which the advantages and disadvantages will be discussed later.

3. Results

3.1. Analysis of the horizontal spatial stand structure

Analysis of the horizontal spatial stem distribution using Ripleys $K(d)$-function showed for all plots high K-values for distances of approximately 1.0 m (SD = ± 0.13 m). This indicates stem aggregations with a mean distance of 1.0 m between the individuals that are not related to stand age (Fig. 4). At 6 plots (no. 1; 2; 4; 5; 8; 12) there is a second peak of K-values for distances around 5.6 m (SD = ± 0.89 m).

3.2. Simulation results with regard to spatial stand structure

The two simulation results that determine the RPI were not considerably different between stands with clustered and stands with random stem distributions. As a result, also the RPI values of all tested scenarios are in both cases mostly equal (Fig. 5). Apparent small variations between the RPI values for clustered and random stem distributions are mainly due to the applied ranking principle (cp. Fig. 3 and Eq. (5)). For these reasons we will only present the results from the simulations in clustered stands, which are also representative for the stands with random stem distributions.

3.3. Simulation results with regard to rock size

Presenting the results of all scenarios in detail would be too exhaustive and therefore we show a summarising overview in Table 3. Additionally, for the three tested rock sizes the characteristic results will be described.

In scenarios 1–3 (Rock diameter: 20 cm; slope angle: 32–38°) the RRH and the RER are both strongly correlated to stand density ($R^2 > 0.98$; Table 3; Fig. 6). Consequently this applies also to the RPI ($R^2 = 0.97$; Table 3). In these scenarios, stands with the highest densities (between 8000 and 10,000 stems ha^{-1}) stop more than

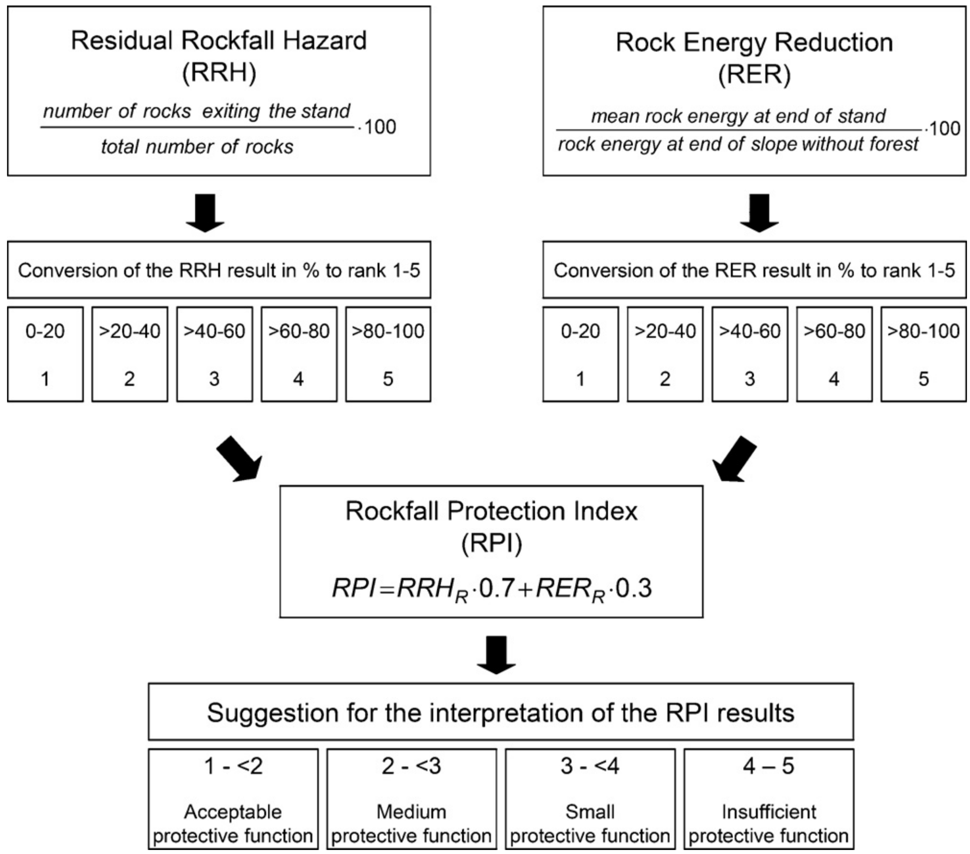

Fig. 3. The RPI concept.

60% of the rocks in scenario 3 and around 80% in scenario 1. At the same time, the mean energies of the rocks that exit a stand at its downslope edge are reduced to approximately half of the energy they would have at the bottom of a non-forested slope, independent of the simulated slope angles.

These results further show that the energies of the rocks exiting from the densest stands are almost uniformly distributed. However, in the case of stand densities lower than 7000 stems ha^{-1}, the number of rocks with few or any tree impacts increases.

For scenarios 4–6 (rock diameter: 50 cm; slope angle: 32°–38°) we could not identify a predominant influence of a specific dendrometric stand parameter on the RRH, RER or on the RPI. However, several stands with different characteristics considerably reduce the RRH and the RER and some offer a medium protective function (RPI: 2 to <3; cp. Table 3).

In scenarios 7–9 (rock diameter: 1 m; slope angle: 32–38°) all the tested stands had an insufficient protective function (RPI 4–5; Table 3). Accordingly the RRH is 100% in almost all those cases. Nevertheless, the stands with the highest basal area (>30 m^2 ha^{-1}) are capable of reducing the RER to approximately 50% on slopes of 32° and to 70% on slopes of 38° (Table 3).

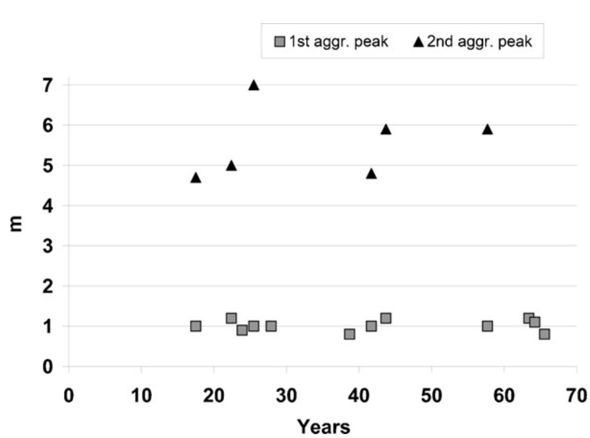

Fig. 4. Location of $K(d)$ peaks indicating stem aggregation.

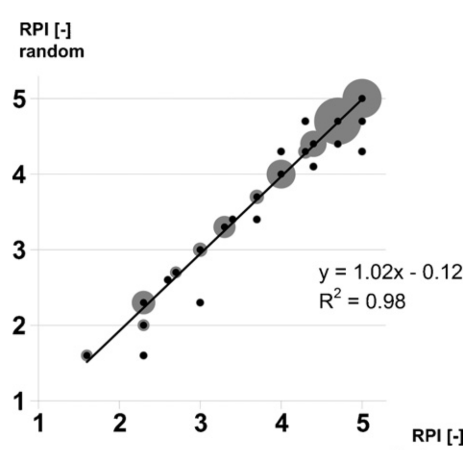

Fig. 5. Comparison between the RPI values of stands with clustered and stands with random stem distributions. Due to the used ranking principle (cp. Fig. 3 and Eq. (5)) many of the 117 RPI results (13 plots × 9 scenarios) were obtained several times. For better illustrating this, the size of the grey surface around the dots represents the number of cases in which the same result was obtained (RPI = 1: best protection; RPI = 5: worst protection).

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Table 3
Results of the rockfall simulations for slopes of 32° and 38° in stands with clustered stem distribution.

Plot no.	Rock diameter: 20 cm						Rock diameter: 50 cm						Rock diameter: 1 m					
	Slope angle: 32° (scenario 1)			Slope angle: 38° (scenario 3)			Slope angle: 32° (scenario 4)			Slope angle: 38° (scenario 6)			Slope angle: 32° (scenario 7)			Slope angle: 38° (scenario 9)		
	RRH [%]	RER [%]	RPI [–]	RRH [%]	RER [%]	RPI [–]	RRH [%]	RER [%]	RPI [–]	RRH [%]	RER [%]	RPI [–]	RRH [%]	RER [%]	RPI [–]	RRH [%]	RER [%]	RPI [–]
1	14	42	1.6	33	41	2.3	93	45	4.4	100	66	4.7	100	84	5.0	100	91	5.0
2	21	53	2.3	36	52	2.3	58	36	2.7	92	49	4.4	100	71	4.7	100	84	5.0
3	28	57	2.3	44	56	3.0	70	47	3.7	95	58	4.4	100	77	4.7	100	87	5.0
4	36	63	2.6	50	63	3.3	56	46	3.0	83	54	4.4	100	68	4.7	100	81	5.0
5	19	53	1.6	33	52	2.3	48	33	2.7	87	45	4.4	100	68	4.7	100	81	5.0
6	82	77	4.7	90	82	5.0	67	71	4.0	82	73	4.7	95	65	4.7	100	78	4.7
7	53	78	3.3	64	76	4.0	35	52	2.3	64	51	3.7	94	51	4.4	100	69	4.7
8	54	74	3.3	65	73	4.0	35	46	2.3	63	49	3.7	92	50	4.4	100	69	4.7
9	74	79	4.0	82	82	5.0	60	66	3.3	76	68	4.0	97	64	4.7	100	79	4.7
10	73	84	4.3	81	85	5.0	56	67	3.3	69	68	4.0	84	56	4.4	99	68	4.7
11	86	88	5.0	92	89	5.0	70	70	4.0	85	71	4.7	99	67	4.7	100	81	5.0
12	87	91	5.0	94	90	5.0	78	81	4.3	92	80	4.7	97	76	4.7	100	85	5.0
13	85	87	5.0	90	89	5.0	74	73	4.0	90	73	4.7	99	71	4.7	100	83	5.0

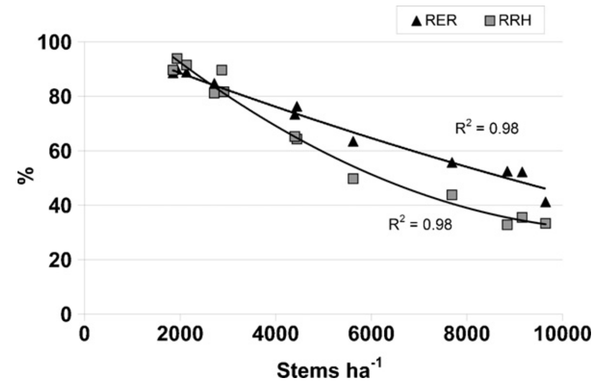

Fig. 6. Correlation of RRH and RER with stand density in scenario 3 (rock diameter: 20 cm; slope angle: 38°).

4. Discussion

4.1. The horizontal spatial stand structure

The stem aggregation in coppice stands due to clumps is clearly displayed with the first peak for high K(d) values, which means that there is a disproportionately large number of distances of approximately 1.0 m between the stems of a plot. This distance does not considerably change with increasing age of the plots, because even if the number of stems per clump will be reduced in older stands, the mean distance between them will be constant. The second peak could represent the mean distance between clumps (plot average: 5.6 m). However, evidence is lacking and an eventual change or supposable increase of this distance with stand age has to be verified by analysing larger plot surfaces.

Consequently this analysis shows that the spatial structure of coppice stands can remain clustered over time. Moreover, the mean number of stems per clump of 3.2 individuals of the 4 oldest stands of our study indicates that this special forest structure can at least persist numerous decades if not centuries. Additionally we would like to note that field observations show that the spatial stand structure, especially in young stands, is also very dependent on the age, as well as on the spacing between the trees of the previous stand on the same site. In future studies, it would be interesting to investigate more thoroughly the effect of stand history. Most certainly, the spatial structure of a coppice stand with a regular cutting cycle of *e.g.* 25 years will differ largely from one that is clear cut only every 50 years.

4.2. Implications of the stand characteristics on rockfall protection

The simulations show that the predominant size of the falling rock conditions the dendrometric stand parameters that determine the protective function of a coppice stand. The predominant influence of stand density on the protective function in the case of small rocks (20 cm Ø) is due to the fact that the developed rock energies are relatively low. This means that even in young stands with small stem diameters only a mean number of 2–4 tree impacts is necessary to dissipate the total kinetic energy of a falling rock (<4 kJ). Most important is therefore a high impact probability to prevent the small rocks from passing between the trees. Hence, the higher the impact probability, i.e. stand density, the better the protective function. This corresponds to the findings of Jahn (1988) who did rockfall experiments with small rocks (13–45 cm Ø).

As stand density is considerably higher in young stands (5000–10000 stems ha^{-1}), it can be concluded that for rock sizes with a diameter of around 20 cm, coppice stands younger than 30 years offer best protection. However, in stands with densities below

7000 stems ha^{-1}, the protective effect decreases because of an increasing number of rocks with very few impacts. Furthermore the results indicate that acceptable protection against very small rocks (*e.g.* with diameters of 10 cm) is only possible with extremely dense stands.

In the case of medium-sized rocks (50 cm Ø), which develop approximately ten times as much energy as small rocks (20 cm Ø), the energy dissipative capacity of the stems becomes more decisive for rockfall protection. However, the results of this study do not permit to clearly identify the stand parameters that are decisive for the protective function against 50 cm Ø rocks. Moreover, the results of scenario 4 (rock diameter: 50 cm; slope angle: 32°), where 4 stands with different characteristics offer the best protection, indicate that there are several combinations of stand density, stem diameters, basal area and species composition possible that provide the same degree of protection. In this context, Woltjer et al. (2008) report for the same rock size only small differences between the influence of the mean tree diameter and the stand density on the mean run out distance. They suggest that beyond this rock size stand density becomes less influential compared to the mean stem diameter.

For large rocks (1 m Ø) the simulation results indicate that coppice stands cannot offer an acceptable degree of protection. The fact that the stands with the highest basal area reduce the mean residual rock energy significantly (down to 50%) however indicates that for this rock size the basal area plays a key role.

4.3. The RPI quantification concept

The current version of RockCop is a simplified model and its results are therefore rather indicative. Absolute output values expressed in physical units like for instance the mean tree free distance (Gsteiger, 1993) or the mean run out distance (Woltjer et al., 2008) would not be appropriate. For that reason we chose to analyse the results based on output values given in percentages. These values have the advantage to allow for comparing between the protective function of different stands as well as to quantify hazard mitigation of the simulated stands in comparison to non-forested slope with identical gradients.

In this study we merged the RRH and the RER, which both contain valuable information on the protective function of a coppice stand, into a RPI. The weighting of the RRH and the RER in Eq. (5) is a subjective choice. We defined a RRH–RER–ratio of 7:3, because we considered to what extend the rockfall hazard is reduced, or in simple words, whether a rock exits a forest stand or not, most decisive. Fact is, that even if the rock energy has been reduced down to 30%, its impact still could be destructive. However, the energy reduction is a very decisive factor regarding the destructive potential and key to the design civil protective works such as rockfall nets.

A major disadvantage of the RPI concept is that the ranking of RRH and RER as well as the choice of the RRH–RER-ratio incorporates subjective qualitative elements into the analysis. For that reason we investigated the influence of the weightings by testing other RRH–RER-ratios (1:1; 3:2 and 4:1). This showed that our interpretations of the RPIs of the different stands hardly changed, because RRH and RER rarely diverged to a large extend.

4.4. RockCop in the light of coppice specific features

To improve this study, realistic data on the energy dissipative capacity of clumps should be integrated into the model. Here it should be considered that the mechanical wood properties change considerably during the first ten to twenty years of a tree's life, because in this period mainly juvenile wood is produced. The microstructure of this wood is characterised by a larger angle between the stem axis and the cellulose fibrils in the cell walls of the wood fibres (fibril angle), cell walls are generally thinner and cellulose content is lower than in mature wood (Kretschmann, 1998). As a consequence the impact toughness is reduced, but at the same time the elasticity is higher than in mature wood. For the moment, it is not known which of these two properties are most important for dissipating kinetic energy from falling rocks.

The protective role of coppice stands could possibly be underestimated by the used model, because the clumps have another protective feature which is difficult to consider: single trees dissipate the kinetic energy of rocks only in singular impacts after which the rocks can easily regain velocity. As clumps consist of a bundle of stems next to each other, they often function as a cage where rocks are trapped between the stems. Elasticity might have an influence on this function. Moreover it should be considered that broadleaf trees growing on slopes produce tension wood at the upslope side of the stem. This leads to considerably higher impact toughness (Anonymous, 1990). Furthermore the connection of the stem with its stool is a weak spot for two reasons. Firstly because at this point there are strong grain deviations, which always lead to a loss of stability (Niemz, 1993) and secondly because the unprotected surface of the stool favours the colonisation with wood decaying fungus that strongly reduce the mechanical resistance as well (Rayner and Boddy, 1988). This brittleness was also observed during the first real-size impact tests on a clump we did in the French Alps.

Regarding the particularity of coppice trees that they grow in clumps, we have to reconsider the conclusion that a clustered or random spatial distribution of stems does not influence the protective role of a coppice stand. This conclusion only accounts for stems with equal mechanical properties, whether or not being part of a clump. In reality, the protective role of stands with a clustered stem distribution will probably differ from comparable stands composed of randomly distributed standards due to mechanical differences between the stems.

5. Conclusion

From this study we conclude that the spatial stand structure of coppice stands can stay clustered over several decades. However, for the investigated stands, the clustering of the stems does not really affect the protective function, assuming that their mechanical properties do not differ from those of standards.

From the simulation results we firstly conclude that the predominant size of the falling rocks conditions which of the dendrometric stand parameters mainly determine the protective function of a coppice stand. In the case of small rocks (20 cm Ø) it is mainly determined by stand density. Therefore young and dense stands ($\geq$8000 stems ha^{-1}) offer the best protection against this rock size. Considerable protection against medium-sized rocks (50 cm Ø) is only provided by few coppice stands. The results indicate that here several combinations of stand density, stem diameters, basal area and species composition are possible to provide the same degree of protection. None of the investigated stands offer sufficient protection against large rocks.

The Rockfall Protection Index used in this study showed to be useful to assess the effect of the coppice stand characteristics on the rockfall protective function. Moreover it illustrates in a simple way to what extend a coppice mitigates the rockfall hazard in comparison with a non-forested slope. Our current research focuses on the behaviour of tree clumps during rockfall impacts as well as on their mechanical properties. Special emphasis will be on root anchorage, mechanical cohesion of stems of the same clump and on the impact toughness of coppice stems.

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