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Mechanical resistance of different tree species to rockfall in the French Alps

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Abstract

In order to determine the mechanical resistance of several forest tree species to rockfall, an inventory of the type of damage sustained in an active rockfall corridor was carried out in the French Alps. The diameter, spatial position and type of damage incurred were measured in 423 trees. Only 5% of trees had sustained damage above a height of 1.3 m and in damaged trees, 66% of broken or uprooted trees were conifers. Larger trees were more likely to be wounded or dead 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.). Winching tests were carried out on two conifer species, Norway spruce (*Picea abies* L.) and Silver fir (*Abies alba* Mill.), as well as European beech, in order to verify the hypothesis that beech was highly resistant to rockfall and that conifers were more susceptible to uprooting or stem breakage. Nineteen trees were winched downhill and the force necessary to cause failure was measured. The energy (E_{fail}) required to break or uproot a tree was then calculated. Most Silver fir trees failed in the stem and Norway spruce usually failed through uprooting. European beech was either uprooted or broke in the stem and was twice as resistant to failure as Silver fir, and three times more resistant than Norway spruce. E_{fail} was strongly related to stem diameter in European beech only, and was significantly higher in this species compared to Norway spruce. Results suggest that European beech would be a better species to plant with regards to protection against rockfall. Nevertheless, all types of different abiotic stresses on any particular alpine site should be considered by the forest manager, as planting only broadleaf species may compromise the protecting capacity of the forest e.g. in the case of snow avalanches.

Introduction

The use of protection forests against the impact of natural hazards e.g. rockfall and snow avalanches is becoming more and more common in Europe (Brang, 2001; Dorren and Berger, 2005; Dorren et al., 2004; Hurand and Berger, 2002; Motta and Haudemand, 2000; Ott, 1996). With the increase in catastrophic events both in the European Alps (Interreg IIIb, 2001; Sauri et al., 2003) and in mountainous regions around the

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world (Tianchi et al., 2002), research into this phenomenon has accelerated. However, although it is understood that the structure of the forest plays a vital role in determining its effectiveness as a protective barrier (Jahn, 1988; Kräuchi et al., 2000), little information exists concerning the mechanical resistance of different tree species to different types of natural hazards. One particular natural hazard which has been much neglected until recent years, is that of rockfall. Not only is the movement of rocks and stones a hazard to both people and infrastructures, but rockfall safety nets are expensive and difficult to install and they deteriorate with time (Dorren, 2003). If further information on the structure of a protection forest, and the most mechanically resistant species to use against rockfall could be obtained, these data could be used as input to models of rockfall dynamics (Dorren et al., 2004) and/or fed directly into management and decision support systems (Mickovski, 2005; Stokes et al., 2004).

Even if a tree species is useful as a barrier against one particular type of hazard, the same species may not be suitable in protecting against a different type of hazard e.g. Norway spruce (*Picea abies* L.) is not especially windfirm (Stokes et al., 2000) nor resistant to rockfall (Hurand and Berger, 2002). However, in preventing snow movement, Norway spruce is highly effective in holding in place the snow mantle (Hurand and Berger, 2002). Therefore, it is necessary to determine which species is best suited to a particular function. In the case of rockfall, different types of rockfall exist, including collapsing in mass where the volume displaced is >5.0 m^3. Individual rockfall occurs more often with smaller volumes (<5.0 m^3) displaced (Berger et al., 2002). It is in this latter case that forests can act as a barrier and provide a protective function. When rocks impact against trees, different types of tree failure can occur, including uprooting and stem breakage (Berger et al., 2002). Certain species, particularly angiosperms, appear to be more resistant to failure than others, often sustaining wounds only (Dorren and Berger, 2005). It is not known which species are the most resistant against the impact of rocks, however, foresters have suggested from experience that broadleaf species are more resistant against rockfall impacts, although no particular reasons are given for this hypothesis. Only in the literature concerning wind damage to forests, can comparisons of different species be found with regards to their mechanical resistance (Meunier et al., 2002; Peltola et al., 2000; Stokes et al., 2000). The most common method to compare the likelihood of stem failure or uprooting, is to winch trees sideways until failure occurs (Cucchi et al., 2004; Gardiner et al., 2000; Moore, 2000; Stokes, 1999; Stokes et al., 2000). Certain species e.g. Sitka spruce (*Picea sitchensis* Bong. Carr) are more susceptible to stem breakage and uprooting than others e.g. European beech (*Fagus sylvatica* L.) (Stokes et al., 2000). Very few data exist concerning broadleaf species, primarily because conifer species are more susceptible to damage during a winter storm, and conifers are economically important timber species.

One of the most important factors governing the ability of a tree to withstand breakage or uprooting during a storm, is the morphology of the root system present (Cucchi et al., 2004; Dupuy et al., 2005; Stokes et al., 2000, 2006) Trees with deep and wide spreading root systems will be better anchored than those with superficial roots only (Stokes, 2002). The shape and size of a root system is influenced by its immediate environment as well as being inherent to a particular species (Köstler et al., 1968). Trees growing on the thin, rocky soils encountered on mountain slopes may therefore possess different rooting types depending on species. The morphology of the root system may also differ to that of the same species growing in a deep soil on flat ground (Köstler et al., 1968). Therefore, a well-anchored species growing in a particular soil type, may become highly unstable in a different environment (Dupuy et al., 2005; Moore, 2000).

In order to identify the type of tree failure which occurs in a forest subjected to rockfall, two studies were carried out on an active rockfall site in the French Alps. Initially, the position, size, species and type of damage sustained to trees growing in a mixed forest were measured. A series of winching tests were then carried out on Norway spruce, Silver fir and European beech, which enabled us to quantify the mechanical resistance of each species. The maximum energy required to cause failure was then estimated, as

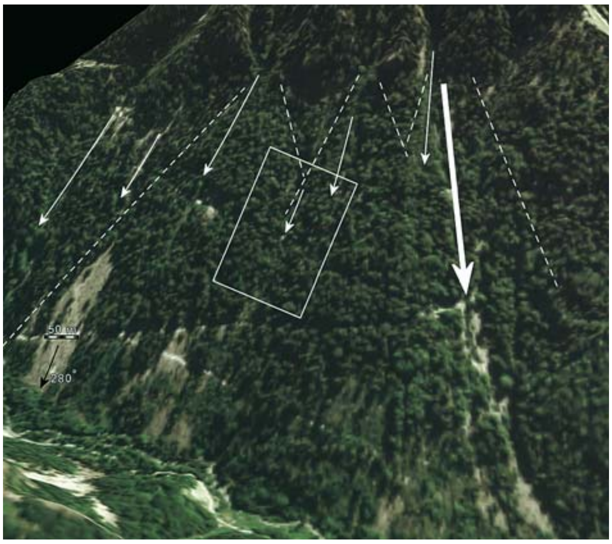

Figure 1. A digital terrain model of the study area overlain by an orthophoto. This figure shows that the site consists of several talus cones (dashed white lines) on which preferential rockfall and avalanche tracks exist (white arrows; the size indicates the magnitude of processes acting in the preferential track). The study site is depicted by the white rectangle.

during an impact between a falling rock and a tree, it is the kinetic energy of the rock which causes tree displacement. Results are discussed with regards to management strategies for protection forests.

Materials and methods

Study site

The study site was situated in the Forêt Domaniale de Vaujany, Vallée de l'Eau d'Olle, Isère (lat 45°12′, long 6°3′), France, at an altitude of 1350–1600 m. This forest is located on a north-west facing mountain side that can be divided into two areas. First, the rockfall source areas, which are a series of steep cliff faces dissected by some denudation niches occurring on top of each other. The mean slope gradient in the source area is 70° up to vertical cliffs. The second part consists of large post-glacially developed talus cones consisting mainly of rock avalanche deposits, snow avalanche deposits and rockfall scree. These large talus cones were formed after deglaciation of the main valley. The retreat of the glacier resulted in tensional rebound of the oversteepened valley slopes. This retreat led to slope instability and landsliding (mainly rock avalanches), which consequently resulted in the build up of the large talus cones (Figure 1). During the Holocene (the last 10,000 years), these talus cones have been colonised by vegetation, eventually resulting in a forest cover. Today, the dominant tree species on the site are Silver fir (*Abies alba* Mill.), Norway spruce (*Picea abies* L.), European beech (*Fagus sylvatica* L.), Sycamore (*Acer pseudoplatanus* L.), European ash (*Fraxinus excelsior* L.) and Common hazel (*Corylus avellana* L.). The forested talus cones have a slope gradient of 38–42° and act currently as rockfall transit and accumulation zones. Rocks impacting trees can cause damage and are therefore disturbing the forest ecosystem. The other major disturbances are snow creep, snow gliding, snow avalanches, ungulate browsing and wind loading. The effects of the mass movement processes are clearly reflected in the slope relief and in the vegetation as distinct preferential tracks or channels for snow transport and falling rocks. In between the preferential tracks, the forest is dominated by un-even aged Silver fir and Norway spruce and in the preferential tracks the forest is dominated by young European beech, ash and hazel trees. A storm in 1960 resulted in the loss of 2220 m^3 of timber throughout the whole forest, of which the surface area is 818 ha (C. Bazin, pers. comm.).

Inventory of damage incurred by rockfall

In order to determine if damage by rockfall was more frequent in certain species compared to others, an inventory of trees with/without damage was carried out. A 200 × 50 m corridor was defined that covered two preferential tracks within the study site, where rockfall appeared to be the most active (Figure 1). All trees > 0.1 m diameter were measured within this corridor. For each tree, the species, DBH, diameter at stem base (DSB) and type of damage were noted. Trees were noted as uprooted, broken in the stem or wounded (height and width of wound measured if below DBH).

In order to compare the extent of wound damage in trees of different sizes, the percentage of dysfunctional cambium was calculated using: (width of wound/tree basal circumference) × 100 (Guyette and Stambaugh, 2004). Analysis of variance and χ^2 tests were carried out to determine if the type of damage sustained was influenced by species and size of trees, using size parameters as covariates where necessary.

Winching tests

In order to determine the mechanical resistance of a tree to failure by rockfall, bending tests *in situ* were carried out. Trees were winched sideways until failure occurs and the force necessary to cause uprooting or stem breakage measured. Such tests were carried out on 19 adult trees. It was not possible to carry out more tests, as suitable tree material was scarce and winching tests dangerous due to the unstable, steep slope. Three species were chosen for this study, as they appeared to sustain different types of rockfall damage at the site (see results of damage mapping). These species were Silver fir, Norway spruce and European beech. Mean DBH for all trees was 0.23 ± 0.08 m and height was 14.90 ± 0.65 m (Table 1). The system employed was similar to that used by Cucchi et al. (2004), Meunier et al. (2002), Moore (2000), Peltola et al. (2000) and Stokes (1999). A motorised winch (16 kN, Hit-Trac 16B, Habegger, Switzerland) was used to winch trees sideways. For large trees, a pulley was also used which doubled the winch capacity. The winch was attached to the base of an anchoring tree at the longest possible distance to the winched tree, in order to obtain a small angle θ (Figure 2). When pulling trees downhill, a pulley was employed to deviate the force applied, so that the winch user would not be in the pathway of falling rocks or branches (Figure 2). The winch cable was attached to the test tree at a height (H_{cable}) of 4.0–8.0 m, as it was physically difficult to attach the cable any higher, due to the high number of branches encountered on most trees, which hindered climbing. The force applied was measured with a load cell (K25H-20 kN, Scaime S.A., France) and measured every second using a datalogger (Almemo 2290-8, Ahlborn, Germany). In order to measure the deflection angle, α, of the stem during winching, two inclinometers were nailed to the tree, one at cable height and the second at the stem base (Figure 2), which measured rotation of the root plate (Cucchi et al., 2004). An identical datalogger was used to record α every second during

Table 1. Means ± standard error of the parameters measured for each species tested in the winching studies and necessary for the calculation of $\mathrm{TM}_{\mathrm{crit,total}}$. Mean ± standard error values of the maximum energy (E_{fail}) required to cause failure in each species are also given

Variables	European beech ($n = 7$)	Silver fir ($n = 6$)	Norway spruce ($n = 6$)
Height (m)	17.7 ± 1.8	12.9 ± 0.8	12.7 ± 1.1
DBH (m)	0.23 ± 0.03	0.24 ± 0.02	0.24 ± 0.01
Stem weight (kg)	479.0 ± 129.0	257.5 ± 50.2	235.2 ± 42.1
Crown biomass (kg)	127.2 ± 36.8	180.4 ± 52.9	145.6 ± 28.4
Total biomass (stem + crown) (kg)	606.0 ± 161.0	437.0 ± 92.9	380.8 ± 63.6
Failure energy (kJ)	38.4 ± 12.7	22.7 ± 5.3	15.3 ± 4.7

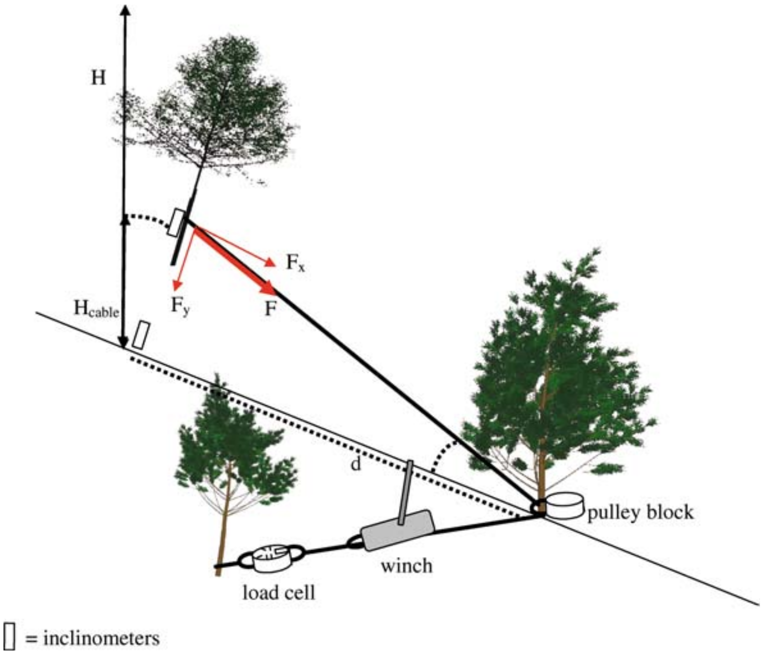

Figure 2. Trees were winched sideways and the force necessary was measured using a load cell located between the winch and anchoring tree. When winching downhill, a pulley was used to deviate the applied force around a neighbouring tree in order to prevent the tested tree or dislodged rocks from hitting the winch user. Inclinometers were attached at the stem base and at the cable attachment height (H_{cable}) in order to measure stem deflection during winching. See Methods section for an explanation of symbols.

winching. The distance between the test tree and anchorage point was also measured.

Once a tree had been winched to failure, several measurements were carried out on the stem and crown which were necessary for calculations of the total critical bending moment ($\mathrm{TM}_{\mathrm{crit,total}}$) (Cucchi et al., 2004). The relative crown length i.e. the distance between the first living branch and the stem apex was determined, along with the height of the first living branch. The stem circumference was measured every 1.0 m, avoiding any bulging whorls or branches. Crown biomass was measured by weighing all the live branches (Table 1). Stem green wood density (wood and bark) was calculated using (Table 1):

$$\mathrm{Density} = \frac{\mathrm{SectionWeight}}{\mathrm{SectionVolume}}, \tag{1}$$

where SectionVolume is the volume of a 1.0 m long section of trunk cut from the middle of the stem volume and weighed (SectionWeight). This density was assumed to be constant throughout the stem. Total stem weight was estimated using:

$$\mathrm{StemWeight} = \sum(\mathrm{SectionVolume}) \times \mathrm{Density} \tag{2}$$

As the local environment around each tree was highly variable, several measurements were made which took into account the immediate vegetation conditions. The number and species of trees within a radius of 5.0 m was recorded, along with the distance to the nearest tree. Soil moisture content was not measured, as it was considered that the large quantity of rocks and stones present would influence uprooting strength more than soil moisture.

Calculation of critical bending moment

The force required to cause failure of a tree was determined from the recorded load cell data, and associated values of σ at the time of uprooting

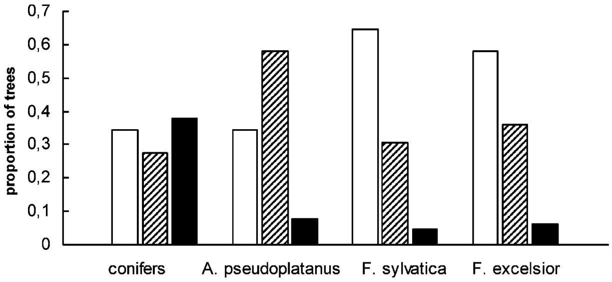

Figure 3. The proportion of healthy, wounded or dead trees were significantly different depending on species ($\chi^2 = 84.4$, $p < 0.001$). Most beech trees were healthy (white bar), whereas a high proportion of sycamore were wounded (hatched bar) and most conifers were either wounded or dead (black bar).

or stem breakage. The critical turning moment applied at the stem base was calculated using the method described in Cucchi et al. (2004):

$$\mathrm{TM}_{\mathrm{crit,applied}} = F_x \times \cos\alpha \times H_{\mathrm{cable}} + F_y \times \sin\alpha \times H_{\mathrm{cable}}, \tag{3}$$

where F_x is the component parallel to the soil surface and F_y the component perpendicular to the soil surface. Both are components of the maximal applied force F(N) and the deflection angle α of the trunk minus the slope angle, when the force was maximal. The tree stem was considered as a rigid cantilever beam and stem curvature was not taken into consideration. The difference between the angle of deflection measured at the stem base and at the height of the cable was therefore considered as negligible. Nevertheless, to account for any stem curvature, we used a mean of the two angles to calculate α. F_x and F_y were deducted from the value of F(N) and the cable angle θ, with regards to the soil surface. θ was derived from the distance d between the tree winched and the anchoring tree (Figure 2), as well as H_{cable}:

$$F_x = F \times \cos\theta \quad \text{and} \quad F_y = F \times \sin\theta \tag{4}$$

The total critical turning moment $\mathrm{TM}_{\mathrm{crit,total}}$ at the stem base adds the critical turning moment applied by the winch (3) to the critical turning moment $\mathrm{TM}_{\mathrm{crit,weight}}$ due to the force resulting from the overhanging weight of the leaning tree during winching. The weight of the winch and cable were neglected. $\mathrm{TM}_{\mathrm{crit,weight}}$ was calculated by resolving tree weight into stem and crown weights where the tree crown was taken as a whole and the tree stem as 1.0 m long sections stacked on top of each other.

$$\mathrm{TM}_{\mathrm{crit,weight}} = W \times G_x, \tag{5}$$

where W is the weight in N and G_x is the final horizontal position of the centre of gravity at the middle of the crown or stem section. As tree displacement was small, the horizontal component of G could be assimilated to the height of G on the stem multiplied by the sinus of the leaning angle given by the inclinometers. For the crown and stem section above the cable attachment point, this angle corresponds to the angle measured at this point. Although (3) and (4) assume the stem as a rigid cantilever, we wanted to take into account the stem lean below this point: leaning angle is an evolution in increments between the stem base angle and the attachment point angle. Stem section mass was deducted from the green wood density determined for each tree and the stem section volume assumed to be a truncated cone form. Hence, $\mathrm{TM}_{\mathrm{crit,crownweight}}$ was directly obtained and $\mathrm{TM}_{\mathrm{crit,stemweight}}$ was the sum of all the moments of tree stem sections.

Calculation of energy required to cause failure

The amount of energy (E_{fail}) required to cause tree failure was calculated by integrating numerically the total overturning moment TM, i.e. including crown and trunk weights, over the angle α of stem lean during winching (where α = the deflection angle of the trunk minus the slope angle when the force was maximal. α was calculated as the mean of the stem two angles measured).

$$E_{\text{fail}} = \frac{1}{2}\sum_{i=1}^{n-1}(\alpha_{i+1} - \alpha_i)(\text{TM}_{i+1} + \text{TM}_i), \qquad (6)$$

where n = the number of data recorded just before tree failure, and indices i the ith record in the data base.

Data were analysed using regression analysis and relationships between a given tree parameter and $\text{TM}_{\text{crit,total}}$ or E_{fail} were compared using analysis of covariance.

Results

Inventory of damage incurred by rockfall

423 trees were measured in the active rockfall corridor. The DBH of all trees was 0.31 ± 0.10 m and DSB was 0.41 ± 0.10 m (values are means ± standard error). The percentage of conifer species on the site was low (23%), with only Norway spruce (5%) and Silver fir (17%) present. Seven broadleaf species were present, with sycamore (24%), European beech (23%) and European ash (23%) being the major species on the site. The remaining four species comprised Common aspen (*Populus tremula* L.) (3%), Silver birch (*Betula pendula* Roth.) (2%), Wych elm (*Ulmus glabra* Huds.) (1%) and European Rowan (*Sorbus aucuparia* L.) (1%). Many trees were damaged or wounded by rockfall, with 50% of broadleaf species and 65% of conifers either wounded or dead. It was not always possible to identify the broken or uprooted conifer species, which were often in an advanced state of decay, therefore both Silver fir and Norway spruce were combined for the statistical analysis. Taking into account only those species present > 5% of the total percentage of trees, a higher number of dead conifers was present than either wounded or healthy conifers whereas very few dead broadleaf trees were present. Beech was the species with the highest number of healthy trees whereas sycamore was the most often wounded (Figure 3). Surprisingly, only eight trees were broken in the stem at a height > 1.3 m and only 12 trees had sustained wounds above this height.

The size of the tree also appeared to influence its state. Conifers were significantly larger in diameter than broadleaf species, and ash was the species with the smallest DSB ($F_{1,386}$ = 3.82, p = 0.01, Figure 4). In all species, the largest trees were the most susceptible to being wounded and in broadleaf species, the smallest trees were most likely to be dead ($F_{2,386}$ = 16.42, p < 0.001, Figure 4). However, a significant negative relationship between the % dysfunctional cambium and tree DBH existed, even though variability was high ($y = -0.0593x + 39.895$, $R^2 = 0.04$, $p = 0.023$). i.e. although larger trees were more likely to sustain damage, the size of wounds were relatively smaller in larger trees. No significant differences within or between tree species were found.

The results of this inventory permitted us to choose three species for the study of tree winching. Both conifer species were chosen along with beech, in order to compare broadleaf and

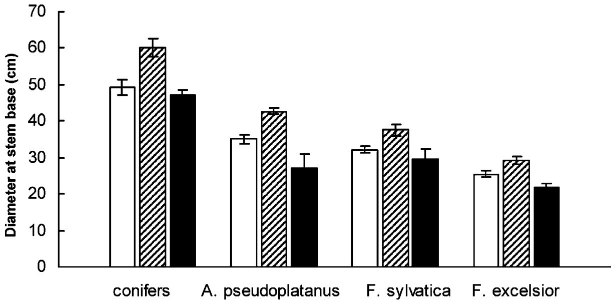

Figure 4. The diameter at stem base (DSB) influenced significantly the state of the tree. Conifers were significantly larger in diameter than broadleaf species, and ash was the species with the smallest DSB. In all species, the largest trees were the most susceptible to being wounded (hatched bar) and in broadleaf species, the smallest trees were most likely to be dead (black bar) when compared to healthy trees (white bar).

conifer species. Beech was chosen because it was the species found to have the highest proportion of undamaged trees (Figure 3).

Winching tests

Out of the 19 trees winched downhill in this study, four European beech, two Silver fir and five Norway spruce were uprooted, whilst the remaining trees all broke in the stem at a height <1.3 m. European beech failed at a mean height of 5.9 ± 1.4%, and fir at 17.3 ± 5.0% of the total relative stem length. Out of the beeches that failed in the stem, all trees were found to be growing < 0.5 m to a large neighbouring beech tree and root grafting could be seen to occur in superficial roots of neighbouring trees when the topsoil was removed with a trowel. One beech tree was discounted from further analysis, as the base of the tree was found to be associated to a neighbouring tree and may have originated from this tree. Although the Silver fir trees were sometimes growing nearby neighbouring Silver fir and beech, no root grafting could be seen to occur. The Norway spruce which broke failed at the stem base, and was found to contain rotten wood in this area.

Linear regressions carried out between $\mathrm{TM}_{\mathrm{crit,total}}$ and different tree characteristics showed that the best relationship was obtained for both DBH and total biomass in European beech, and crown biomass in Silver fir (Table 2). No significant relationship was found between $\mathrm{TM}_{\mathrm{crit,total}}$ and any size parameter for Norway spruce. Results showed European beech was significantly more resistant to failure than Silver fir when $\mathrm{TM}_{\mathrm{crit,total}}$ was regressed with DBH, DBH^2 and crown biomass (Table 2). Although no significant relationship in $\mathrm{TM}_{\mathrm{crit,total}}$ and any size parameter was found in Norway spruce, it could be seen that $\mathrm{TM}_{\mathrm{crit,total}}$ was very low for this species (39.4 ± 7.6 k Nm). No significant differences in $\mathrm{TM}_{\mathrm{crit,total}}$ were found between uprooted and broken trees, probably due to the low number of trees tested.

Variability in E_{fail} was high both within and between species (Table 1) and significant relationships between E_{fail} and DBH or DBH^2 were found in European beech only, the best being with DBH (Figure 5). E_{fail} in European beech was significantly greater than that in Norway spruce for DBH ($F_{1,8} = 11.55$, $p = 0.009$) and DBH^2 ($F_{1,8} = 7.54$, $p = 0.025$) only.

Discussion

Although we cannot be certain that any particular tree was damaged through falling rocks, the type of damage incurred suggested that rockfall was the main abiotic stress in the corridor chosen. Nevertheless, snow or wind damage may also have resulted in uprooted or broken trees. 66% of uprooted or broken trees were conifers, but it was not always possible to determine the actual species. Only 5% of trees were broken or wounded above DBH, as the average rock rebound height was 1.0 m at this site (Dorren and Berger, 2005). Large trees were more likely to be

Table 2. Significant regression equations for $\mathrm{TM}_{\mathrm{crit,total}}$ and each parameter measured during the winching studies of European beech and Silver fir

	European beech			Silver fir			Comparison between species	
Variables	Regression	p	R^2	Regression	p	R^2	$F_{2,15}$	p
DBH (m)	$y = 1983690x - 307681$	0.011	0.76	$y = 1120579x - 177738$	0.017	0.80	6.73	0.008
DBH^2 (m^3)	$y = 3824259x - 67648$	0.016	0.71	$y = 2269314x - 44133$	0.010	0.84	5.42	0.017
($\mathrm{H} \times \mathrm{DBH}^2$) ($\mathrm{m}^3$)	$y = 5881x + 130851$	0.030	0.64	$y = 130311x - 12751$	0.005	0.88	–	ns
Crown biomass (kg)	$y = 1290x - 2514$	0.027	0.66	$y = 460x + 8856$	0.002	0.92	5.44	0.017
Total biomass (stem + crown) (kg)	$y = 318x - 30875$	0.011	0.76	$y = 248x - 16879$	0.012	0.83	–	ns

Data for Norway spruce were not significant and therefore not included. Regressions between species were compared using analysis of covariance.

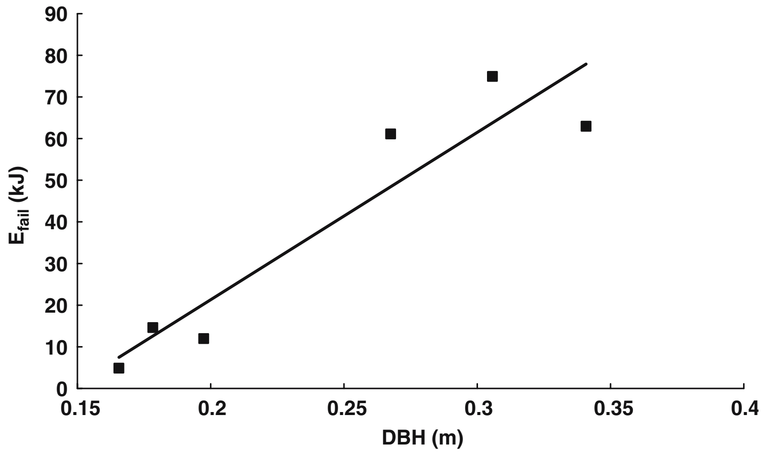

Figure 5. The amount of energy (E_{fail}) required to cause tree failure increased significantly with stem diameter at breast height (DBH) in European beech only ($y = 410.853x - 59.057$, $R^2 = 0.88$, $p = 0.006$).

wounded than smaller trees, which may be due to a decrease in rockfall activity over the last 50 years. However, smaller trees were more likely to die if damage was sustained. Small conifers were less numerous due to over browsing by ungulates in the valley (C. Bazin, pers. comm.), which will also bias the results in that small, damaged conifers were fewer due to this problem. A large amount of mosses were observed growing on the rocks along the rockfall corridor, which also suggests a decrease in rockfall activity over recent years.

The increase in the likelihood of damage with stem diameter may not only be due to a decrease in rockfall activity, but the fact that large trees are more likely to be hit by falling rocks. Whereas small trees are more likely to break and therefore die, older species will resist uprooting or breakage and sustain wounds. The larger the tree, the smaller the percentage of cambial damage that will occur. Nevertheless, certain broadleaf species are able to produce scar tissue faster than fir or spruce. This scar tissue will form around the wound and protect it from pathogen attack (Shigo, 1986). Silver fir and Norway spruce will therefore be more susceptible to infection through pathogens, leading to internal stem rot and decay, and ultimately resulting in weakened mechanical resistance to rockfall. Bark thickness was not taken into account, but is known to protect the living cambium from wounding (Guyette and Stambaugh, 2004). A future study should examine the influence of bark thickness on the percentage wound damage to a stem, for different species. Bark is usually thicker in older trees, which may be a further reason why wound size was relatively smaller in large trees.

The winching tests revealed that most Silver fir trees failed in the stem, whereas Norway spruce usually failed through uprooting. Fir trees possessed very few roots, but these roots were large and long and penetrated between the numerous rocks present in the soil (Stokes et al., 2006). Therefore, it can be considered that these trees were well anchored, as the moment required to resist overturning was greater than that needed to cause stem failure. Norway spruce possessed more superficial root systems, also with few roots (Stokes et al., 2006), and the only Norway spruce that broke in the stem was rotten at the stem base. Root systems of European beech were highly branched and deeper than spruce (Stokes et al., 2006). European beech failed several times in the stem, but only in trees which were growing nearby other beech trees. A high amount of root grafting could be seen to occur between neighbouring beech trees, which will strongly increase root anchorage. Although spruce and fir can also graft with tree roots of the same species (Bormann and Graham, 1959), no signs of root grafting were visible in the superficial surface roots of these trees.

European beech was the most resistant species to failure, and mean $TM_{crit,total}$ was nearly double that of Silver fir and was three times larger than in Norway spruce. The best correlations between $TM_{crit,total}$ and tree size parameters were found to be DBH and total biomass in beech and crown biomass in fir. In previous studies, the best correlations were usually with stem mass (Gardiner et al., 2000; Meunier et al., 2002) or $H \times DHB^2$ (Cucchi et al., 2004). It is surprising that no significant relationship was found between $TM_{crit,total}$ and any parameter measured in Norway spruce. It would probably be necessary to test a larger number of trees in order to obtain better regressions. The rocky nature of the soil also added to the variability encountered between trees. The value of $TM_{crit,total}$ was high for beech, but comparable to data for other certain species found in the literature e.g. *Pinus pinaster* Ait. (Cucchi et al., 2004) and *P. radiata* D. Don (Moore, 2000). Nevertheless, $TM_{crit,total}$ is usually much lower, and the values for fir and spruce were similar to those for *Betula* spp. and *P. sylvestris* L. (Peltola et al., 2000). Very few data exist for comparisons with broadleaf species, and none for trees growing in such conditions.

The energy (E_{fail}) required to cause tree failure was calculated from static winching data, and therefore did not take into account crown or whole stem characteristics. The effect of these components on the maximal amount of energy that can be dissipated by a tree (E_{max}) is considerable, as shown by Dorren and Berger (2005). Nevertheless, these authors obtained E_{max} values ranging from 40–115 kJ for Silver fir with a similar DBH to trees from our study. Our results showed that E_{fail} was significantly higher in European beech compared to Norway spruce, and was strongly related to stem diameter in the former species. Therefore, European beech is not only more mechanically resistant to failure, but can also resist rockfall better as stems can deflect more during an impact. These results are coherent with the results obtained by dynamic impact tests as described by Dorren and Berger (2005). Again, the lack of significant relationships between E_{fail} and stem parameters in Silver fir and Norway spruce tested in our experiments, may be due to a lack of data.

These results suggest that beech would be a better species to plant with regards to rockfall protection. Broadleaf species can also regenerate after damage, and produce large quantities of scar tissue if wounded by a falling rock. The disadvantage of broadleaf species is that they do not prevent the formation of homogeneous snow layers due to their reduced canopy surface in the winter. As a result the snow avalanche risk increases in comparison to coniferous forests. Nevertheless, more broadleaf species would need to be tested in order to determine which are the most resistant to rockfall, and thus the most useful species to plant in a rockfall protection forest. The main remaining task for protection forest managers will be to define against which natural hazard the forest has to protect. If both rockfall and snow avalanches are occurring, a mixed forest would be the most effective for protection.

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