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Permanence of resilience and protection efficiency in mountain Norway spruce forest stands: A simulation study

Thomas Cordonnier [a,b,*], Benoît Courbaud [b], Frédéric Berger [b], Alain Franc [a,c]

[a] Laboratoire Ecologie Systématique et Evolution, Département Ecologie des Populations et des Communautés, Université Paris XI, 91405 Orsay Cedex, France
[b] Unité de Recherche Ecosystèmes Montagnards, Cemagref, BP 76, 2 rue de la Papeterie, 38402 Saint-Martin-d'Hères Cedex, France
[c] UMR Biodiversité, Gènes et Ecosystèmes, Equipe Pathologie Forestière, INRA, 69 route d'Arcachon 33612 CESTAS Cedex, France

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ABSTRACT

An objective of mountain forest management is to increase the ability of forest stands to protect human activities against natural hazards such as rock-falls and snow avalanches in a sustainable way. The challenge is to find a compromise between efficient instantaneous protection, favoured by dense stands, and continuous renewal, minimizing time periods of low protection efficiency. We used a Norway spruce stand dynamics model to compare the respective advantages of individual tree and gap selection silviculture in this context. We simulated stand dynamics over 800 years with either individual tree or gap thinning every 20 years with several thinning intensities. At each time step, we evaluated stand resilience, protection efficiency against rock-falls, protection efficiency against avalanches, and structural complexity with four indicators based on stand structure. Every scenario produced short time periods with low stand resilience and protection efficiency. Such periods can be tolerated if they are sufficiently rare compared to the local disturbance regime. We characterized the permanence of resilience and protection of a forest stand as its ability to remain within boundary values of the different indicators, without going out of them during continuous time periods longer than fixed maximum durations. Permanence of resilience and permanence of protection decreased with thinning intensity. Efficient protection against rock-falls was obtained with gap thinning of intermediate intensity while protection against avalanches was obtained only for very low thinning intensities. For our ecological context, the best compromise between resilience and protection was obtained with three 10 m radius gaps per hectare every 20 years (9.5% of the area of a stand). This strategy led to uneven-aged stand structures with a high diversity of diameters classes. Our results suggest that small gap silviculture may be a good way to combine forest renewal and protection efficiency in mountain regions.

1. Introduction

In the Alps, many forests play a significant role of protecting human infrastructures (roads, houses, bridges) against natural hazards, especially rock-falls and snow avalanches (Ortloff, 1999; Führer, 2000; Brang, 2001; Dorren et al., 2004; Brang et al., 2006; Stoffel et al., 2006).

The protection efficiency of these forests depends directly on stand structure, i.e. density, mean stem size and stem size distribution (Brang et al., 2006). These stand characteristics are of prime importance in case of rock-falls because they influence the probability that rocks will be slowed down or stopped by trees (Dorren et al., 2005). In case of avalanches, trees prevent the formation of large homogeneous snow layers. Snow intercepted by tree canopies is transformed to a denser state, less prone to avalanches, before falling on the ground (Mayer and Stöckli, 2005).

Norway spruce (*Picea abies* L.) forests constitute the most important type of protection forests in the European Alps, because of their large extension and their location at key altitudes (1000–1800 m), between villages and alpine meadows, often on very steep slopes. However, the natural dynamics of Norway spruce forests are characterized by periods of low mature stand density and thus of poor protection efficiency (Motta and Haudemand, 2000; Brang et al., 2006; O'Hara, 2006). The low species diversity of these forests and the mid shade tolerance of Norway spruce seedlings (Rameau et al., 1993) lead to dynamics characterized by whole stand replacement (Motta et al., 1999; Oliver and Larson, 1996). Regeneration is usually effective only in large gaps (more than 5000 m^2) or in senescent stands displaying large mortality (Wasser and Frehner, 1996; Motta and Haudemand, 2000).

* Corresponding author. Present address: Département Recherche, Office National des Forêts, Boulevard de Constance 77300 Fontainebleau, France. Tel.: +33 1 60 74 92 28.
E-mail address: thomas.cordonnier@onf.fr (T. Cordonnier).

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As management of Norway spruce forests has been highly conservative during the previous century (Leclerc et al., 1998; Brang, 2001), many spruce stands display now regular structures with high density that are prone to windstorm damage, and thus unable to provide a sustainable protection.

The main goal of protection forest management is to improve the ability of stands to ensure a continuous effect of protection against natural hazards (Motta and Haudemand, 2000; Kräuchi et al., 2000; Brang et al., 2002). Silviculture guidelines for protection forests have been developed recently in Switzerland (Wasser and Frehner, 1996; Frehner et al., 2005), Italy (Dotta and Motta, 2000; Berretti et al., 2006) and France (Gauquelin and Courbaud, 2006). They recognise the impossibility of managing mountain forests in a stationary state because of the oscillations in stand structure created by natural dynamics and disturbance. As a consequence, these guidelines set as a silvicultural objective the limitation of periods of low protection efficiency. Otherwise, variation in structure is tolerated as long as protection is sufficiently efficient. In this context, uneven-aged silviculture systems, by maintaining a permanent forest cover, form the basis of protection forest management (Chauvin et al., 1994; Motta and Haudemand, 2000; O'Hara, 2006). However, the classical selection system appears difficult to apply in Norway spruce forests because of seedling low shade tolerance. A group selection approach, leading to the creation of canopy gaps, appears more promising (Dorren et al., 2004).

Three important assumptions behind the promotion of group selection silviculture strategies in mountain protection forests deserve more testing. The first one is that the higher stand stability (resilience and resistance) obtained with uneven-aged structures will automatically provide higher protection efficiency. High stand resilience requires the existence of saplings, which can develop only in stands of low adult tree density (Brang, 2001). In contrast, stands with high densities of adult trees stop a higher percentage of rocks (Dorren et al., 2005), have a higher effect of snow stabilization (Mayer and Stöckli, 2005) but are often highly deficient in seedlings and saplings. In this work we tested the hypothesis that resilience and protection may be conflicting not only on the short term, but also on the long term, leading to a tradeoff between these management objectives.

A second classical assumption is that sound management of mountain forests can provide effective natural protection devices. We tested the hypothesis that silviculture is not always sufficient to continuously maintain forest protection efficiency.

A third current assumption is that group selection is more efficient than individual tree selection in managing Norway spruce protection forests. Large gaps are nevertheless potential areas of avalanche initiation (Wasser and Frehner, 1996) and we hypothesised that the best spatial strategy of thinning depends on the type of risk encountered.

To test these hypotheses, we used an individual-based, spatially explicit forest stand dynamics model (Courbaud et al., 2001). We simulated thinning strategies with different intensities and different spatial characteristics. Model outputs were the temporal dynamics of one indicator of resilience, two indicators of protection efficiency and one indicator of structure complexity derived from stand characteristics. To acknowledge the transient nature of our indicators, we analysed these times series by adapting the concept of permanence stemming from biology and community ecology (Freedman and Moson, 1990; Hutson and Schmitt, 1992; Law and Morton, 1996; Jansen and Sigmund, 1998). In the context of community ecology, species composition is considered as permanent if the density of every species remains within a range of values defined by the permanence criteria m and M, and the community composition is repelled by these boundaries. In contrast to the classical focus on system equilibrium, the concept of permanence describes the capacity of a system to remain within a range of satisfactory values. We used this concept to analyse the dynamics of our indicators relative to boundaries representing minimum or maximum values set for their efficiency.

2. Method

2.1. The simulation model

To perform this analysis, we used the model "Mountain" (Courbaud et al., 2001; Goreaud et al., 2006) implemented on the software CAPSIS (de Coligny et al., 2004). This model is individual based and spatially explicit. It describes the growth, mortality, and regeneration of Norway spruce trees in uneven-aged stands on slopes. Individual diameter and height growth depend on the size of a tree and the amount of solar radiation it intercepts throughout a growing season. Radiation interception is calculated based on a detailed 3D geometric representation of the canopy and on the solar movements throughout the season (Courbaud et al., 2003). Individual seedlings appear on 4 m^2 cells mimicking the small densities usually observed in mountain forests where regeneration is often limited to safe-sites such as bare ground, stumps and dead woody debris (Brang, 1998). Seedling establishment, seedling growth and seedling mortality depend on the amount of solar radiation that reaches the center of their cell. Regeneration occurrence mimics frequency of mast seeding years observed in mountain spruce stands (Mencuccini et al., 1995). Adult mortality probability depends on diameter increment. The model has been calibrated and evaluated using both field measurements of radiation and growth and the qualitative analysis of dynamic patterns simulated (Courbaud et al., 2003; Goreaud et al., 2006).

2.2. Simulation experiment

Our simulation experiment was designed to compare the effect of two different silviculture strategies, carried out at various intensities, on two indicators of protective function, one indicator of forest stability and one indicator of forest structural complexity. To understand the long-term effects of these strategies, we performed simulations on a 1 ha plot with a north facing slope of 40° for a span of 800 years. We ran 10 replicates of each silviculture strategy and calculated the mean value of each indicator every 5 years. We started every simulation from bare ground and analysed specifically the period 300–800 years, corresponding to mature forest stands. For this study, we chose a case where regeneration was not highly limited by safe-sites (all cells can be regenerated), but was limited by light availability.

As our simulations were performed over long time spans, with events like individual mortality and establishment mimicked by stochastic processes, they should not be seen as predictions but as realistic scenarios of stand dynamics. For instance, Goreaud et al. (2006) have shown with the same model that uncertainties in the initial spatial structure lead to uncertainties in the structure of the simulated stand which increase with time. To check the potential impact of such phenomena in this study, we calculated every 5 years for each silvicultural scenario the standard deviation of the different indicators over our 10 simulation replicates. Standard deviations increased slightly with time but this trend was not significant for a period of 800 years. Overall, temporal variability was of the same magnitude in the different silviculture strategies and did not prevent their comparison.