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Stem breakage of trees and energy dissipation during rockfall impacts

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Summary The capacity of individual trees to dissipate the energy released by rockfalls has previously only been quantified based on data obtained from static tree-pulling tests or from dynamic impact tests on wood samples. We predicted that these data are not representative of the maximum amount of energy that can be dissipated by living trees during rockfall impacts. To test this prediction, we carried out rockfall experiments on a forested slope in the French Alps. To calculate the rock's energy before and after impact, rockfalls were filmed digitally. The recordings of nine impacts causing instantaneous breakage of *Abies alba* Mill. trees were analyzed in detail. An exponential relationship between stem diameter at breast height (DBH) and the maximum amount of energy a tree can dissipate was highly correlated for all of our experimental data. We applied this relationship to other tree species based on published fracture energies. The relationships obtained for *Cedrus* spp., *Fagus sylvatica* L. and *Picea abies* (L.) Karst. were significantly correlated with data from other dynamic impact tests in the field and with maximum bending moments obtained from tree-pulling experiments. Multiple linear regressions showed that impact height influences the energy that will be dissipated by an *A. alba* tree, particularly for trees with a DBH less than 15 cm. For trees with a DBH greater than 15 cm, the effect of impact height was minimal up to a height of 1 m. There was a strong relationship between the amount of energy dissipated by a tree and the horizontal distance between the impact center and the vertical central axis of the tree.

Keywords: dynamic impact test, fracture energy, maximum bending moment, protection forest.

Introduction

In mountainous areas, trees can prevent snow avalanches and stop falling rocks (Brang 2001, Berger et al. 2002). The amount of energy dissipated by individual trees growing in mountain forests is determined by the species and site conditions, as well as the nature of the hazard (Kräuchi et al. 2000). Mountain forests in the European Alps have a long history of providing protection (Schönenberger 2000, Dorren et al. 2004*a*), but attempts have been made only during the last few decades to quantify this protective effect of forests. Among the tools employed in these studies, simulation models may prove to be the most useful (e.g., Dorren and Seijmonsbergen 2003).

To model protection provided by forests, it is necessary to include both forest growth and natural hazard models. This requires a detailed knowledge of how single trees function when facing natural hazards. Although some attempts have been made to assess the capacity of trees to dissipate energy, e.g., snow avalanche simulation modeling (Bartelt and Stöckli 2001), rockfall modeling (Zinggeler 1990, Dorren and Seijmonsbergen 2003, Dorren et al. 2004*b*, Perret et al. 2004), rockfall hazard assessments (Jahn 1988, Gsteiger 1993) and snow or wind damage studies (Peltola et al. 1999, Gardiner et al. 2000), there is little information on the amount of energy that can be dissipated by living trees.

There is a relatively large amount of experimental data on maximum bending moments. These data have often been obtained by static tree-pulling tests on trees with stem diameters at breast height (DBH) up to 35 cm (Petty and Swain 1985, Mizuyama and Narita 1988, Nicoll and Ray 1996, Papesch et al. 1997, Stokes 1999, Moore 2000, Peltola et al. 2000). However, these data may not be representative of trees with a large DBH (> 40 cm) or of more instantaneous impact forces, such as rockfalls or avalanches. For example, Mizuyama and Narita (1988) showed that static tests produce energy dissipation values that are about 64% ($n = 5$) lower than dynamic impact tests on the same tree species (*Cedrus* spp.).

Other data that could be used for calculating the energy dissipative capacity during dynamic impacts of tree species occurring in the European Alps, or comparable mountain ranges, are fracture energy values obtained by dynamic impact tests on wood samples (e.g., Couvreur 1982, Sell 1987, Rupé 1991, Niemz 1993). Wood samples of *Abies alba* Mill. have fracture energy values between 4 and 5.5 J cm^{-2}, whereas the fracture energy values of *Fagus sylvatica* L. samples are about twice as high. The limitation of these data is that they do not account for the behavior of the different compartments of living trees, such as the living wood, the tree crown and the root–soil system. Couvreur (1982) showed that the maximum energy dissipated by an *F. sylvatica* tree during a dynamic impact test in the field was more than 2.5 times the value derived from a dynamic impact test in the laboratory on a green, knot-free sample from a similar tree. To account for this difference, Zinggeler (1990) doubled the fracture energy value for *F. sylvatica*—obtained by Sell (1987) by impact tests on dry wood samples — in his rockfall model.

We predicted that static tree-pulling tests and dynamic impact tests on wood samples produce values that are not representative of the amount of energy that can be dissipated by living trees during rockfall impacts or comparable dynamic impacts. Because there are no published data for living trees, our overall objective was to quantify the energy dissipative capacity during rockfall impacts of the dominating tree species in rockfall protection forests in the European Alps. Our specific aims were to: (1) develop a relationship between DBH and the maximum amount of energy that can be dissipated by an *A. alba* tree; (2) use literature data on fracture energy to establish similar relationships for other tree species; and (3) quantify the effect of the position of the impact center on the tree stem on the amount of energy that is dissipated by a tree.

Materials and methods

Rockfall experiments

The study site is in the Forêt Communale de Vaujany in France (45°12′ N, 6°3′ W, 1200–1400 m a.s.l.) and covers an area of about 0.9 ha on a forested, northwest-facing Alpine slope, with a mean gradient of 38°. The main tree species on the site are silver fir (*A. alba*, 50%), Norway spruce (*Picea abies* (L.) Karst., 25%), beech (*F. sylvatica*, 17%) and sycamore (*Acer pseudoplatanus* L., 4%). Other species present are *Sorbus aucuparia* L., *Betula pendula* Roth, *Ulmus glabra* Huds., *Ilex aquifolium* L., *Fraxinus excelsior* L. and *Corylus avellana* L. Mean stand density is 290 trees ha^{-1}. We mapped and measured all 271 trees in the study site; mean DBH was 31 ± 21 cm (± SD). During the experiments, we threw individual spherical rocks (mean diameter of 0.95 m) down the slope. The goal of the experiments was to calculate the energies of falling rocks before and after impact by capturing the rockfall event on digital film.

Before each rockfall experiment, we coated the rock with biodegradable paint, so that it left traces after impacting the tree stems. A tractor with a front end loader was used to throw the rocks down the slope. We captured the trajectory of the rock with an Impulse LR 200 laser distance meter (Laser Technology, Centennial, CO) to obtain 3D information about the rockfall trajectories. Five high-speed digital cameras installed along the experimental site provided a 2D view (Figure 1). The cameras were fixed at a height of 10 m in trees situated 30 m away from the experimental rockfall path. We also described and measured all the tree impacts and the resulting tree damage, including the size of bark wounds, the impact height, and the horizontal distance between the impact center and the vertical central tree axis (CTA) seen from the impact direction. We threw 118 rocks in total, of which 102 were analyzed. The reasons for excluding 16 of the rockfalls from analysis were: (1) they stopped within the first 10 m after sliding on the slope surface; (2) their trajectory was too far from the cameras due to lateral deviation of the falling rock; or (3) they broke into pieces during tree impact or on the slope surface. On average, we carried out eight rockfall experiments per day.

Calculation of the rockfall impact energy

We analyzed the digital films of the rockfall trajectories with the free program AviStep 2.1.1, developed by M. Delabaere (Saint Denis de la Réunion, France). This program extracts the position and velocity of a moving particle for each individual image in a digital film. The principle is as follows. First, each film has to be referenced in the *x* and *y* directions, which means that, in the first frame of each film, we defined the distance in meters between two known points in the terrain, which were clearly recognizable. In our case, we used known distances between clearly marked trees. Then, we analyzed the trajectory of each falling rock in 2D based on a sequence of movie images. Because we used high-speed digital cameras we were able to register the velocities (in both the *x* and *y* directions, as well as the resultant translational velocity) of each falling rock every 1/25th s. Therefore, we could accurately determine the translational velocity of a falling rock before and after tree impact. Determining the angular velocity was more difficult, because we had to determine the number of sequential images required for the rock to rotate once, which was not always easy to recognize.

Figure 1. A sequence of images extracted from a digital film showing a 0.95-m-diameter rock impacting an *Abies alba* tree with a stem diameter of 58 cm. The white circle indicates the position of the rock. In photograph 1, the impacted tree is hidden behind other trees. The following photographs show how the tree stem splits in two and consequently falls down.

Before each rockfall experiment, we measured the rock volume. All rocks had about the same shape (spherical), volume ($0.49\ m^3$) and density ($2800\ kg\ m^3$). With this information, we determined the mass of the rock and, therefore, the translational kinetic energy ($E_{k\text{-trans}}$), as well as the rotational energy (E_{rot}), at any point in the trajectory, provided that the rock was clearly visible in the movie images. The total kinetic energy ($E_{k\text{-tot}}$) (J) was calculated as:

$$E_{k\text{-tot}} = E_{k\text{-trans}} + E_{rot} = 0.5mv^2 + 0.5I\omega^2 \quad (1)$$

where m is the mass of the rock (kg), v is the translational velocity (m s^{-1}), I is the moment of inertia for a sphere ($0.4mr^2$, where r is the radius; kg m^2), and ω is the angular velocity (rad s^{-1}). We obtained the maximum amount of energy a tree can dissipate by calculating the difference between the kinetic energy of a rock that caused stem breakage before and after impact. We used only the total kinetic energy as the translational kinetic energy to assess whether the effect of the rotational energy could be neglected, therefore minimizing the uncertainty in our results.

Nine impacts causing instantaneous breakage of *A. alba* trees could be analyzed with sufficient detail from the film recordings. This enabled us to establish a function describing the relationship between DBH and the maximum amount of energy (J) that can be dissipated ($E_{\mathrm{diss,max}}$) by an *A. alba* tree. We used DBH in our function because it is easy to measure in the field and because relationships between DBH and resistance to fracturing have been found by many different studies (e.g., Peltola et al. 2000, Cucchi et al. 2004). We determined a best-fit function on the basis of the coefficient of determination (R^2) and its level of significance (P), the mean error (ME) and the root mean square error (RMSE). The ME and the RMSE were calculated as:

$$\mathrm{ME} = \frac{1}{n}\sum_{i=1}^{n}\frac{100\,(C_i - O_i)}{O_i} \qquad (2)$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{100\,(C_i - O_i)}{O_i}\right)^2} \qquad (3)$$

where n is number of observations, C_i is the calculated value and O_i is the observed value.

Use of literature data on fracture energy

To compare the established relationship between DBH and $E_{\mathrm{diss,max}}$ of *A. alba* to other dominant tree species in rockfall protection forests in the European Alps, we used literature data on fracture energy values of different wood samples. These data have been obtained from dynamic impact tests in the laboratory by Couvreur (1982), Sell (1987) and Rupé (1991). The tests carried out by Rupé (1991) were identical to the laboratory tests described by Couvreur (1982), who used green, knot-free wood samples with a length of 30 cm and a height and width of 2 cm. Sell (1987) used dry, knot-free samples and reported that the mean fracture energy is 12.5% higher for *P. abies* samples (4.5 J cm^{-2}) than for *A. alba* samples (4 J cm^{-2}). Couvreur (1982) and Rupé (1991) both reported that the mean fracture energy of *P. abies* samples is 90% of the mean fracture energy of *A. alba* samples. Rupé (1991) further showed that the mean fracture energy of *Cedrus* spp. samples is 70% of the mean fracture energy of *A. alba* samples. On the basis of the mean fracture energy values reported by these authors, we calculated fracture energy ratios for different tree species (Table 1). By applying these ratios to the established $E_{\mathrm{diss,max}}$ function for *A. alba*, we transferred our basic DBH and $E_{\mathrm{diss,max}}$ relationship to the tree species shown in Table 1.

To assess whether the maximum bending moment (Mb), which is used in many wind-modeling studies (e.g., Peltola et al. 1999, Gardiner et al. 2000), is a good indicator of the maximum energy that can be dissipated by a tree at a rockfall impact, we compared our $E_{\mathrm{diss,max}}$ values for *P. abies* with the Mb values. We are aware that the Mb value is not equal to the $E_{\mathrm{diss,max}}$ value of a tree; however, to obtain energies from Mb values, the calculation described by Stokes et al. (2005) can be used.

The Mb that a tree stem can withstand at the stem base without breakage can be calculated from DBH and the modulus of rupture (MOR) of the tree (Sunley 1968, Petty and Worrell 1981, Petty and Swain 1985, Peltola et al. 1999):

$$\mathrm{Mb} = \frac{\pi \times \mathrm{MOR} \times \mathrm{DBH}^3}{32} \qquad (4)$$

Here, we assume that the induced stress in the outer fibers of the tree stem is constant at all points, as first proposed by Metzger (1893) and again later by Morgan and Cannell (1994). A condition for using Equation 4 is that the tree must be well anchored in the soil. For *P. abies*, we used the mean MOR value obtained by Peltola et al. (1999, 2000) and Gardi-

Table 1. Minimum, mean and maximum fracture energies of different wood samples as obtained by Couvreur (1982) and Rupé (1991) and the mean ratio to *Abies alba* and *Fagus sylvatica*.

Tree species	Fracture energy (J cm^{-2})			Ratio to	
	Minimum	Mean	Maximum	*Abies alba*	*Fagus sylvatica*
Cedrus spp.	3.3	3.3	3.3	0.7	0.4
Picea abies	4.0	4.4	4.8	0.9	0.5
Larix decidua Mill.	4.0	4.4	4.8	0.9	0.5
Abies alba	4.3	4.9	5.5	1.0	0.6
Pinus nigra Arn.	5.5	5.5	5.5	1.1	0.7
Pinus sylvestris L.	5.5	5.5	5.5	1.1	0.7
Acer pseudoplatanus	5.5	5.5	5.5	1.1	0.7
Fraxinus excelsior L.	7.3	7.3	7.3	1.5	0.9
Fagus sylvatica	7.5	8.1	8.8	1.7	1.0
Quercus robur L.	8.8	10.6	12.5	2.2	1.3
Robinia pseudoacacia L.	11.5	13.4	15.3	2.7	1.6

ner et al. (2000), which is 32.5 MPa. Other data on the Mb of *P. abies* are presented by Stokes et al. (2005), who carried out tree-pulling tests at our study site.

Subsequently, we validated the relationship for *Cedrus* spp. with data obtained by Mizuyama and Narita (1988) from static tree-pushing tests using a bulldozer. In addition, we used data from dynamic impact tests, also carried out by Mizuyama and Narita (1988) and by Nonoda et al. (2004). During these dynamic impact tests, fracture energy was measured by impacting *Cedrus* spp. trees with a metal ball that was attached to a crane by a metal cable. Although this tree species does not occur on our study site, these data provide another possibility for validating the method of transferring the basic relationship we obtained for *A. alba* to other tree species. The relationship we obtained for *F. sylvatica* was validated with results from similar dynamic impact tests on *F. sylvatica* trees with diameters ranging from 20 to 35 cm, carried out by Couvreur (1982).

Relationship between energy dissipation and impact position

During the experiments, we registered and measured 286 tree stem impacts. Thirty-two tree impacts (16 on *A. alba* trees, 14 on *F. sylvatica* trees, and one each on an *Acer pseudoplatanus* tree and a *P. abies* tree) were captured in detail on digital film, which allowed us to establish a relationship between the energy dissipated by the tree and the horizontal distance between the impact center and the vertical CTAs, as seen from the impact direction (see Figure 2). The other 254 films could not be used, because the impact was hidden behind other trees. According to the distance between the impact center and the CTA, we defined three main impact types: frontal, lateral and scratch (Figure 2). For each impact type we determined the frequency and efficacy with which trees stopped a falling rock. In addition, we used multiple linear regression based on least squares of impact data on nine *A. alba* trees to find a relationship between observed $E_{diss,max}$ and different combinations of impact height and DBH.

Results

Energy dissipation during rockfall impacts

We observed many different rockfall impact effects, including stem bark wounds, tree uprooting, stem fracture, stem breakage and crown decapitation. We also found that translational kinetic energy could be transferred to rotational energy during a rockfall impact on a tree stem. Analyses showed that, on average, the angular velocity after tree impact is 170% of the angular velocity before the impact. Neglecting the rotational energy in the calculation of the total kinetic energy before and after an impact increased the resulting $E_{diss,max}$ values by only 0.2% on average. Therefore, we decided to use only the translational kinetic energy for all energy dissipation calculations to eliminate the uncertainty caused by errors in the angular velocity measurements.

Figure 3 shows the DBH of the nine broken *A. alba* trees and the energy that was dissipated during the impact. The line in the figure is the best-fit function ($R^2 = 0.92$, $P < 0.001$, ME = –14.1%, RMSE = 39.0%, $n = 9$). It shows that the amount of energy that can be dissipated by a living tree increases exponentially with its DBH. The best-fit function for *A. alba* has the formula:

$$E_{diss,max} = 38.7\,\text{DBH}^{2.31} \tag{5}$$

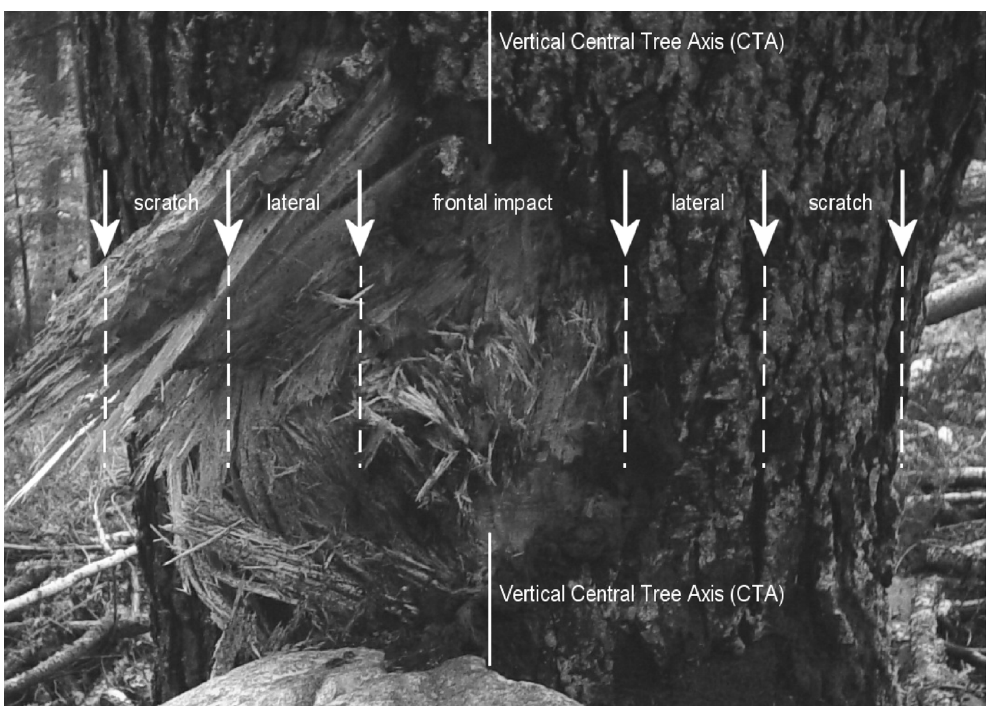

Figure 2. Three main impact types according to the horizontal distance between the impact center and the vertical central tree axis (CTA), as seen from the direction of impact.

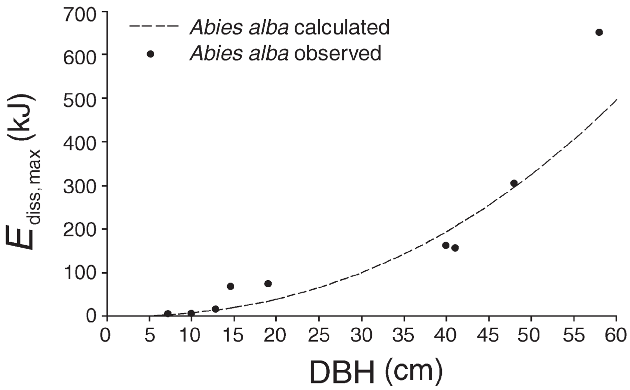

Figure 3. Relationship between the maximum amount of energy that can be dissipated by *Abies alba* ($E_{\text{diss,max}}$) and its diameter at breast height, based on nine rockfall impacts causing stem breakage.

where $E_{\text{diss,max}}$ is the maximum amount of translational kinetic energy (J) that can be dissipated by the tree during a rockfall impact.

Comparison with published fracture energy values

In our experiments, an *F. sylvatica* tree with a DBH of 34 cm resisted four frontal impacts from large, high-velocity rocks without fracturing. We also observed that *A. alba* and *P. abies* trees were generally less resistant to stem breakage than broadleaved species.

We established relationships between DBH and $E_{\text{diss,max}}$ for *P. abies*, *Cedrus* spp. and *F. sylvatica* by multiplying Equation 5 by the ratio of the species fracture energy to that of *A. alba* (see Table 1). Figure 4 shows the relationship between DBH and $E_{\text{diss,max}}$ obtained for *P. abies*, as well as the Mb values for *P. abies* based on the mean MOR value (32.5 MPa) obtained by Peltola et al. (1999, 2000) and Gardiner et al. (2000). The solid circles in Figure 4 represent the Mb values for *P. abies* obtained by Stokes et al. (2005). Figure 4 shows that, for *P. abies* with a DBH < 35 cm, our data correlate well with the data on bending moments reported by Stokes et al. (2005), Peltola et al. (1999, 2000) and Gardiner et al. (2000) (R^2 = 0.79, $P < 0.001$, $n = 12$), although our values are, on average, 1.8 times higher ($n = 12$). For larger trees, the relationship based on MOR and DBH yielded higher Mb values than our $E_{\text{diss,max}}$ values.

Figure 5 shows a similar difference between our data for *Cedrus* spp. and data obtained from static tree-pushing tests in Japan by Mizuyama and Narita (1988), with our values being on average, 2.6 times higher ($n = 7$). Figure 5 also shows the results of dynamic impact tests on *Cedrus* spp. trees carried out in the field by Mizuyama and Narita (1988) and Nonoda et al. (2004). These published data correlate well with our calculated data for *Cedrus* spp. ($R^2 = 0.62$, $P < 0.015$, $n = 9$).

Our calculated data for *F. sylvatica* correlate well ($R^2 = 0.89$, $P < 0.001$, $n = 7$) with the data obtained by Couvreur (1982), although on average, our values are 6% lower ($n = 7$) (Figure 6). Couvreur (1982) also proposed a relationship between DBH and $E_{\text{diss,max}}$ for *F. sylvatica* trees, based on the results of dynamic impact tests in the field. This relationship, designated "*F. sylvatica* fit" in Figure 6, and is similar to the relationship we found.

Figure 6 shows two additional DBH–$E_{\text{diss,max}}$ relationships that are based on laboratory impact tests ($n = 16$) conducted on *F. sylvatica* samples by Couvreur (1982) and Sell (1987). Both these relationships provided energy dissipation values that are 61% lower than the values we obtained for *F. sylvatica*.

Relationship between energy dissipation and impact position

Analysis of the translational kinetic energy before and after 32 impacts on different tree species showed that the fraction of $E_{\text{diss,max}}$ dissipated by a tree depends on the horizontal distance between the impact center and the vertical CTA. It can be calculated with the sigmoidal function (Figure 7):

$$dE = -0.046 + \frac{0.98 + 0.046}{1 + 10^{-8.007(0.58 - ((C_i - \text{CTA})/0.5\,\text{DBH}))}} \qquad (6)$$

where dE (%) is the fraction of $E_{\text{diss,max}}$ that is dissipated during the impact and C_i – CTA is the horizontal distance between the impact center and the vertical CTA seen from the impact direction (m), where C_i is the calculated value. This function is

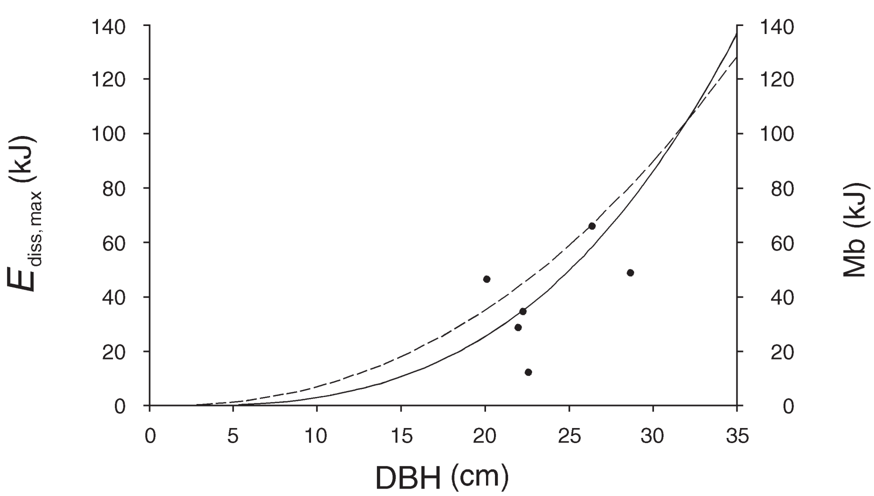

Figure 4. Relationships between stem diameter at breast height (DBH), the maximum bending moment (Mb) and the maximum amount of energy that can be dissipated by *Picea abies* ($E_{\text{diss,max}}$). The $E_{\text{diss,max}}$ of *P. abies* (calc) is the relationship calculated on the basis of our field data for *Abies alba* and the ratio presented in Table 1 (dashed line); Mb of *P. abies* (Stokes et al. 2005) are results of tree-pulling tests at our study site (●); Mb of *P. abies* (Peltola et al. 1999, 2000, Gardiner et al. 2000) are based on the relationship between the mean modulus of rupture and Mb of *P. abies* (solid line).

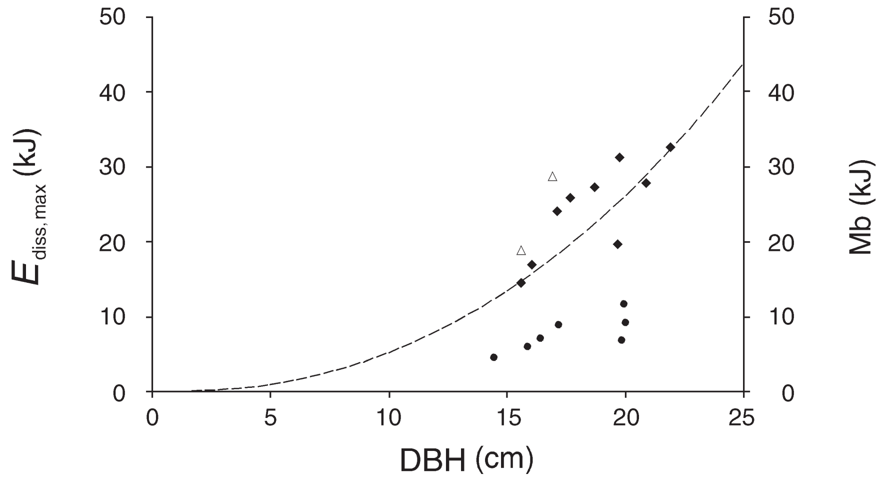

Figure 5. Relationships between diameter at breast height (DBH), the maximum bending moment (Mb) and the maximum amount of energy that can be dissipated by *Cedrus* spp. ($E_{\mathrm{diss,max}}$). The dashed line is the relationship of *Cedrus* spp. calculated on the basis of our field data for *Abies alba* and the ratio presented in Table 1; Mb of *Cedrus* spp. (●; Mizuyama and Narita 1988, static test) are results of tree-pushing tests; *Cedrus* spp. (△; Nonoda et al. 2004, dynamic test) and *Cedrus* spp. (◆; Mizuyama and Narita 1988, dynamic test) are the results of dynamic impact tests in the field.

highly correlated to the experimental data ($R^2 = 0.98$, $P < 0.001$, ME = 4.8%, RMSE = 26.5%, $n = 32$).

Table 2 presents the occurrence frequencies of the three main impact types observed during the rockfall experiments (frontal, lateral and scratch), as well as the percentage of effective impacts, i.e., the tree impacts that immediately stopped the falling rock.

The maximum impact height of all 286 registered impacts was 2 m. The maximum height of the center of the 32 impacts was 1.8 m (minimum = 0.15 m, mean = 0.74 m, standard deviation (SD) = 0.42 m). The results of the multiple linear regressions between the $E_{\mathrm{diss,max}}$ and combinations of the impact height and the DBH of the nine broken *A. alba* trees are presented in Table 3. The maximum impact height in this data set is 1 m (minimum = 0.5 m, mean = 0.77 m, SD = 0.15 m). High coefficients of determination were obtained for the regression model numbers 3, 4 and 5. With respect to ME and the RMSE, model numbers 3 and 4 gave the best results. Model 5 assumes that the higher the impact occurs on the tree stem, the greater the energy dissipated, which is not realistic. Model 4 assumes that impact height does not influence the amount of energy that will be dissipated. This leaves Model 3 as the most acceptable model, which takes into account the effect of impact height on $E_{\mathrm{diss,max}}$. With this model, we calculated that the mean percentage of dissipated energy that is determined by impact height is 99% for trees with a DBH up to 10 cm, 23% for trees with a DBH between 10 and 15 cm and 2% for trees with a DBH > 15 cm.

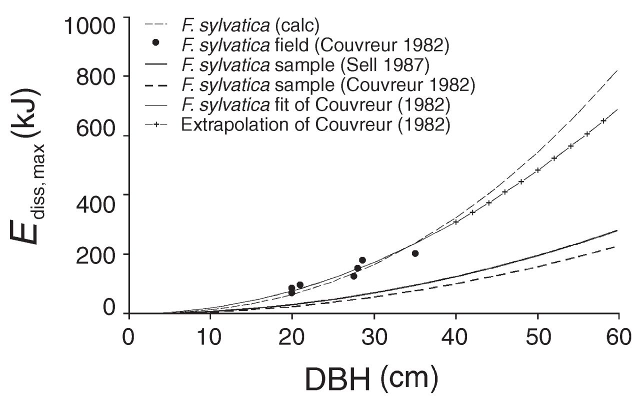

Figure 6. Relationship between the maximum amount of energy that can be dissipated by a *Fagus sylvatica* tree ($E_{\mathrm{diss,max}}$) and its diameter at breast height (DBH). *Fagus sylvatica* (calc) is the relationship calculated on the basis of our field data for *Abies alba* and the ratio presented in Table 1; *F. sylvatica* field (Couvreur 1982) are data obtained by dynamic impact tests in the field; *F. sylvatica* sample (Sell 1987) and *F. sylvatica* sample (Couvreur 1982) are relationships calculated on the basis of dynamic impact tests on wood samples in the laboratory; and *F. sylvatica* fit and extrapolation of Couvreur (1982) is the proposed relationship based on the field data and its extrapolation for diameters larger than 40 cm.

Discussion

The overall objective of this study was to quantify the energy dissipation capacity during rockfall impacts of dominant tree species in rockfall protection forests in the European Alps. Three major findings are discussed.

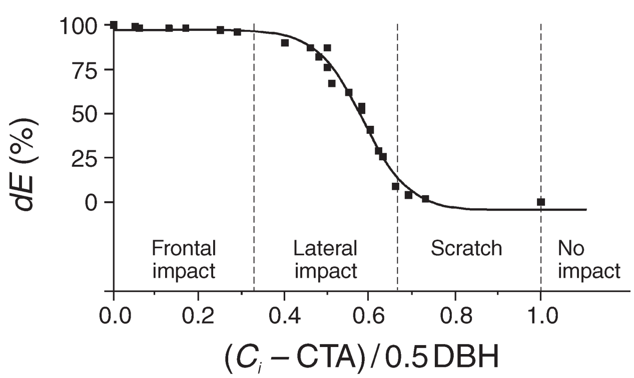

Figure 7. Sigmoidal relationship between the horizontal distance between the impact center and the vertical central tree axis (CTA) seen from the impact direction (C_i – CTA) and the fraction of the maximum amount of energy dissipated by a tree ($E_{\mathrm{diss,max}}$). Abbreviations: dE = the fraction of $E_{\mathrm{diss,max}}$ that is dissipated during the impact; C_i = calculated value; and DBH = diameter at breast height.

Table 2. Frequency of different types of impacts (%) and the efficacy of trees at stopping rocks, based on an analysis of 286 tree impacts.

Type of impact	Occurrence (n = 286)
Frontal	63.8% (14% of these were effective)[1]
Lateral	20.0% (20% of these were effective)
Scratch	16.2% (0% of these were effective)

[1] The rock stopped immediately after the impact.

The first major result was the empirical demonstration of an exponential relationship between DBH of *A. alba* trees and the maximum amount of energy they can dissipate ($E_{\text{diss,max}}$) during a rockfall impact. This relationship was highly correlated for all of our experimental data.

During a rockfall impact, the kinetic energy of the rock causes displacement and deformation of the tree stem as well as of the root–soil system. If the tree is anchored well enough in the soil to prevent uprooting and if the stem does not fracture or break, a sinusoidal shockwave is transferred through the stem to the tree crown. As a result, most coniferous trees start swaying and, depending on how closely the tree crown is surrounded by other stabilizing tree crowns, they lose their top. The root–soil system, the stem and the tree crown thus all play important roles in dissipating the impact energy. The volume of a tree increases exponentially with DBH (e.g., Morgan and Cannell 1994, Peltola et al. 2000), which probably explains why the energy dissipative capacity increases exponentially with increasing DBH.

To establish the relationship between DBH and $E_{\text{diss,max}}$, we used only the translational kinetic energy, instead of the total kinetic energy, before and after impact. This resulted in $E_{\text{diss,max}}$ values that were about 0.2% too high on average, but the procedure minimized the uncertainty caused by errors in the angular velocity measurements.

The second major finding was that the basic exponential relationship between DBH and $E_{\text{diss,max}}$ for *A. alba* can be transferred to other tree species by using published data on fracture energies. Validation of the relationships for *Cedrus* spp., *F. sylvatica* and *P. abies* with data from other dynamic impact tests in the field and Mb, demonstrated that the fracture energies of wood samples are good indicators of the energy dissipative capacities of different living trees. The correlations were high and significant (R^2 between 0.62 and 0.89, minimum level of significance $P < 0.015$). We now use this method to obtain relationships between DBH and $E_{\text{diss,max}}$ for different tree species in our simulation models when no other data are available.

We confirmed that broad-leaved trees are generally more resistant to breakage than conifers; however, the relationships for the tree species other than *A. alba*, *Cedrus* spp., *F. sylvatica* and *P. abies* still have to be validated by additional impact tests. Dynamic impact tests on wood samples are not suitable for this purpose, because they yield lower energy dissipation values than dynamic impact tests on living trees.

Application of the results of this study to research on rockfall protection forests depends on the development of a method for transferring the DBH–$E_{\text{diss,max}}$ function both to trees that commonly grow in clumps (e.g., *C. avellana*) and to homogeneous coppice stands. Although it is known that tree species that grow in clumps and homogeneous stands provide quite effective protection against rockfall, there are currently no available quantitative data on the energy dissipation capacity of such tree and stand structures.

The Mb obtained by tree-pulling tests correlates well with our data for trees with a DBH up to 35 cm, suggesting that it is a useful indicator of $E_{\text{diss,max}}$. For such trees, the Mb equation (Equation 4), which raises the DBH to the third power and multiplies it by MOR, works well. However, for trees with a small DBH, the Mb values are slightly lower than our $E_{\text{diss,max}}$ values, and for trees with a large DBH, they are higher. The use of a mean MOR value may be a limitation, because it is highly dependent on the shape of the tree and on wood quality (Peltola et al. 2000). Moreover, applying a bending moment invokes different mechanics than applying impact energy. Therefore, Mb values can be used only as an indicator of $E_{\text{diss,max}}$, as done in this study. To calculate the energy from an Mb value, the bending moments obtained during the tree pulling experiment should be integrated over the stem bending angles at the stem base, as described by Stokes et al. (2005). The energy values obtained by Stokes et al. (2005) are lower than our values, because only the energy dissipation of the root–soil or the stem compartment system is taken into account.

The third main result of our study is the quantification of the change in energy dissipation associated with the horizontal position of the center of the rockfall impact on the tree stem, which confirms the assumption made by Dorren and Seijmonsbergen (2003) and Dorren et al. (2004*b*) in their simulation studies. The relationship we obtained correlated highly with the experimental data.

Table 3. Regressions between the observed fraction of the maximum amount of energy dissipated by a tree ($E_{\text{diss,max}}$) and combinations of impact height (H; m) and diameter at breast height (DBH; cm) for *Abies alba* (n = 9). Abbreviations: X, b_1 and b_2 = regression variables; ME = mean error; and RMSE = root mean square error.

Variables	Model no.	X	b_1	b_2	R^2	ME (%)	RMSE (%)	P
$b_1(\text{DBH})^X + b_2H$	1	1	9.035	–1.0442	0.74	–22.9	146.5	0.005
	2	2	0.1615	–0.1609	0.89	–25.7	70.6	0.0001
	3	2.31	0.048	–0.05	0.92	–13.1	48.7	0.0001
	4	2.31	0.0387	0	0.92	–14.1	39.0	0.0001
	5	3	0.003	0.1254	0.96	–15.9	67.4	0.0001

The multiple linear regressions between $E_{diss,max}$ and combinations of impact height and DBH showed that impact height influenced the energy dissipated by a tree, especially for trees with a DBH up to 15 cm. For trees with a larger DBH, we found that the effect was minimal (2%). Although these findings are based on a small data set—one tree species only, and minimum and maximum impact heights of 0.5 and 1 m, respectively—we believe that impact height also plays an important role in the case of bigger trees, because the local tree mass available to resist the impact decreases with height and the cantilever beam effect changes. We speculate that these effects probably start to play a significant role in impacts above 1.5 m. In tree-pulling studies, some work has already been done on the effect of pull height on the Mb and stem breakage (e.g., Wood 1995, Moore 2000), but it would be interesting to determine the effect of height of a dynamic impact on $E_{diss,max}$. At the experimental site, impacts did not occur above 2 m, because of the slope gradient and the absence of cliffs in the forest. In many rockfall protection forests throughout the Alps, slope gradients are 50° or more and high cliffs occur within the forests. Rockfall originating from such cliff faces often results in tree impact heights above 2 m. The highest rockfall impact on a tree stem we observed in the European Alps was at a height of 8 m and occurred after a rebound on the slope surface.

In conclusion, our results provide insight into the responses of single trees during rockfall impacts and will help improve quantification of the protective effects of forests against rockfalls. More accurate comparisons of the protection afforded by forests with civil engineering works will facilitate the combined use of silvicultural interventions and technical protective structures in rockfall protection forests.

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