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Protection against rockfall along a maturity gradient in mountain forests

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ABSTRACT

When harvesting activities stop, forest stands become steadily richer in very large trees and deadwood, maturity attributes that are crucial for forest dwelling species. On the other hand, the maturation process, associated with large trees and large gaps between trees, has traditionally been thought to be detrimental to the protective function of the forest against gravitational hazards such as rockfall. However, the findings of recent studies have contested this belief, first because they showed that natural dynamics in aging stands is rather gradual in space and time, and second because they highlighted that deadwood may play an important role in protection forests.

In this study, we assessed the protection efficiency of the forest along a maturity gradient in uneven aged stands, using a network of permanent sample plots in the French Alps. Plots were selected according to management plans to represent four successive stages along the maturity gradient: young stands, adult stands just after logging, post-adult stands that escaped one to two rotations, and mature stands. We checked that stands gradually matured using the total number of very large trees (dbh > 77.5 cm), the total volume of deadwood, and the total volume of degraded large logs.

We then developed a specific module to integrate deadwood into the Rockyfor3D rockfall simulation model and assessed the rockfall protection of the plots. Mature stands, although not having reached the protection efficiency of young and dense stands, can provide adequate protection against rockfall. First, because mature stands are rather dense (more than 500 stems ha^{-1}). Second, because large logs increase the surface roughness of the forest floor and act as additional obstacles to the propagation of rocks.

Consequently, mature stands originating from aging irregular stands play a fitting role in protection forests, thereby reconciling biodiversity conservation objectives with protective functions. When mature stands originate from aging regular stands dominated by a cohort of very large trees, a cautious approach to management will better initiate a progressive irregularization process before promoting patches of mature stands.

1. Introduction

When harvesting activities are stopped or delayed for several decades, natural forest dynamics steadily lead to maturity or old-growth forest attributes. Studies comparing unmanaged versus managed forests (see, for example, Bouget et al., 2014; Burrascano et al., 2013; Marage and Lempérière, 2005; Pernot et al., 2013; Whitman and Hagan, 2007) or focusing on time since logging abandonment gradients (Lassauce et al., 2012, 2013; Pernot et al., 2013; Sitzia et al., 2012; Vanderkhove et al., 2009) highlight the following major structural changes during the maturation process: stands become richer in very large trees, large snags and large pieces of lying deadwood in various degradation stages increase, and tree microhabitats develop. Some studies also report that canopy gaps become more frequent (Rugani et al., 2013).

Maturity attributes are crucial for species that depend on forest cover continuity, deadwood, and very large trees (Paillet et al., 2010). This is the case for bryophytes (Boudreault et al., 2002), lichens (Boudreault et al., 2002; Nascimbene et al., 2010; Troy McMullin et al., 2010), saproxylic fungi (Penttilä et al., 2004), saproxylic beetles (Martikainen et al., 2000; Similä et al., 2002; Stenbacka et al., 2010; Lassauce et al., 2011), spiders and ground beetles (Isaia et al., in press), and cavity-nesting birds (Bütler et al., 2003). Consequently, to improve biodiversity conservation, multifunctional forest management aims at restoring maturity attributes, using various strategies. These strategies consist in

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extending rotations, maintaining existing maturity attributes at the time of harvest (e.g., retention forestry), and, in isolated cases, man-made restoration of maturity attributes (Martikainen et al., 2000). They also consist in setting aside forest areas from logging operations. All around the world, areas "left for natural dynamics" vary in terms of size, from small patches of around 0.5 ha (patches of mature stands) to large forest reserves of more than 1000 ha (Schmitt et al., 2009).

On the other hand, when the forest has a protective role against gravitational natural hazards (e.g., avalanches, rockfall) it is recommended to short-circuit the natural sylvigenetic cycle before the mature stages (OFEFP, 1996; Gauquelin and Courbaud, 2006). Indeed, typical non mature forests characterized by dense crown cover (>50%), high stem density (>400 stems ha^{-1}), and an absence of large gaps (>15 m width) have been shown to adequately protect downhill areas from rockfall and avalanches (Renaud et al., 1994; Cattiau et al., 1995; Dorren et al., 2004). On the contrary, mature forests, traditionally associated with large trees and a brutal senescent phase occasioning large gaps, are thought to be detrimental to the protective function (Leclerc et al., 1998). Consequently, mountain silvicultural guidelines (OFEFP, 1996; Gauquelin and Courbaud, 2006) promote gap or group selection silvicultures to renew forest stands and maintain patches of very dense young stands along the slopes (Cordonnier et al., 2008; Rammer et al., 2015).

However, as underlined by Brang et al. (2006), natural forest dynamics in aging stands is rather gradual in space and time in most European mountain forests. Small-scale disturbances, due to the death of isolated trees or small clumps of trees, are dominant and senescent phases are quite rare. Moreover, recent studies comparing managed and unmanaged forests report that the total stem number can be significantly higher in unmanaged than in managed forests. This is, for example, the case for beech-dominated forests in French mountainous areas (Pernot et al., 2013) and for Norway spruce-dominated forests in the Swiss Alps (Krumm et al., 2011). In these cases, unmanaged stands may provide adequate protective functions against rockfall and avalanche hazards.

In addition, to date, most of the studies that evaluated the protective function of a forest did not integrate the role played by deadwood in protection efficiency. However, recent studies showed that fallen dead stems increase the surface roughness of the forest floor and can thereby impede the release of avalanches and increase the protection function against natural hazards (Ammann, 2006). This may compensate for a lack of density in the living stand for a certain period, estimated around 10 years by Schönenberger et al. (2005) or Bigot (2014), during which the stand is regenerated and gradually recovers its protective ability. Moreover, ecological engineering has developed methods using deadwood to ensure the protective function of the forest in regeneration patches (Frehner and Wasser, 2005; Bourrier et al., 2012). Finally, large pieces of deadwood are known to facilitate seedling establishment and growth in constrained climatic conditions, thus improving stand resilience. We lack studies integrating the role played by deadwood when assessing the protective function of a forest.

In this work, we aimed to assess the protection efficiency of the forest against rockfall along a maturity gradient using a network of permanent sample forest plots in the French Alps. We first selected plots according to the date of their last logging operations and, based on structural indicators, we checked that the forest became gradually mature. Then, we used a process-based rockfall simulation model (Rockyfor3D – Dorren, 2012) to quantify the protective function of the forest, integrating deadwood.

We addressed the following issues: (1) Considering living trees, is the maturation process detrimental to the protective function? (2) Does the integration of deadwood modify the assessment of the protective function in mature and immature stands? (3) What are the consequences for forest management: are patches of mature stands prohibited in protection forests?

2. Materials and methods

2.1. Plot selection and plot data

Plots were selected within a network of 80 permanent sample plots covering the northern French Alps, from the montane belt to the subalpine belt. Plots were established by Irstea and the French Forest Service (ONF) between 1994 and 2002 to study the growth and the dynamics of managed and unmanaged forests. Their areas vary from 0.25 to 1 ha. The dominant management system is uneven-aged management and consists in single-tree or small-group selection cutting. Forests stands were, according to ecological conditions or management history, pure or mixed stands dominated by European beech (*Fagus sylvatica*), Silver fir (*Abies alba*), and Norway spruce (*Picea abies*).

Living and dead standing trees of more than 7.5 cm dbh are regularly measured in diameter, once every 5 years on average, and, in most of the plots, spatially located with *x*, *y*, and *z* coordinates. Since 2010, we progressively added the measurement of deadwood components using a standardized protocol dedicated to French natural reserves (Bruchiamacchie, 2005). This protocol mixed circular subplots with a radius of 20 m for large pieces of deadwood (snags, logs, and stumps more than 30 cm in diameter), circular subplots with a radius of 10 m for small pieces of standing deadwood (snags and stumps from 7.5 to 30 cm in diameter), and line intersect sampling for small logs (7.5–30 cm in diameter). We assessed the decomposition stage of deadwood using three categories: fresh, partly degraded, and very degraded. We also measured the length of large logs, 30 cm in diameter or greater. We established one to two subplots (three to six transects for line intersect sampling) in each plot, depending on the plot size.

According to management plans and interviews with managers, we selected 24 plots in order to distinguish four groups of six plots representing four successive stages along a Time Since Logging Abandonment (TSLA) gradient (Fig. 1).

We then checked our TSLA gradient regarding the density of stumps of more than 30 cm in diameter and their degradation stages (Table 1). The young stage comprises plots representing young stands that have never been logged. They originate from the colonization of open areas that started 80–100 years ago or from old large clearcuts. Stumps may be absent or present in abundance but, if so, very degraded. The so-called adult stage is made of plots that have just been logged. There are numerous stumps in various degradation stages: two thirds of the stumps are fresh stumps. The so-called sub-adult stage comprises plots that were not logged during the last 20 years (they escaped one to two rotations). There are numerous stumps, but most of them are very degraded. The mature stage is made up of plots that have not been logged for at least 40 years or have never been logged. Stumps are absent or rare and very degraded.

The dendrometric structures of the four groups showed tangible differences (Table 1). Young stands are very dense (831 ± 95 stems ha^{-1}) and dominated by small and medium-sized trees, their average basal area is quite high reaching 48 ± 6 m^2 ha^{-1}. Adult stands have the lowest density (302 ± 31 stems ha^{-1}) and lowest basal area (36 ± 4 m^2 ha^{-1}). The average densities of the sub-adult and mature stands do not reach the average density of the young stands but are quite high, 521 ± 45 stems ha^{-1} and 527 ± 81 stems ha^{-1}, respectively. The density of the mature stands is, however, highly variable ranging from 292 to 840 stems ha^{-1}. The average basal areas of the