Selecting tree species for use in rockfall-protection forests

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Abstract
Research on protection forests designed to alleviate rockfall hazard has increased enormously over the last decade. Data are available concerning the most suitable stem spacing and density regimes in stands. The species used in protection forests can also influence enormously the effectiveness of the forest in conferring a protective role. Little information exists, however, about either the mechanical resistance of different species to rock impacts or the recovery processes after sustaining a wound. This paper provides a short review of the work carried out on the mechanisms by which different subalpine forest species sustain rockfall impacts, and considers the management of protection forests in relation to species and time. Broadleaved species are generally more mechanically resistant than conifers and heal more quickly after wounding. When felled, trees can be used as barriers to obstruct or change the trajectory of falling rocks. If used as such, the decay rates of logs from coniferous species tend to be lower than those for typical subalpine broadleaved species. By accumulating and integrating existing knowledge, a forester must determine the exact nature of the hazard on a given site, and the role of the protection forest. Typical subalpine broadleaved species are more efficient in protecting human life and property against rockfall activity, but are less effective than conifers in preventing winter snow movement.

Keywords: Alps, *Fagus sylvatica* L., *Picea abies* L., *Abies alba* Mill., *Larix decidua* Mill., protection forest, rockfall, landslide

1 Introduction

The role of protection forests in preventing or mitigating natural catastrophes has received increasing attention over the last decade (Motta and Haudemand 2000; Brang 2001; Hurand and Berger 2002; Dorren *et al.* 2004a, 2004b, 2005). This increase in research is due to the recent awareness of the problems associated with abiotic hazards in mountainous areas, as well as to the increase in such hazards as a result of climate change. The predicted increase in extreme weather events (Sauri *et al.* 2003; Maracchi *et al.* 2005) will have consequences for mass movement activity, including snow avalanches and rockfall. Although it is understood that the structure of a forest plays a vital role in determining its efficiency as a protective barrier (Kräuchi *et al.* 2000; Dorren and Berger 2006), little information exists concerning the effectiveness of different tree species in ameliorating the impacts of different abiotic hazards.

Forests subjected to avalanches and rockfall will sustain varying degrees of damage. With avalanches, the energy needed to fracture and transport a dense forest of spruce trees is very low compared with the kinetic energy of a good-sized avalanche, which typically ranges between 10^4–10^5 megajoules (BARTELT and BUSER 2001). Forests do not generally protect communities and infrastructure by stopping a moving avalanche, rather their primary role lies in stabilizing the snow mantle on steep slopes. In the case of rockfall, different magnitudes of event have differing effects. Trees offer little protection when the volume of the displaced substrate is > 5.0 m^3 and the role of protection forests in such cases is limited or negligible. In the European Alps, most rockfalls are low magnitude/high frequency events with single rocks (volume < 5.0 m^3) being displaced (BERGER *et al.* 2002; STOFFEL *et al.* 2005b). In such cases, forests can act as an effective barrier and provide a protective function, and they have therefore been researched intensively in recent years (DORREN *et al.* 2004a, 2004b, 2006; BRAUNER *et al.* 2005; SCHÖNENBERGER *et al.* 2005; STOFFEL *et al.* 2005a, 2005b). Not only is the movement of rocks and stones a hazard to both people and infrastructure, but rockfall restraining nets are expensive and difficult to install. They also deteriorate with time. Although there has been research into the structure of protection forests (e.g., DORREN and BERGER 2006), data on the best species to use in rockfall protection forests are sparse. If available, these data could be used as input to models of rockfall dynamics (DORREN *et al.* 2004b) and/or fed directly into management and decision support systems (BRAUNER *et al.* 2005; MICKOVSKI and VAN BEEK 2006).

When trees are subjected to rockfall, they may uproot, suffer stem breakage, or kinetic energy may be transferred to the crown, causing breakage. Certain tree species, particularly angiosperms, appear to be more resistant to mechanical failure than others, often sustaining only wounds (DORREN *et al.* 2005; STOKES *et al.* 2005). Although there has been very little research into the fundamental mechanisms associated with these three types of failure (STOKES *et al.* 2005, 2006), information on the biomechanical behaviour of individual tree species may shed new light on tree failure mechanisms. In particular, by using knowledge gained from studies of wind storm damage to trees (NICOLL *et al.* 2005) or snow avalanches (JOHNSON 1987), we can obtain a better understanding of tree mechanical stability on sloping ground. However, the type of loading, although comparable, is not the same between trees subjected to wind or avalanches and those hit by falling rocks. In the former cases, the trunk sustains a load distributed over the stem and canopy, whereas with rockfall, a single high energy impact occurs at one point on the tree. Rockfalls are therefore more likely to induce fracture or shear than is the case with wind or snow loading.

2 Biomechanics – the mechanical behaviour of individuals

In an inventory in the French Alps (STOKES *et al.* 2005) of the type of damage sustained in an active rockfall corridor (Fig. 1), it was found that 66 % of broken or uprooted trees were conifers. Larger trees were more likely to be wounded or killed than smaller trees, although the size of the wounds was relatively smaller in larger trees. The species with the least proportion of damage through stem breakage, uprooting or wounding was European beech (*Fagus sylvatica* L.). STOKES *et al.* (2005) therefore set up a series of experiments to examine why European beech should be less susceptible to damage from rockfall.

The most common method to determine tree resistance to mechanical failure is to winch trees sideways and measure the force necessary to cause stem breakage or uprooting (CUCCHI *et al.* 2004; PELTOLA *et al.* 2000; NICOLL *et al.* 2005; STOKES *et al.* 2005). This technique has been used most often in studies of tree resistance to windthrow during winter storms. Trees will uproot if poorly anchored, or suffer stem breakage if the moment required to resist overturning is greater than that necessary to break the trunk. To estimate the resistance of trees to failure by rockfall, STOKES *et al.* (2005) carried out winching tests on

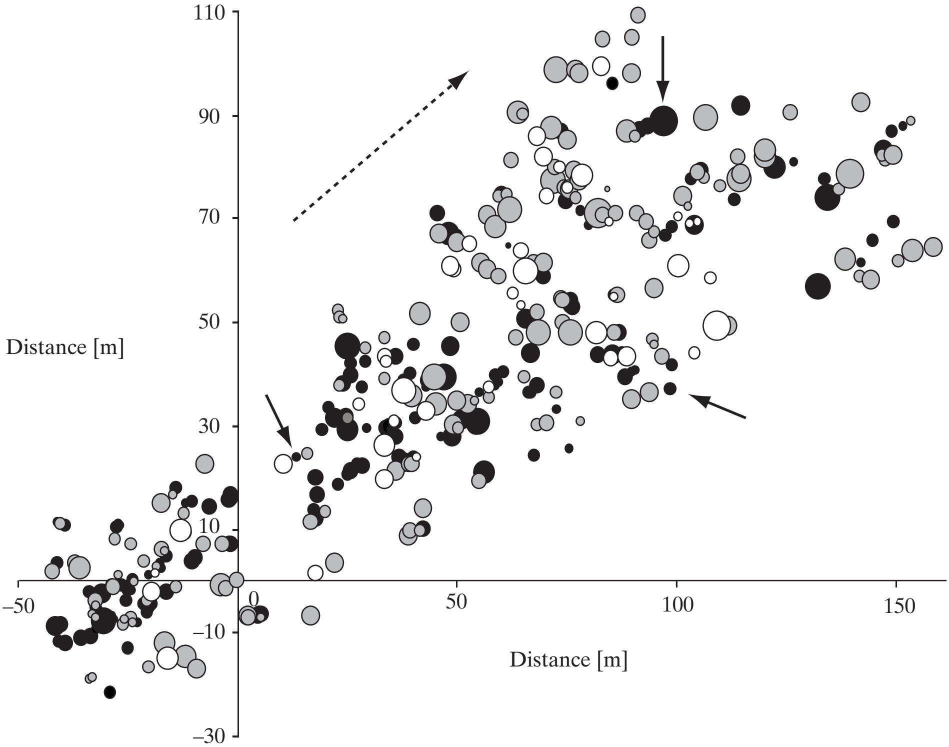

Fig. 1. Spatial distribution of trees measured in an active rockfall corridor in the French Alps. The size of each symbol represents the tree basal area. Symbols have been enlarged by 15 % for better viewing, although some symbols now overlap. A large number of trees are wounded (grey symbols) and solid arrows indicate where healthy trees (black symbols) have been protected from falling rocks by wounded or dead trees (white symbols). The dotted arrow shows the slope direction and hence the direction of rock fall. The axes cross at 0 m, where an initial GPS reading was taken next to a path through the forest.

two conifer species, Norway spruce (*Picea abies* L.) and silver fir (*Abies alba* Mill.), as well as on European beech, to determine why beech was resistant to rockfall whereas the conifers were susceptible to uprooting or stem breakage. Trees were winched downhill and the force necessary to cause failure was measured using a load cell. The kinetic energy required to break or uproot a tree was then calculated. Most fir trees failed in the stem, while spruce usually failed through uprooting. Beech was either uprooted or broke in the stem, but was twice as resistant to failure as fir, and three times more resistant than spruce. The energy necessary to cause failure was strongly related to stem diameter only in European beech, and was significantly higher in this species than in Norway spruce.

Using a similar approach, DORREN *et al.* (2005) and DORREN and BERGER (2006) determined the efficiency of different subalpine forest species to mitigate rockfall impacts. In a complex set of experiments in the field, they released individual rocks onto a forested slope and measured the rock's trajectory and the number of trees impacted, using high-speed digital video cameras. By calculating the energy dissipated during a rockfall impact for different species, DORREN *et al.* (2005) determined that the order in which species could dissipate energy, and hence were more resistant to rockfall, was: *Quercus robur* L. > *F. sylvatica* > *Acer pseudoplatanus* L. > *A. alba* > *Larix decidua* Mill. / *P. abies.*

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How is this resistance achieved? By examining trees which have and have not failed under mechanical loading, various authors have identified tree size and shape, wood strength, and root system characteristics as the most important factors governing tree stability (COUTTS 1983; JOHNSON 1987; QUINE *et al.* 1995; PELTOLA *et al.* 2000; CUCCHI *et al.* 2004). Using the same reasoning, we can determine the different factors conferring resistance to rockfall. Stem breakage is the mode of immediate failure most likely to occur above ground; the fracture energy per unit volume of wood is therefore a good indicator of the likelihood that a tree stem will fail through fracture. Combined with information about the Young's Modulus (the material parameter governing reversible deformation) of wood for different species, BRAUNER *et al.* (2005) and DORREN and BERGER (2006) found that the unit fracture work for bending and splitting was significantly higher in European beech than in Norway spruce. Differences among species in the mechanical properties of their wood are largely due to xylem structure, which is unique for each species (see MATTHECK and KUBLER 1997 for a review). Therefore, wood properties alone can account for the greater resistance of European beech to rock impacts. Nevertheless, this species was also significantly more resistant to overturning than silver fir or Norway spruce (STOKES *et al.* 2005), which implies that the root system characteristics also differ among the three species.

Root anchorage is largely governed by root system morphology, but very little work has been carried out on this parameter as a component of tree anchorage. Hypotheses about the role of root system shape and morphology have been introduced by several authors (COUTTS 1983; CUCCHI *et al.* 2004; MICKOVSKI and ENNOS 2002; DUPUY *et al.* 2005a, 2005b), who have concluded that root depth, topology, biomass, and number are all important factors to consider when examining tree anchorage. STOKES *et al.* (2006) studied the root systems of different subalpine forest species that had failed in winching tests. They found that European beech had a significantly greater number of roots than either Norway spruce or silver fir (Fig. 2). Norway spruce had a higher proportion of total root length near the soil surface, whereas European beech had the greatest proportion in the intermediate depth class and silver fir had the highest maximum root depth. Norway spruce had a significantly lower proportion of oblique roots than the other two species, resulting in a plate-like root system which was less resistant to overturning than silver fir or Norway spruce. These results imply that root number and depth are the most important components of root system anchorage, and that species with shallow, plate-like root systems will be the least resistant to overturning. Therefore in a rockfall-protection forest, highly branched and deep-rooted tree species should be encouraged. Sufficient spacing should be left between trees to allow for optimal root system growth, but without compromising the ideal structure of the stand

a) b) c)

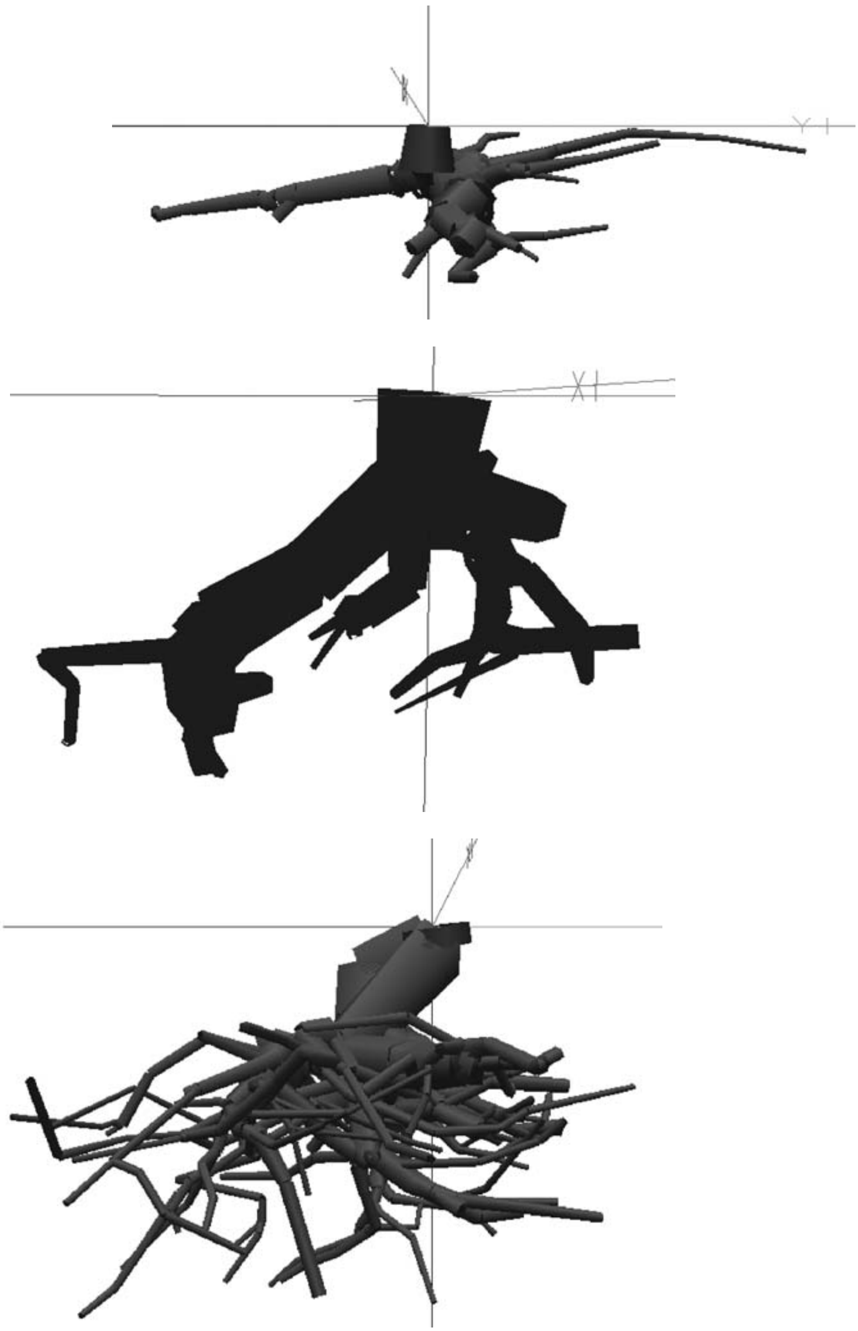

Fig. 2. Representative root system images of different subalpine forest species. The morphology and topology of each root system was measured and three-dimensional images reconstructed using the method described in DANJON *et al.* (1999). a) Norway spruce, b) silver fir and c) European beech. Images provided by F. Danjon, INRA, Bordeaux, France.

(DORREN and BERGER 2006). Several authors suggest that root system growth and morphology may also be influenced by slope angle, with larger roots clustering uphill in downy oak (*Quercus pubescens* Willd.) and Manna ash (*Fraxinus ornus* L.) (CHIATANTE *et al.* 2003; DI IORIO *et al.* 2005). Such asymmetric growth is considered as an adaptive strategy that improves tree anchorage. It is not known if root system architecture differs among species according to slope angle. If such differences do occur, further studies should be carried out on the interaction between slope gradient and root growth. On slopes subjected to rockfall, the steeper the slope, the greater the acceleration of falling rocks and the higher the rebound height (maximum height between the rock and the slope surface). The kinetic energy of falling rocks is increased and the likelihood of damage to the forest is therefore greater. If some trees are better anchored on steep slopes due to adaptations to their root systems, it would be useful to identify these species and encourage their establishment on steeper sites.

3 At the stand level – species in space and time

Protection forests must be considered both temporally and spatially. The structure of a mature forest is important in determining the trajectory of falling rocks (DORREN and BERGER 2006), but it is also necessary to consider how the forest will change over time. DORREN *et al.* (2004a) likened a rockfall-protection forest to a panarchy (GUNDERSON and HOLLING 2002), where the steering variables are the frequency and magnitude of rockfall, regeneration, the growth of individual trees, mortality, and silvicultural interventions. Each one of these factors is, in turn, influenced strongly by species type. Once a disturbance has occurred in a forest system, the species type and composition will determine the ecosystem response to the disturbance. Initially, tree failure and wounding will occur. The mode and likelihood of failure has already been discussed. If stem breakage occurs, most broadleaved species can resprout from the root system or stem. Coniferous species do not have this ability due to intrinsic physiological differences, and so will normally die. In trees that do not fail, but which are hit by falling rocks, wounds that may ultimately lead to mortality may be sustained. Mortality rates differ among tree species damaged by rockfall. In one study, the mortality rate of Norway spruce increased by 66 % after sustaining a rockfall wound, whereas in European larch *(Larix decidua),* the rate only increased by 23 % (BRAUNER *et al.* 2005). The explanation for this lower rate of mortality is that the bark of larch is thicker. Thicker bark helps protect the internal parts of the tree against low-energy rock impacts and can also grow faster around the new wound, thus accelerating the healing process. If wounds do not heal quickly, trees are more susceptible to attack by pathogens. Even if pathogens do not result in tree mortality, the mechanical resistance of the wood may be reduced.

Recently, dendrogeomorphology has been used to estimate the amount of damage sustained by particular tree species and the rate of healing after wounding by falling rocks. Such techniques can determine the effects of rockfall activity on forests over several decades and even centuries (STOFFEL *et al.* 2005a). By combining this methodology with direct observations in the field, STOFFEL *et al.* (2005b) determined that most rockfall activity occurred in April and May, the season which corresponded to maximum global insolation at the study site. Fortunately, tree wound closure is significantly slower in the dormant winter period, so if rockfall activity is high in spring, the delay in recovery is minimized (DUJESIEFKEN *et al.* 2005).

Once a disturbance has occurred in a forest, trees which have been felled by rockfall activity, avalanches or wind storms must be replaced by young trees. The species composition of a stand will have consequences for future protection. Fast-growing species, such as *Acer pseudoplatanus, Pinus sylvestris* and Norway spruce, which colonize patches formed after a disturbance event (SCHONE and SCHWEINGRUBER 2001; WOHLGEMUTH *et al.* 2002), might not confer the same potential protection against rockfall activity as some slow-growing broadleaved species. A forester must decide whether to let natural regeneration take its course, or to speed up restoration by planting trees (SCHÖNENBERGER 2002; SCHÖNENBERGER *et al.* 2005). Thus information about which species to plant is of utmost importance, but there are few supporting data.

Insufficient information is available concerning the complex relationship between species, tree age, and protection ability. Intuitively, older and larger trees should have the greatest resistance to falling rocks. However, recent evidence suggests that young, healthy trees planted at a higher density than older, large trees (which often have internal decay) provide greater protection (DORREN *et al.* 2005). In practice, the most effective age of the stand for "capturing" falling rocks is still unknown. Even if protection can be maximised at a certain age, it would be unwise to encourage the practice of even-aged stand management. In an uneven-aged forest stand, large trees provide protection against falling rocks to younger trees growing downslope (Fig. 1). Once the younger trees reach a certain diameter (DORREN *et al.* 2005 suggest 0.35 m at a stem height of 1.3 m), the upslope protective tree could be felled.

4 Dead or alive – species still counts

Felled trees also serve a protective function. If felled and positioned correctly in rockfall corridors, logs, snags and windthrown trees can "catch" or re-direct falling rocks into stands with a high stem density or channels with a high surface roughness, such as depressions where rocks have accumulated (KUPFERSCHMID ALBISETTI *et al.* 2003; DORREN *et al.* 2005; SCHÖNENBERGER *et al.* 2005). When felled, the wood of some species is more mechanically resistant and durable (resistant to pathogen decay over time) than that of others. By leaving felled snags and logs on-site, it has been predicted that in Norway spruce stands, effective protection against rockfall activity and avalanche release will be provided for 30 years (KUPFERSCHMID ALBISETTI *et al.* 2003). In experiments where the durability of felled logs in a subalpine forest was tested over several years, it was found that European beech and silver birch (*Betula pendula* Roth.) were significantly less durable than Norway spruce or silver fir, with > 20 % wood degradation in only two years (STOKES 2002). Such findings can be used to design the optimum forest for protection against rockfall. Such knowledge can then be used in models and decision support systems (BRAUNER *et al.* 2005; MICKOVSKI and VAN BEEK 2006).

5 Conclusions

Although species is a very important factor when considering the effectiveness of a protection forest, the spatial distribution of these species should also be taken into account. Once the morphology and biomechanical behaviour of a given species is known, managing that species in terms of planting, thinning, and felling will improve the protective function. For example, not only does the presence of a forest have a potential effect on the movement and trajectory of falling rocks, but it can affect the rockfall source area (DORREN *et al.* 2005).

Tree roots can grow between rocks or even into the bedrock and act as wedges. During a windstorm, wind-driven loading forces will be transmitted from the stem to the roots, resulting in root movement and subsequent dislodging of rocks. STOKES *et al.* (2006) showed that Norway spruce roots were displaced significantly when the tree stem was winched sideways, thereby increasing the risk of rocks being dislodged where this species grows. It therefore seems advisable to remove unsuitable trees from high-risk source areas, such as cliff tops. In the rockfall transport and accumulation areas, however, tree species with deep, highly branched root systems (e.g. European beech), will be better anchored, increasing the protective function of the forest.

The exact nature of the risk on the slope in question should be examined carefully. A forester wishing to provide protection against rockfall may consider planting broadleaved species; however, such a forest stand would be less resistant to winter avalanches than a stand composed of, for example, Norway spruce. Broadleaved species can also regenerate after damage, and heal more quickly if wounded by a falling rock. The disadvantage of broadleaved species is that they do not prevent the formation of homogeneous snow layers due to their reduced canopy surface and hence reduced snow interception in winter (HURAND and BERGER 2002). As a result, the snow avalanche risk increases in comparison to coniferous forests. The main remaining task for protection forest managers will be to identify which natural hazard the forest is designed to protect. If both rockfall and snow avalanches are occurring, a mixed forest would be the most effective form of protection. However, more information is needed concerning which species to plant and how to manage these species in space and over time.

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