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Novel quantitative indicators to characterize the protective effect of mountain forests against rockfall

S. Dupire[a,*], F. Bourrier[a], J.-M. Monnet[a], S. Bigot[b], L. Borgniet[a], F. Berger[a], T. Curt[c]

[a] Université Grenoble Alpes, Irstea, UR EMGR, 2 rue de la Papeterie-BP 76, F-38402 St-Martin-d'Hères, France
[b] Université Grenoble Alpes, F-38402 Grenoble, France
[c] Irstea, UR EMAX, F-13185 Aix en Provence, France

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ABSTRACT

Natural hazards are frequent in mountain areas where they regularly cause casualties and damages to human infrastructures. Mountain forests contribute in mitigating these hazards, in particular rockfalls. Assessing the protective effect of a forest against rockfall is a difficult task for both forest managers and rockfall experts. Accurate and simple tools are therefore required to efficiently evaluate the level of protection that results from the presence of forest.

This study defines three novel indicators to quantify the protective effect of forests against rockfalls, regarding (1) the reduction of the frequency of rockfalls, (2) the reduction of their maximum intensity, and (3) the combination of the reduction of the frequency and the energy of the rocks. The first two indicators are relevant for rockfall experts whereas the third is mostly interesting for foresters as it summarizes the protective effect of forest. The Rockyfor3D model was adapted and used to simulate rockfalls propagation on 3886 different forest stands located in all the French Alps. The results of the simulations were used to calculate the three indicators for each forest stand. Finally, the relations between the forest structures and compositions and the indicators values were investigated.

Our principal result shows that only three forest characteristics are required to accurately predict the indicators and evaluate the protective level of a forest against rockfall. The two first variables correspond to the basal area and the mean diameter at breast height (DBH) of the forest stand which are two parameters commonly used by forest managers. The third characteristic is the length of forest in the maximum slope direction which can be computed with a geographic information system (GIS). The method proposed in this study is easily reproducible and is suitable to evaluate the protective effect of European mountain forests at different scales. At local scale, the proposed indicators can enrich rockfall studies in which forests are usually set aside to simplify the evaluation. Moreover, the indicators may find direct applications with foresters by allowing them to identify the protective level of their forest and consequently to adapt their management. Finally, the indicators are convenient to perform spatial analysis and produce maps of the protective effect of mountain forests that could find many applications in land settlement or evaluation of ecosystem services.

1. Introduction

Forests have a prominent place in the mountain areas of the world. Mountain forests represent 23% of the global forest cover with over 9 million km^2 (Price et al., 2011). They provide many goods and services essential to human life and activities. In addition to the wood resources they represent, mountain forests also constitute a reserve of biodiversity and contribute to the landscape attractiveness and the environmental quality. A significant proportion of mountain forests also protect human beings and infrastructures against natural hazards such as rockfall, snow avalanches, flash floods and soil erosion (Brang et al., 2001). For instance, in France, about 25% of the Alpine forests are located between rock release areas and human infrastructures and may contribute to reduce rockfall damages and casualties (Toe and Berger, 2015).

An increasing number of studies have demonstrated that forests can be an efficient and cost-effective rockfall protection structure

* Corresponding author. Tel.: +33 476762829.
E-mail address: sylvain.dupire@irstea.fr (S. Dupire).

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(Notaro and Paletto, 2012; Wehrli et al., 2006, 2005), especially for small mass events (<5 m^3) (Berger et al., 2002). On forested slopes, a falling rock can impact or break a tree with two responses after the contact: the rock is either stopped or deviated (Dorren et al., 2006). Each time an impact occurs, the total energy of the rock is partially reduced (Bertrand et al., 2013; Dorren and Berger, 2006). Therefore, forests contribute to reduce both the energy and the number of rocks that threaten human lives and infrastructures (Stoffel et al., 2006).

In mountain areas, optimizing forest management to mitigate natural hazards while maintaining other ecosystem services is a long-term fundamental objective. For this purpose, several empirical target values for stand parameters (mainly tree density, basal area, tree diameter and spatial distribution) have been proposed to optimize the protective effect of forests (Perret et al., 2004; Wasser and Frehner, 1996; Gsteiger, 1993). These approaches have the advantages of being simple and directly practicable by forest managers. However, they are mainly based on expert observations and are therefore insufficient to characterize and understand in details the functional processes involved in the interaction between forest and rockfalls. Recent studies proposed to use process-based rockfall modelling approaches that precisely describe rockfall trajectories including impacts against trees (Fuhr et al., 2015; Radtke et al., 2014; Stoffel et al., 2006). For instance, the RockyFor3D model has accurately predicted different rockfall patterns for several forested and non-forested sites in mountainous terrain (Dorren et al., 2006).

Until now, numerical methods have only been used on a restricted number of sites and forest stand structures. Moreover, few studies propose to use quantitative indicators to characterize the protection provided by forest (Radtke et al., 2014). However, both forest managers and civil protection agents need quantitative indicators in order to accurately assess the protective effect of a particular forest and decide whether additional civil engineering measures are needed.

The aims of this study are (1) to define novel indicators allowing practitioners to characterize the protective effect (PE) of a forest and (2) to apply them to quantify and compare the PE of the main forest structures and compositions existing in the French Alps. For this purpose, we first evaluated the importance of non-forest inputs on the propagation of the rocks simulated with Rockyfor3D. Second, we applied the model on 3886 forest plots of the French National Forest Inventory (NFI). Third, we proposed and calculated new indicators to quantify both the rockfall frequency and the rock energy reduction for each forest plot. Finally, we introduced a new practical method, based on the results of the simulations, to rank and predict the PE of the different forest structures and compositions in the French Alps.

2. Materials and methods

Fig. 1 shows the different steps of the methodology followed in this study. The different processes are detailed hereafter.

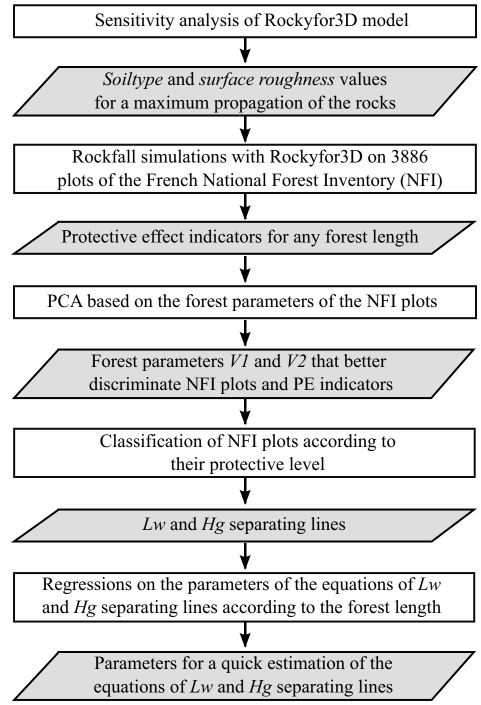

Fig. 1. Steps of the study. White rectangles correspond to processes. Grey-coloured parallelograms are results.

2.1. Rockfall simulation settings

The RockyFor3D software is one of the few rockfall simulation models (Dorren, 2015; Woltjer et al., 2008) which explicitly takes into account the protective effect (PE) of forests. Moreover, Rockyfor3D source code was made available for this study which made it possible to add new functionalities and to run the model in batch mode on a computing centre. RockyFor3D calculates trajectories of single, individually falling rocks, in three dimensions (Dorren et al., 2006). The model simulates the propagation of rocks down a slope on a rasterized digital terrain model by successive sequences of free flights through the air, rebounds on the slope surface, and impacts against trees. When a rock impacts a tree, it loses part of its kinetic energy depending on the tree type (broadleaves versus conifers), on the vertical and horizontal locations of the impact on the tree, and on the rock trajectory before impact (Dorren, 2015). Rockyfor3D uses raster maps as input files that define slope surface, topography and characteristics of forest and rock. The *calculation screens* option allows the collection of detailed data on rockfall kinematics (mainly energy, passing height and velocity) of each rock arriving on a certain line (i.e. *calculation screen*) positioned along the slope surface.

In order to identify the best settings of Rockyfor3D model, a first set of simulations was run to understand the relative importance of the surface roughness and *soiltype*. These parameters were tested on virtual digital terrain models (DTM) with 2-m resolution, a regular slope α and a length L of 2100 m (Fig. 2a). Surface roughness was tested in the range 0–80 cm with a 1-cm increment. In Rockyfor3D, *soiltype* is directly linked to the normal coefficient of restitution R_n used in the rock rebound calculation. *soiltypes* 1–6 were tested which corresponds to R_n values in the range 0.21–0.58. Each (*soiltype*, surface roughness) combination was also tested on the slope range 20°–50° and with three rock volumes 0.5 m, 1 m and 5 m. For each simulation, 15,000 spherical blocks with a density of 2600 kg m−3 were released on a contour line situated at the top of the virtual terrain. To ensure identical initial conditions for all simulations, we modified Rockyfor3D model to allow the parametrisation of an initial velocity and direction of the rock. Initial velocity was set to 12 m s−1 and initial direction was chosen to have a normal incidence angle of 25° for the first soil rebound. Those values are commonly observed in field experiments on forested slopes (Bourrier et al., 2009). Calculation screens were located every 5 m along the slope surface in order to record the number of passing blocks depending on the distance to the release line. The ground distance from departure where 90% of the blocks were stopped (d_{stop}) was used as indicator in order to compare the results of the simulations.