Forest Ecology and Management 382 (2016) 269–279

Contents lists available at ScienceDirect

Forest Ecology and Management

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

The protective effect of forests against rockfalls across the French Alps: Influence of forest diversity

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ARTICLE INFO

Article history:
Received 1 August 2016
Received in revised form 7 October 2016
Accepted 8 October 2016
Available online 18 October 2016

Keywords:
Mountain forest
Protection capability
Rockfall
Ecosystem services
Biodiversity
Alps

ABSTRACT

The role of forests in the mitigation of natural hazards has been repeatedly demonstrated. The protective effect of mountain forests against rockfalls has especially been pointed out because it can constitute a natural and cost-effective protection measure in many situations. However, this particular ecosystem service may substantially differ according to the structure and the composition of the forest. Until now, the rockfall protection capability has always been studied at a local scale with only few forest types. Moreover, the comparison of the protective effect of the different forest types studied remains difficult because different methods and indicators were used. For the same reasons, it is not possible to draw conclusions about the influence of biological and structural diversities on the protection capabilities of forests from former works.

The aims of this study were (1) to quantitatively assess the protective effect of forests at the French Alps scale and build a classification based on the protection capability, (2) to compare the protective effect of the different forest types present in the French Alps and (3) to analyze the relations between the protective effect and the forest diversity in terms of stand structure and tree composition. For this purpose, the model Rockyfor3D was used to simulate the propagation of rocks on 3886 different forest plots spread over the whole French Alps. Quantitative indicators characterizing the protective effect of each forest plot were then calculated from the simulation results and used to perform the different analyses.

Our results emphasized the importance of taking into account the length of forest in the maximum slope direction for an accurate assessment of the protective effect. Thus, the minimum length of forest to get a reduction of 99% of the rockfall hazard was chosen as indicator to compare protective effect between forests. Using this indicator, half of the French Alpine forests presented a high level of protection after a short forested slope (190 m). A decreasing gradient in the protection capabilities was observed from forest types dominated by broadleaved species to those dominated by conifer species. Moreover, considering an equivalent proportion of conifers, stands dominated by shade-tolerant tree species showed better ability to reduce rockfall hazard. Finally, our study highlighted that a high biodiversity and a structural heterogeneity within the forest have a positive effect on the reduction of rockfalls hazard.

1. Introduction

Mountain forests represent a renewable wood resource and provide a wide range of ecosystem services (Briner et al., 2013). Among them, the protection of human beings and infrastructures against natural hazards is essential, especially in Alpine regions (Bebi et al., 2001). A significant part of the forested area in the Alps provides a natural protection against rockfall (Toe and Berger, 2015; Brang et al., 2001). On forested slopes located below a departure area, it is common to observe scars on trees resulting from one or several rockfall impacts (Favillier et al., 2015). Each impact against a tree reduces the energy of the block which results in a lower velocity or a complete stop (Bertrand et al., 2013; Dorren and Berger, 2006). After a forested slope, both the energy (intensity) and the number of rocks (frequency) threatening human lives and infrastructures are reduced, especially in the case of small volume events ($\leqslant 5\ m^3$) (Berger et al., 2002).

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http://dx.doi.org/10.1016/j.foreco.2016.10.020

Quantifying the protective effect of a forest is of major importance to provide reliable recommendations to forest managers and enrich the argumentation concerning the consideration of forests in local or regional land use management strategies (Notaro and Paletto, 2012). Although early studies were restricted to a qualitative assessment of the protective effect of forests (Wasser and Frehner, 1996; Gsteiger, 1993), the quantitative evaluations have taken a prominent place since the development of reliable modeling tools such as Rockyfor3D (Dorren et al., 2006). Maringer et al. (2016) evaluated the protective capability of beech forests after a fire, Rammer et al. (2015) analyzed the effect of forest management on rockfall protection and timber production in a mature spruce stand and Radtke et al. (2014) focused their work on coppice forests of Northern Italy. Fuhr et al. (2015) is the only reference based on many different mountainous uneven aged stands taken across Northern French Alps. Thereby, most of these works limited their analysis to a local scale or to only one forest type. Mountainous forest stands of *Abies alba*, *Picea abies* and *Fagus sylvatica* and more recently coppices have been particularly studied. Although these types of forests are very common, forests are much more diverse at the Alpine scale. Therefore, the current overview of the protective effect of Alpine forests remains incomplete. Even if common trends are noticeable, it is not possible to quantitatively compare the protective effect between the different forest stands as the methods and the indicators used in the previous studies were not standardized.

The aims of this study were (1) to quantitatively assess the protective effect of forests at the French Alps scale and build a classification based on the protection capability, (2) to compare the protective effect of the different forest types present in the French Alps and (3) to analyze the relations between the protection potential and the forest diversity in terms of stand structure and tree composition. For this purpose, we first used the model Rockyfor3D to simulate the propagation of rocks on 3886 different forest plots spread over the whole French Alps from the Mediterranean sea to the Swiss border. Second, quantitative indicators characterizing the protection potential of each forest plot were calculated from the simulation results and used to build the classification based on protection capabilities. The forest plots were then grouped according to their structure and composition in order to compare the protective effect between the different forest types. Finally, the interactions between forest diversity and protection capabilities were analyzed.

2. Material and methods

2.1. Source and selection of forest data

Forest plots were extracted from the permanent sample plots of the French National Forest Inventory (NFI) based on a systematic grid of 1 km × 1 km covering the complete country. 10% of the plots are measured each year (approximately 6700 forest plots) resulting in nine fractions from 2005 to 2013. NFI data collection is based on circle plots (Robert et al., 2010) where stand properties and topographic data are assessed in a 25-m radius. On each plot, tree characteristics are inventoried for all trees with a diameter at breast height (DBH) greater than or equal to 7.5 cm.

This study used only the plots with a terrain slope greater than or equal to 20° and located in the Alpine region (Fig. 1). When the slope is lower than 20° rocks have a rolling mode of motion and their velocity decreases quickly (Dorren, 2003). Thus, the choice of a 20° threshold allows considering the protection potential of forests in both transit and deposition zones. This procedure resulted in the selection of 3886 NFI plots measured during the period 2005–2013.

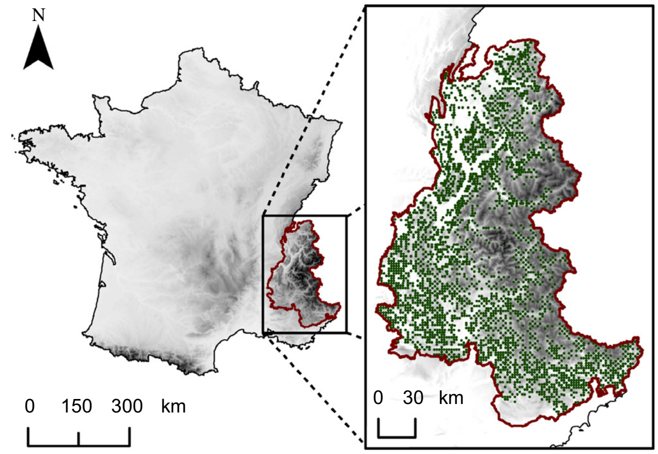

Fig. 1. Map of the 3886 selected NFI Alpine plots (green dots). French Alpine region is delimited by the red line.

2.2. Rockfall simulations on NFI plots

The RockyFor3D software (Dorren, 2015) is a rockfall simulation model taking explicitly into account the protective effect of forests. The trajectories of single, individually falling rocks are simulated in three dimensions (Dorren et al., 2006). The propagation of rocks on a rasterized digital slope is modeled as a succession of sequences of free flights through the air, rebounds on the slope surface, and impacts against trees.

For each NFI plot, rockfall simulations were run on a virtual slope surface in order to focus on the protective effect of forests. Each virtual digital terrain model had a 2-m resolution, a regular slope α corresponding to the NFI plot slope and a total length L of 2100 m in the slope direction. Calculation screens were located every 5 m along the slope surface to register both kinetic energy and number of passing blocks depending on the distance to the release line. The protection potential of the forest was evaluated by comparing the results of simulations with forest and without forest on this virtual slope surface (Fig. 2).

In order to compare and emphasize differences in the protection provided by the different stand structures and compositions,

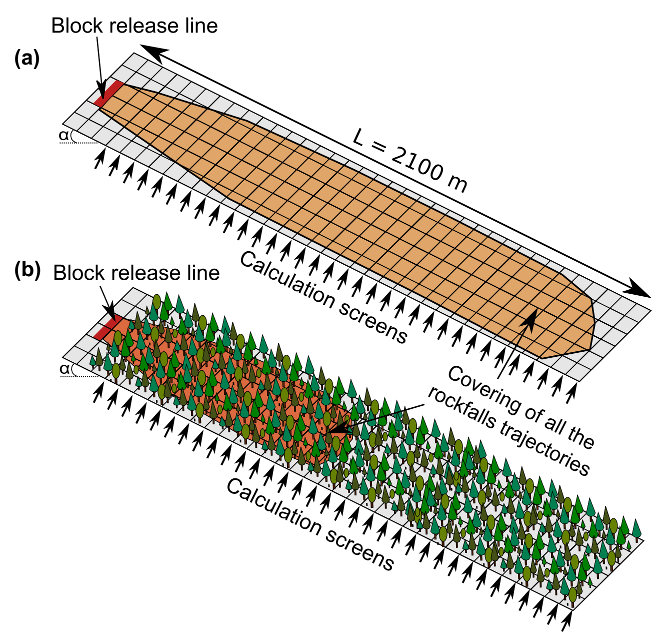

Fig. 2. Virtual terrain with uniform slope α and length L. Calculation screens are located every 5 m along the non-forested (a) and forested (b) profiles.