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ORIGINAL PAPER

Quantifying the protective function of a forest against rockfall for past, present and future scenarios using two modelling approaches

Christophe Bigot · Luuk K. A. Dorren · Frédéric Berger

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Abstract Following a major rockfall event in 1987, two types of protection measures were taken in the village Saint Martin le Vinoux (French Alps). Firstly, technical measures using civil engineering were installed, and secondly, a forest management intervention to increase its protection was carried out. This study aims to assess whether this intervention was successful in the sense that it improved the protective function of the forest. We evaluated the rockfall risk for the situation of 1987 (before the intervention), today and the future, using model simulations with past, present and future vegetation cover scenarios. To increase the meaningfulness of our results, we used two different models, called Rockfor$^{.NET}$, which is a rapid one-dimensional rockfall forest evaluation tool, using simple slope and forest characteristics and RockyFor, a process based on three-dimensional rockfall simulation model that takes the barrier effect of individual trees explicitly into account. Both models correctly predicted that the forest was not capable of stopping rocks from the 1987 rockfall event. Further, both models indicate an increase of the number of rocks reaching the base of the slope from 1987 onwards. RockyFor shows an increase from 11% in 1987 to 19% in 2086. Rockfor$^{.NET}$ shows an increase from 26% in 1987 to 56% in 2086. We conclude that a second attempt to increase the protective function of the forest should aim at restoring a dense coppice stand.

Keywords Protection forest · Spatial simulation · Rockfall

1 Introduction

In mountainous areas rockfall is a common but dangerous natural process as witnessed by many reports of damage and sometimes deaths. A rockfall is a fragment of rock detached by sliding, toppling or falling that falls along a vertical or sub-vertical cliff and proceeds

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C. Bigot · F. Berger
Cemagref Grenoble, 2 rue de la Papeterie, BP 76, 38402 Saint Martin d'Hères, France

L. K. A. Dorren (✉)
Hazard Prevention, Federal Office for the Environment FOEN, 3003 Bern, Switzerland
e-mail: luuk.dorren@bafu.admin.ch

down the slope by bouncing, flying and rolling (after Varnes 1978). To face the risk posed by rockfall, there are several types of technical measures based on protective structures, such as rockfall nets and dams (Peila et al. 1998). These means, however, are very expensive and are generally considered aesthetically not appealing. Forests can offer an effective protection against falling rocks if their structure is well adapted to this function (Gsteiger 1993; Motta and Haudemand 2000; Corominas et al. 2005; Le Hir 2005; Gauquelin et al. 2006). Protection forests form a part of the natural landscape and their maintenance is cheaper than technical measures (Cattiau et al. 1995). For these reasons, the protective effect of forests is increasingly taken into account in natural hazard management. An example where forests have been used to protect against rockfall is the case of the village of Saint Martin le Vinoux in the Isère region in the French Alps. There, a major rockfall event occurred in 1987 during which a rock mass of 50 m^3 toppled and fractured into several individual blocks that were propagated into the forest. Ten blocks of 0.3–0.5 m^3 arrived on the main road, and three blocks from 1 to 3 m^3 reached the residential area, causing damage, but no victims (Besson 2005). Subsequently, rockfall nets have been installed. In the 1990s, the forest covering the slope was defined as protection forest by the RTM service (Restauration des Terrains en Montagne). A first study was carried out in 1991 to investigate and consequently to optimise the protective function of the existing forests, using a 2D rockfall model developed by Cemagref (Rupé 1991). On the basis of this study, it was decided to carry out cuttings in the existing forests and create vegetation bands parallel to the contour lines separated by open spaces of 20 m and to plant additional trees in those open spaces (Rupé 1991; Masson 1992). This intervention was carried out in 1992 (Gros 1993).

Today, we questioned whether our proposed intervention was successful in the sense that it improved the protective function of the forest. Due to the scientific progress in the field of rockfall modelling since the 1990s, we can use such models to answer this question. Therefore, the objective of this study was to assess the rockfall risk for the situation of 1987 (before the intervention), today and the future. To achieve this we simulated the 1987 rockfall event with past, present and future vegetation cover scenarios. To increase the meaningfulness of our results we used two different models.

2 Materials and methods

2.1 Used models

The first model used in this study is Rockfor$^{.NET}$. This is a rapid assessment tool, freely and publicly available on the internet (http://www.rockfor.net), which has been developed and extensively described by Berger and Dorren (2007). The tool is based on findings from real size rockfall experiments on forested and non-forested slopes (cf. Dorren et al. 2005). Rockfor$^{.NET}$ is a one-dimensional model that quantifies the protective capacity of a forest stand against rockfall. The required input data provide a basal representation of the rockfall and slope characteristics and are easy to acquire. The underlying idea of the tool Rockfor$^{.NET}$ is that the existing forest is considered as a sequence of open rockfall nets that all consist of a row of trees or tree curtains. Rockfor$^{.NET}$ firstly calculates the total energy developed by a falling rock, as calculated with the energy line principle (Fig. 1). Then, it calculates the energy dissipative capacity of each curtain and the number of curtains required for dissipating the total energy of the rock. This energy dissipative capacity of each curtain is determined by the occurring tree species in the forest and the mean tree

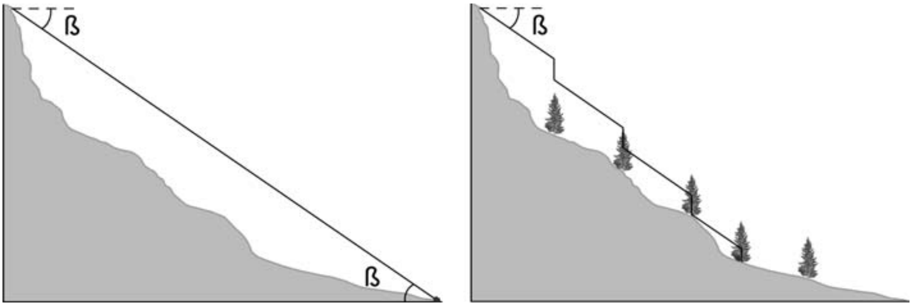

Fig. 1 Scheme explaining the principle of the energy line and Rockfor$^{\cdot\text{NET}}$

diameter in the stand. Subsequently, the required number of curtains is converted in a required basal area using the mean DBH. Finally, Rockfor$^{\cdot\text{NET}}$ calculated the basal area that is theoretically encountered by the rock when it falls through the given forest. The protective role of the forest against rockfall can subsequently be quantified by comparing the required basal area with the theoretically encountered basal area. For further details we refer to Berger and Dorren (2007). The output of Rockfor$^{\cdot\text{NET}}$ is the Probable Rockfall Hazard (PRH), which is the percentage of rocks surpassing the forested area on an active rockfall slope. Since Rockfor$^{\cdot\text{NET}}$ is a global tool, only one value for the mean tree diameter can be given for the forest covering the study area. As such, the tool is very sensitive to this parameter (cf. Wehrli et al. 2006), as well as to the stem number or the total basal area in the stand. In the terrain it is very easy to estimate these parameters in a homogenous forest stand. However, for a large slope surface, which consists often of an assemblage of such homogenous stands, it is less easy to come up with one representative value, which can be considered as weak point of the tool.

The second model used in this study is RockyFor, which is a combined deterministic/probabilistic 3D rockfall simulation model. RockyFor uses raster maps as input files and simulates trajectories of falling, bouncing and rolling rocks within single raster cells (Dorren et al. 2006; Stoffel et al. 2006). RockyFor allows a more thorough analysis of the rockfall hazard because slope irregularities are taken into account, and it provides spatially explicit output. Moreover, it explicitly simulates the impact of falling rocks against trees. The model consists of three modules: The first module calculates the rockfall trajectory, based on the topography of a site, which is represented by a Digital Elevation Model (DEM). The second module calculates the energy loss due to impacts against single trees. Thereby, the exact position of a falling rock and its current energy are modelled. The third main module calculates the velocity of the falling rock after a rebound on the slope surface (for details see Dorren et al. 2004). Here, the decrease of velocity after a rebound is mainly dependent on the tangential coefficient of restitution (r_t), which is determined by the composition and size of the material covering the surface and the radius of the falling rock itself (Kirkby and Statham 1975). The r_t essentially determines how much translational kinetic energy is lost during a rebound because of the roughness of the slope surface.

From both models, we used the PRH, expressed as the percentage of simulated falling rocks that would surpass the forested part of the slope and arrive at the regional road (Fig. 3), as in indicator for the rockfall hazard. For each scenario the PRH was calculated with the two models.

2.2 Data used

Data used in this study can be grouped into four main types: (1) information on the 1987 rockfall event, (2) dendro-chronological data for constructing forest growth scenarios, (3) raster data needed for the simulations with RockyFor, and (4) transect data required for Rockfor$^{.NET}$.

(1) Information on the 1987 rockfall event was provided by geological and forest reports of Besson (2005) and Gros (1993). These reports mentioned the initial rockfall volume of 50 m^3 (limestone), which fractured into individual, rectangular shaped rocks, with a maximal volume of 1 m^3. Thirteen of those arrived on the main road as well as in the residential area. The total volume of these 13 rocks corresponded to 6 m^3, which is 12% of the initial volume, repartitioned in rocks with volumes of 0.3, 0.5 and 1 m^3. We also found that the forest cover at that time consisted of a *Quercus pubescens* Willd. coppice and an isolated square shaped mature *Pinus nigra* Arnold stand. The mean DBH in the coppice stand was 16 cm and the density 700 stems ha^{-1}. In the *Pinus nigra* stand, this was, respectively, 26 cm and 1,200 stems ha^{-1}.

(2) The dendrochronological data for constructing forest growth scenarios consisted of 13 tree core samples of *Pinus nigra* trees, extracted with an increment corer. On the basis of the measured widths of the tree rings, we reconstructed radial growth over a period of approximately 100 years analogue to Perret et al. (2006).

During the forest intervention in 1992, 9,800 trees were planted, on average 1,186 trees ha^{-1} (60% *Pinus nigra*, 33% *Robinia pseudoacacia* L. and 7% other species, e.g. *Acer* spp., *Quercus pubescens*). During fieldwork we noticed that the *Pinus nigra* trees planted in 1992, which were still alive, did grow following the growth curves in Fig. 2 during the first 14 years (max growth in height approximately 2 m). However, as shown by a field inventory in 2006, 80% of the planted trees died because of the competition with other vegetation species, such as bramble (*Rubus eubatus*), and destruction or uprooting of young plants by wild boars (*Sus scrofa*) looking for earthworms (e.g. *Lumbricus terrestris*).

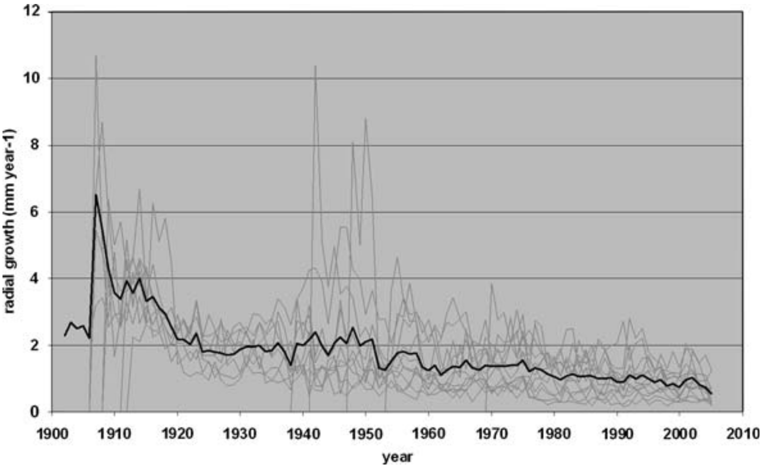

Fig. 2 Radial growth of 13 *Pinus nigra* trees in mm year^{-1} from 1902 to 2005 (in grey) and the mean growth (in black)

(3) The raster data needed for the simulations with RockyFor were obtained by means of a field mapping campaign using an orthophoto taken in 2003 and subsequent GIS analyses. A Digital Elevation Model (DEM) with a resolution of 5 m × 5 m (384 rows and 368 columns) was created on the basis of digitised contour lines with an equidistance of 5 m. Field mapping was required to create a polygon map, which was finally converted into a raster map with the same resolution and dimension as the DEM. The polygon map consisted of terrain units with similar slope and vegetation characteristics. To record these characteristics, circular plots with a diameter of 8 m were inventoried systematically along three transects in the rockfall propagation area (Fig. 3), starting at the source area down to the stopping area, i.e. from the bottom of the cliff to the residential area. Additional plots were added outside the three transects to increase the coverage of the whole study area. For each polygon the following attributes were recorded:

- the mean slope gradient (data measured)
- the elasticity of the ground, determining the normal coefficient of restitution r_n, divided into five classes (soft surface/loose soil: $r_n = 0.25$–0.3; medium hard/compact soil: $r_n = 0.3$–0.35; medium hard/scree: $r_n = 0.35$–0.4; hard/bedrock partially covered with scree or soil: $r_n = 0.4$–0.45; very hard/bedrock: $r_n = 0.45$–0.5) (data estimated)
- the mean obstacle height of the surface in the polygon to calculate the tangential coefficient of restitution following the method of Dorren et al. (2005) (data estimated)

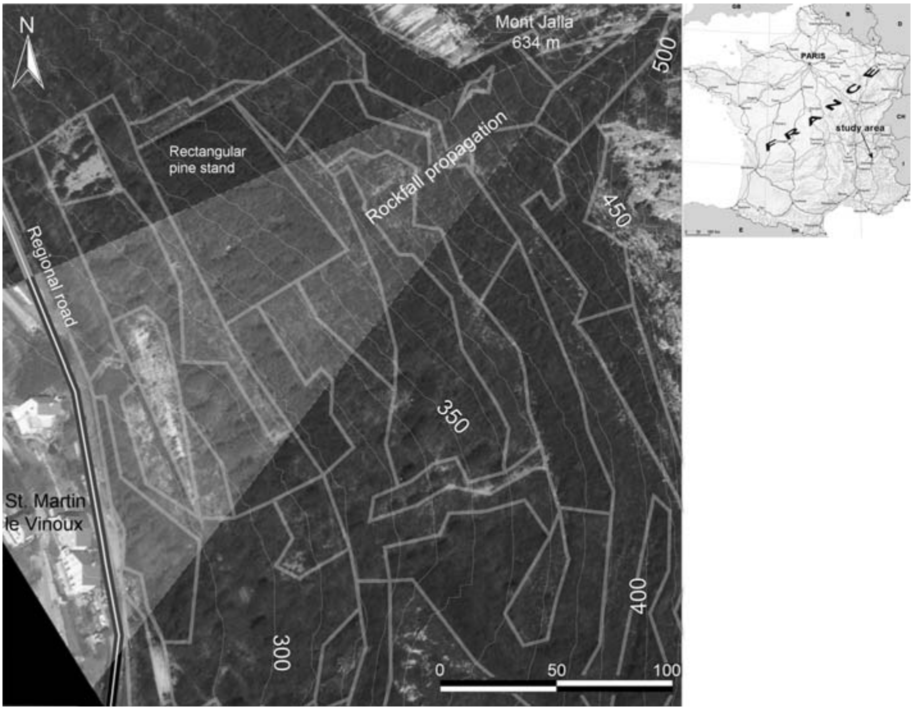

Fig. 3 Map of the study area with the main endangering rockfall zone. The grey polygons represent the polygons mapped in the field. The white numbers indicate the altitude

- the total basal area using a relascope (Bitterlich 1948) (data measured)
- the number of stems per hectare in the polygon (data counted)
- the distribution of the tree diameters (mean and standard deviation) measured at breast height (DBH) for all individual trees thicker than 10 cm, because smaller, individual trees are not considered to provide effective protection against rockfall (data measured)
- the occurrence or distribution of the dominant tree species (%) (data counted)

(4) The transect data for Rockfor$^{\cdot NET}$ was obtained by calculating firstly the average values of the characteristics recorded in the circular plots along the three transects described above. As such, we obtained the mean DBH (cm) in the forest covering the slope, the mean density (stems ha^{-1}) and the species composition (in %). Secondly, we used GIS analyses to calculate

- the total slope length (in m), between the source area and the lower border of the forested slope, measured over the slope surface
- the cliff height (m)
- the mean slope gradient (°)

The value for the rock density of the occurring limestone was set to 2,500 kg m^{-3}. All the values used for the simulations are presented in Table 2.

2.3 Scenarios

We defined four scenarios presented in Table 1.

Scenario 1 is based on the forest characteristics before the forest interventions of 1992 took place. At that time the whole slope was covered with 80% *Quercus* coppice with a DBH mean of 14 cm and 20% mature *Pinus nigra* trees with a DBH mean of 25 cm (see Table 2).

Scenario 2 represents the current forest cover (forest cover of 1987 transformed into vegetation bands parallel to the contour lines separated by open spaces of 20 m).

Scenarios 3 and 4 are future predictions of the development of the current forest cover taking into account forest development over 40 and 80 years. The growth of the planted *Pinus nigra* trees that are still alive was based on the growth curves in Fig. 2. The *Quercus* coppice, consisting of trees of all age classes with a maximum DBH of 18 cm and a standard deviation of 13 cm, was assumed not to change in density. The rectangular shaped

Table 1 Description of data acquisition to determine the different scenarios

	Year	Definition	Methods
Scenario 1	1987	Reference event, forest cover of 1987	Literature
Scenario 2	2006	14 Years after the intervention, current forest cover	Field work Geomorphology and forest inventories
Scenario 3	2046	Current forest cover evolved during 40 years	Dendro-chronological study Growth table determined with LinTab
Scenario 4	2086	Current forest cover evolved during 80 years	Dendro-chronological study Growth table determined with LinTab

Table 2 Input and output data of the two used models (data present mean values for the whole slope)

General description	Site characteristics				Mean forest characteristics				Rock characteristics		Rockfall hazard		
Scenario	Fall height (m)	Slope gradient (°)	Length forest non-slope (m)	Length forest slope (m)	Stand density (stems ha^{-1})	G (m^2 ha^{-1})	DBH (cm)	Species composition	Rock volume (m^3)	Geology and form	PRH Rockfor^{Net} (%)	PRH RockyFor (%)	PRH observed (%)
Scenario 1	20	35	10	270	700	14.1	16	80% *Quercus* 20% *Pinus nigra*	{0.3; 0.5; 1}	Limestone regular	26	11	12[a]
Scenario 2	20	35	10	270	330	6.6	16	80% *Quercus* 20% *Pinus nigra*	{0.3; 0.5; 1}	Limestone regular	50	12	n/a
Scenario 3	20	35	10	270	314	7.1	17	80% *Quercus* 20% *Pinus nigra*	{0.3; 0.5; 1}	Limestone regular	64	15	n/a
Scenario 4	20	35	10	270	314	8.9	19	80% *Quercus* 20% *Pinus nigra*	{0.3; 0.5; 1}	Limestone regular	54	19	n/a

[a] Estimated on the basis of rock volumes as explained in Sect. 2

Pinus nigra stand (cf. Fig. 3), belonging to a private owner, was assumed to become less dense (mortality estimate of 3% year^{-1}, based on unpublished of plots inventories by Cemagref technicians). This mortality rate corresponds well to mortality rates in *Pinus sylvestris* stands observed by Monserud and Sterba (1999). Growth of the individual *Pinus nigra* trees was based on a linear projection of the mean growth of all the samples trees ($n = 13$) during the last 15 years (radial increment of 0.89 mm year^{-1}).

In all the scenarios, three rock volumes were calculated (0.3, 0.5 and 1 m^3, rectangular limestone rocks) and an initial fall height of 20 m. The input data used for calculating the rockfall hazard for the four scenarios are given in Table 2.

2.4 Study area

The study area is located in Saint Martin le Vinoux (French Alps), which is part of the conurbation of Grenoble, between 45°12′ latitude and 5°43′ longitude. The maximum altitude in the study area is 634 m. Saint Martin le Vinoux has 5,200 habitants and total surfaces extend of 1,000 ha. It is particularly at risk from rockfall originating from the cliffs of the Chartreuse massif. Yearly precipitation is about 975 mm and the mean temperature is around 12°. The site is SW exposed. The geology consists of Jurassic limestones with layers between 20 cm and 2 m thick, dipping towards NNE, interlayered with marly limestone of few centimetres thick (Gidon 1981). The soil is calcareous lithosol with a soil depth <10 cm. The soil is quite homogeneous throughout the study area. During the 19th century, the lower part of the current forest consisted of vines and agricultural fields. Before 1990, the dominant forest stand mainly consisted of *Quercus pubescens*. Currently, the height of the trees varies between 8 and 10 m, with a maximum DBH of approximately 25 cm. A second distinct forest stand consists purely of *Pinus nigra* and has a square shape (cf. Figs. 3 and 4). The trees in this stand are currently 100 years old. The trees are more or less planted in a grid with 5 m distance between the stems. They have a height varying from 20 to 25 m and a DBH of 20 to 35 cm.

Fig. 4 Left: overview of the study site, with the *Pinus nigra* stand. Right: rock from the rockfall event of 1987, stopped in *Pinus nigra* stand

3 Results

The Probable Rockfall Hazard (PRH) below the forested part of the slope for Scenario 1 (1987 forest conditions) as calculated by Rockfor$^{.NET}$ is 26%, while RockyFor provides a PRH of 11% (Table 2). The rockfall hazard observed in reality in 1987 was 12%. Calculation of the PRH in Scenarios 2, 3 and 4 shows that PRH almost doubles in 100 years time. The PRH obtained with Rockfor$^{.NET}$ increases from 26% to 54% and with RockyFor from 11% to 19% (Fig. 5). Rockfor$^{.NET}$, however, shows that there is a slight decrease of the PRH after 2046. The results further show that for all the scenarios after the interventions of 1992 the PRH is higher than before.

In addition to the PRH, expressed as one number that represents the number of rocks reaching the road, RockyFor provides detailed and spatially distributed information on the rockfall trajectories, in contrast to Rockfor$^{.NET}$. Figure 6 shows the stopping positions of 1,000 simulated rocks for the Scenarios 1 and 4, as well as the stopping positions observed in 1987. The figures show a correspondence between the distribution of observed and simulated stopping positions in Scenario 1.

The passage frequency map shown in Fig. 7 shows the number of times that a simulated rockfall trajectory crossed a raster cell for Scenario 1. Such a map is indicative of the preferred rockfall tracks on the slope and the runout zone. This map corresponds well with the distribution of stopping positions observed in 1987.

4 Discussion

4.1 Model results

To assess whether the intervention of 1992 improved the protective function of the forest cover, the two models allowed a retro and future analysis of the rockfall risk for the period 1987–2086. The study showed that both models provided results which indicated that the Probable Rockfall Hazard increases with time. One difference between Rockfor$^{.NET}$ and RockyFor is that RockyFor includes a realistic rock volume distribution, meaning that

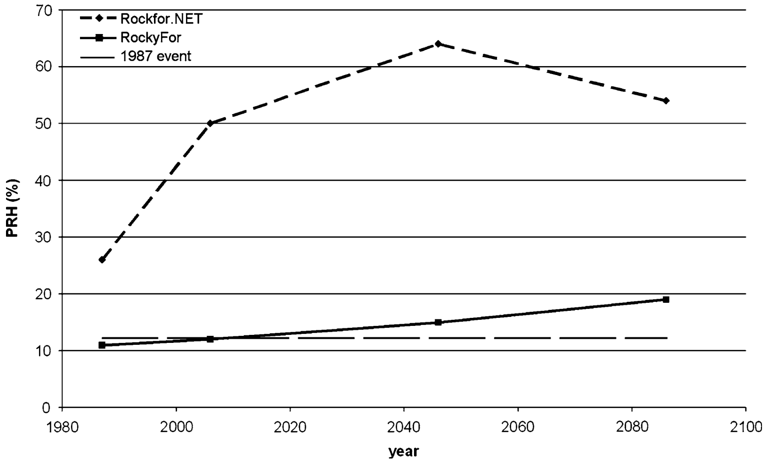

Fig. 5 Evolution of the Probable Rockfall Hazard over time for the two used models

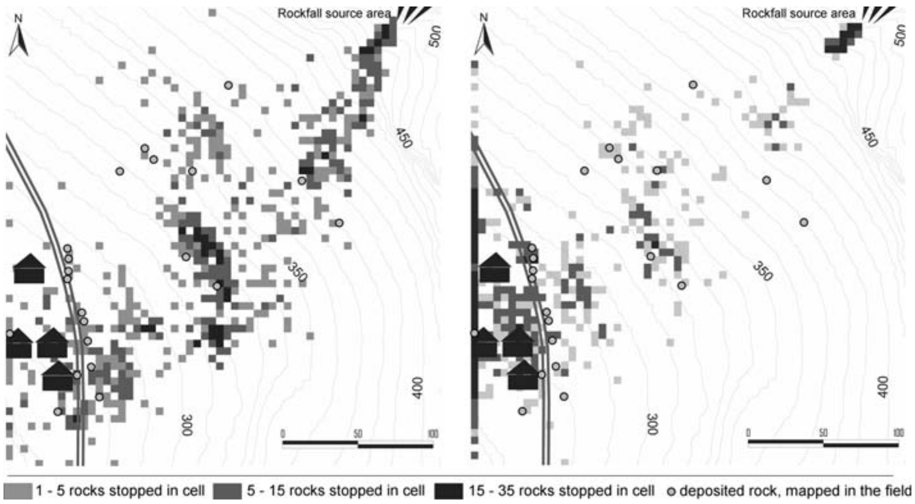

Fig. 6 Observed and simulated rockfall trajectories in 1987 (left figure) and 2086 (right figure). This raster map is the area of blocks stopped; the darker the cell, the higher the simulated area stop of the numbers of blocks (three classes are shown; the darkest class corresponds to 15–35 rocks, the lightest one to 1–5 rocks)

small and large rocks are simulated. Rockfor$^{\cdot\text{NET}}$ calculates a PRH with one volume given, which is generally set as the largest individual. Therefore, the calculated PRH values are usually higher than those given by RockyFor. Rockfor$^{\cdot\text{NET}}$ allows a rapid estimate of the PRH on a slope as a function of forest characteristics. The results of the Rockfor$^{\cdot\text{NET}}$ analysis can also be used to determine if a detailed 3D trajectory study using RockyFor would be needed that takes into account the evolution of a protection forest (Stoffel et al. 2006).

4.2 Protective effect of the forest

The forest that covers the study area is almost continuously under attack by falling rocks, which increases the vulnerability of the forest reducing its protective function. Many rocks (comprising a wide range of volumes) pass through the forest. As shown by the simulations, the interventions of 1992 worsened the situation rather than improving it. This is quite logical, because the interventions led to a stand density decrease of almost 50% and therefore a decrease in the probability that rocks impact trees. Both our observations on the field and the simulation show that a lot of rocks are being stopped by the trees in the *Pinus nigra* stand. This stand structure (mean DBH 26 cm, stand density 1,200 trees ha^{-1}) is logically more adapted for having an important protective role than the *Quercus* coppice structure (mean DBH 16 cm, mean stand density 500 trees ha^{-1}) on this site. The fact that *Pinus nigra* trees are currently falling over in the stand shows that its structure is not very stable. Scenario 2 shows a light increase of the PRH as calculated by RockyFor (increase of 1%). Rockfor$^{\cdot\text{NET}}$ calculated an increase of 25%. One of the reasons is that the protective function of the *Pinus nigra* stand cannot be included well in Rockfor$^{\cdot\text{NET}}$.

In Scenarios 3 and 4, the forest evolves without further human interventions. RockyFor predicted an increase of the PRH during this period. In contrast, Rockfor$^{\cdot\text{NET}}$ predicted a decrease of the PRH between Scenarios 3 and 4. The results of Rockfor$^{\cdot\text{NET}}$ are directly related and very sensitive to changes in the DBH (cf. Wehrli et al. 2006). Therefore, the

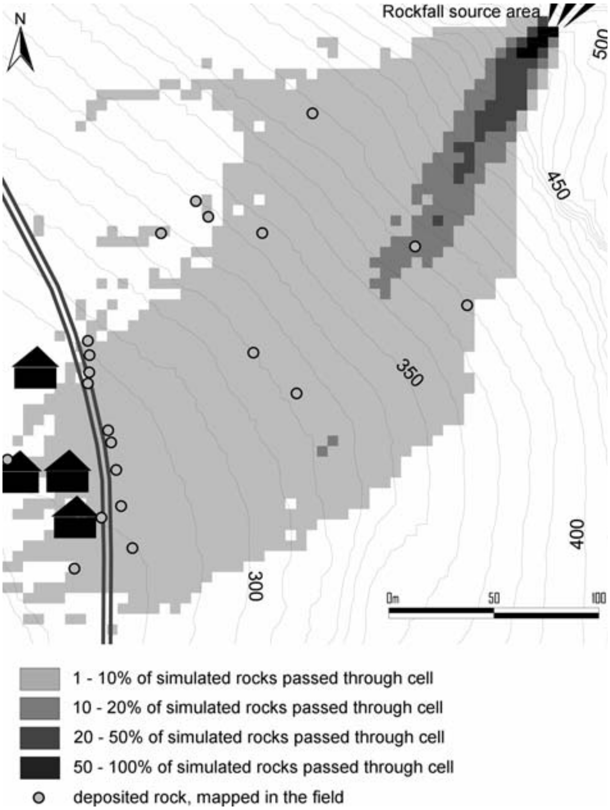

Fig. 7 Observed stopping positions (encircled dots) and passing frequencies of the simulated rockfall trajectories in Scenario 1. The darker the cell, the higher the simulated frequency of a rock passing through that cell (four classes are shown; the darkest class corresponds to 50–100% rocks, the lightest one to 1–10% rock)

calculated PRH decreases. In RockyFor, however, a change in the mean DBH of 2 cm will not have an enormous effect. As shown in the results, the wide variety of probabilistic algorithms can lead to an increase of the PRH of 4% while the mean DBH increase with 2 cm. In RockyFor, it is more important where the trees are spatially positioned.

Based on the results provided by both models, we can state that the intervention in 1992 worsened the situation. Some of the early studies on the protective role of forests (Couvreur 1982; Jahn 1988; Rupé 1991) overestimated the protection provided by the forest. Since Cemagref researchers working on this topic and RTM practitioners worked together on this project, the forest interventions of 1992 can be considered logical. Latest research and related research tools now show that the interventions did not have the desired effect. The logic of the mixed Cemagref/RTM team was to slowly optimise the protective function of the forest of that time and not to transform it. As a result, we observed and will probably continue to observe an increase of the rockfall hazard, mainly caused by the reduction of the number of stems in the *Pinus nigra* stand, due to natural mortality and drought. At the same time, we note that the presence of trees on the slope has a canalising effect on the rockfall trajectories. This allows localising positions for installing technical measures (rockfall nets, dams) to ensure effective protection. In conclusion we can say that the intervention of 1992 did not improve the protective function of the forest. If the forest stand would have evaluated normally from 1991 onwards, the degree of protection offered by forest possibly would have decreased less. If the commune of St. Martin le Vinoux would decide to carry out a second attempt to increase the protective function of the forest, we would propose to aim at restoring a dense coppice stand.

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