Internationales Symposion
INTERPRAEVENT 2004 – RIVA / TRIENT

PREDICTING THE PROTECTION OF FORESTS AGAINST ROCKFALL FOR AUSTRIA

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ABSTRACT

Forests are an important factor in the protection against rockfall and their decline could lead to a serious increase in rockfall activity. Little however is known about forest growth in rockfall protection forests and its influence on rockfall prevention. The objective of this work was to develop a tool to predict growth for rockfall forests in Austria and to analyse the change of the protective function for the typical rockfall site Finkenberg. Therefore we reparameterized the forest growth simulator PROGNAUS for rockfall sites (slope > 50 %). Further we introduced rockfall damage as an independent variable in the models and added a model that estimates the probability of each tree to get a new rockfall damage. We found that rockfall damage decreased basal area increment and increased tree mortality. We then simulated forest growth for the Finkenberg for the next 50 years. While at the beginning of the simulation period rockfall protection is satisfactory, during the simulation period protection decreases.

Key words: Protection forest, rockfall damage, individual tree model

INTRODUCTION

Mountain forests are an important factor for rockfall protection. Through their impact on trees falling boulders loose kinetic energy, and they consequently decrease their velocity or get stopped and deposited. Thus the rockfall runout distance on a forested slope is considerably shorter, whereas the factor of retention is higher than on slopes without forests.
Dorren (2003) could show in a simulation study for the Außerbach forest in the Montafon region (Vorarlberg, Austria) that the absence of forests leads to a significant increase in rockfall hazard. These results are confirmed by an experiment of Jahn (1988) who released over 100 rocks on a forest trajectory and on a comparable tree free trajectory. He then observed that maximum rockfall runout distance on the forest trajectory was only half (50.8 %) of the maximum runout distance on the tree free trajectory whereas the factor or retention was 3-10 times higher.

Many mountain forests however are reported to be in a poor condition. A common problem is overmaturity of stands which consequently makes stands unstable and susceptible to wind throw and bark beetle attacks. The decline of forests could lead to a significant increase in rockfall activity and rockfall runout distances and it is therefore desirable to prevent forest

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decline and to maintain forests in a good state. Different silvicultural treatments for the maintenance and restoration of rockfall forest have been proposed: E.g. the felling of narrow strips perpendicular to the slope (Ott et al. 1997), or structure thinning (Ott et al. 1997, Zinggeler 1989), which aims at converting the stands to uneven-aged forests, but the decision between different options is sometimes difficult.

A useful tool to compare different management scenarios on a long term (20-50 years) are individual tree growth models. Individual tree growth models are flexible systems of growth projection, that are designed for a continuum from even-aged pure to uneven-aged mixed species stands and thus their application is not limited to even-aged production forests. They are robust enough to predict stand growth within a reasonable range and allow simulating different management scenarios.

There are however two important factors that limit the applicability of individual tree growth models for rockfall sites:

1) Gsteiger (1989) suggests that rockfall itself has an important influence on forest growth
2) On rockfall sites it might be of special interest not only to simulate forest growth, but also to simulate rockfall damage.

The objective of this work was to develop a tool for growth predictions on rockfall sites for Austria that takes into account the influence of rockfall on forest growth and that predicts future rockfall damage. In this work we adapted the individual tree growth model PROGNAUS (Prognosis Austria). First we tested if rockfall damage has an influence on forest growth and then we added a model to predict new rockfall damage for sample trees.

We applied the adapted simulator to predict a typical rockfall forest in Finkenberg (Tyrol, Austria) and compared observed and predicted growth and simulated stand development for 50 years.

MODEL

The individual tree growth model PROGNAUS (Prognosis Austria) was originally developed to predict growth in uneven-aged and mixed forests. The model was intended for growth simulations in Austria and it was therefore developed from the large and representative data of the Austrian National Forest Inventory.

PROGNAUS can be used to simulate different thinning and harvesting regimes. It was for example used to determine annual allowable cut for a forest management district in conversion to uneven-aged management (Ledermann 2002b) and to predict future timber supply for Austria (Sterba et al. 2000).

The simulator, like most individual tree models, consists of the following 5 components, which are discussed in detail in the respective publications:

- Basal area increment model (Monserud and Sterba 1996, Hasenauer 2000)
- Height increment model (Schieler 1997)
- Crown ratio model (Hasenauer and Monserud 1996)
- Mortality model (Monserud and Sterba 1999)
- Ingrowth model (Ledermann 2002a)

The individual models were implemented in a software package (Ledermann 2001) and are therefore easily applicable. In a simulation run first the mortality of the next period is determined. The remaining trees are then grown using a basal area increment and a height increment model. Crown ratio, an important factor for tree growth is then updated and finally the ingrowth of regeneration over the threshold of 5 cm breast height diameter is predicted.

DATA

The Austrian National forest inventory

We, like in the original simulator, used the data of the Austrian National Forest Inventory (ANFI) (Forstliche Bundesversuchsanstalt 1981, Forstliche Bundesversuchsanstalt 1994) to reparameterize the models of PROGNAUS for rockfall sites and to develop a model for new rockfall damage.

The ANFI is a systematic permanent inventory. Plots are clustered at the four corners of a 200 m × 200 m square, the distance between clusters is 3.89 km. Permanent sample plots were established from 1981-1985, but rockfall damage was only recorded at the second and third inventory 5 and 11 years later. Thus we used only data from these two inventories (= one growth period). Further we restricted ourselves to plots with a slope of more than 50 %, because most authors agree that rockfall processes are only initiated on slopes of more 58 % - 67 % (John and Spang 1979, Heim 1939, Jaeckli 1957 in: Gsteiger 1989). Thus choosing 50 % as a threshold all rockfall relevant plots should be included and plots with no or negligible rockfall omitted. The dataset we finally used included 1869 plots.

On each sample plot site, stand and tree parameters are recorded. Site and stand parameters include elevation, aspect, slope, relief, soil parameters and ground vegetation parameters.
Individual trees are selected by two different methods: (i) trees with a dbh from 5-10.4 cm are sampled using fixed radius plots, (ii) trees with a dbh >10.4 cm are selected by angle count sampling with a basal area factor of 4 m^2ha^{-1} (Bitterlich 1948). For each tree species, dbh and the presence (1) or absence (0) of different types of stem damage, for example rockfall, logging or peeling damage, is recorded. Because damages at an inventory can not always be attributed to their cause it was also possible to assign a damage to the category „logging or rockfall damage“. We treated only damage that could be ascribed with certainty to rockfall as rockfall damage. Further we classified trees that did not have a rockfall damage at the beginning of the growth period and had a damage at the end of the growth period as trees with new rockfall damage. Trees with “logging or rockfall damage“ were however included as predictors in the model of new rockfall damage.

Finkenberg

The data of the rockfall site Finkenberg, a site that has been intensely studied in previous rockfall investigations (Hösle 1997), was used to test the adapted model.
Stands in Finkenberg are situated in the Limestone Alps at an elevation of 700-1400 m. They are facing south-southwest with an average inclination of 40°. Geologically the area is highly structured, gneiss and slates are overlapped by calc-cliffs. Soils are Rendzic Leptosols and Chromic Cambisols.

The total investigated area is 41 ha comprising 11 stands. In each stand a transect line, representing a gradient in rockfall activity, consisting of 5 sample plots was placed in fall line (Fig. 1). The distance between the plots was 20 m in fall line and each following plot was shifted two meters outward from the preceding circle to avoid that gullies fall between transect lines If it was possible, a second sampling line was placed in the stand at a distance of 20 m.

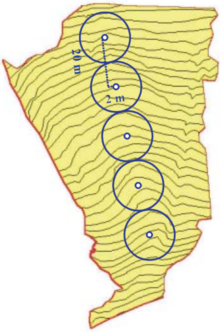

Fig. 1 Position of the sample plots in a stand

The stands were sampled using fixed radius plots (r = 9.77 m) with an area of 300 m². On the plots site and stand parameters were assessed according to the ANFI. At the 75 th percentile tree of the basal area distribution height was measured and increment cores were taken.
All stands are old spruce dominated stands with high basal areas (55-79 m^2ha^{-1}). The current increment is low with 3.6 to 6.0 $m^3ha^{-1}a^{-1}$. Rockfall damage to stands was considerable amounting to 44 - 95 % of the stands basal area. Regeneration was not satisfactory on any of the sample plots and totally lacked on 40 % of the plots.

METHODES

Model parameterization

To account for the influence of rockfall on forest growth we introduced rockfall damage in the basal area increment model and the spruce mortality model. Further we tested if the presence of rockfall damage on a plot has a significant influence on the probability of ingrowth.
To refit the mortality model for other species than spruce there were not enough dead and damaged trees observed. Also we did not change the height increment and the crown ratio model, because we assumed that the influence of rockfall damage on both is negligible. But we added a model to predict new rockfall damage to the simulator.

To refit (fit) the models we used log-linear regression for the continuous response variable basal area increment and logistic regression for the binary response variables mortality, ingrowth and new rockfall damage.
In the log-linear model all variables had to be significant at the level $\alpha = 0.05$ and the variance inflation factor had to be < 5 (Van Laar 1991). As measures for the goodness of fit we use the coefficient of multiple determination. Due to the transformation of dependent variable in the log-linear models the regression passes through the mean of the transformed variable instead of the untransformed mean. This will lead to a bias in predictions and we corrected for this bias according to the following equation:

$$\lambda = \frac{\Sigma BAI_{\Pr edicted}}{\Sigma BAI_{Observed}} \tag{1}$$

where:	λ	Correction factor
	$\Sigma BAI_{Predicted}$	Sum of predicted basal area increment
	$\Sigma BAI_{Observed}$	Sum of observed basal area increment

In the logistic model parameters were estimated using the maximum likelihood method. The Wald Chi-square statistic had to be significant at $\alpha = 0.05$. Models were selected based on the likelihood ratio and tested with the Hosmer-Lemeshow goodness of fit test. To evaluate model discrimination the area under the ROC-curve (Receiver Operating Characteristics curve) was calculated. The area under the ROC-curve is 0.5 for models with no discriminative ability, whereas an area of 1.0 indicates perfect discrimination. In practice models with an area under the ROC-curve > 0.8 are considered good models (Hosmer and Lemeshow 2000).

$$\mathbf{p} = \boldsymbol{\pi}(\mathbf{x}) = \frac{1}{1 + e^{-(\beta_0 + x_1\beta_1 + x_2\beta_2 ... + x_k\beta_k)}} \tag{2}$$

where:	p	Probability for an event, expectation, average value
	e	Base of natural logarithm
	$ß_0$-$ß_k$	Estimated parameters
	x_1-x_k	Independent variables

Simulation

For the simulation of stand growth on the rockfall site Finkenberg we applied the newly developed models and simulated stand growth for the next 50 years.

As a measure for the protective function we calculated the mean tree free distance according to Gsteiger (1989) for a rock diameter of 30 cm. The tree free distance is defined as the distance a rock passes between hitting two trees. It depends on the stand area, the assumed diameter of the falling rocks, and the sum of the diameters at breast height of all trees larger than 8 cm. It can be calculated according to the following formula:

$$MTFD = \frac{A}{N * D_{Rock} + \rule{2em}{0.5pt}\,dbh} \tag{3}$$

where:	MTFD	Mean tree free distance [m]
	A	Area [m²]
	N	Number of trees
	D_{Rock}	Diameter of the rock [m]
	Dbh	Diameter of trees at breast height (1.3 m) for trees > 8 cm [m]

RESULTS

Model reparameterization

The reparameterization of the models for rockfall sites showed, that rockfall has a significant influence on basal area growth and mortality, whereas no influence on ingrowth could be detected. Basal area increment of individual spruce, beech and broadleaf trees, was decreased through rockfall by 5.7 %, 17.3 % and 23.3 %, respectively, whereas the growth of fir, larch and pine was unaffected. Mortality for damaged spruce trees was 1.66 times higher, than for undamaged ones. Including rockfall damage in the basal area increment model and the mortality model improved both models, the improvement in overall model performance was however small.

New rockfall damage

Fitting a model for new rockfall damage gave the following results (Tab. 1): In a given year on average 0.36 % of the trees got a new rockfall damage. The probability however for a new damage depended on damage percent in the stand, slope, stand density (i.e. CCF), soil type and tree species of the subject tree.

Tab. 1 Coefficients for the model for new rockfall damage. Predictions are for individual trees for a 6-year period.

Variable	Unit	Coefficients	Standard error
Intercept		-6.210900	±0.350900
Rockfall	%	0.108547	±0.008345
Rockfall ^{2}	%	-0.000999	±0.000124
RockHarvest	%	0.048761	±0.011147
RockHarvest ^{2}	%	-0.000403	±0.000206
Slope	%	0.010900	±0.004560
CCF (Krajicek et al. 1961)		0.001210	±0.000367
Leptosols from calcareous material		0.388000	±0.131800
Larch		-1.072400	±0.330300

n = 14413
a priori probability = 2.15 %
Annual rate of new rockfall damage = 0.36 %
ROC = 0.831

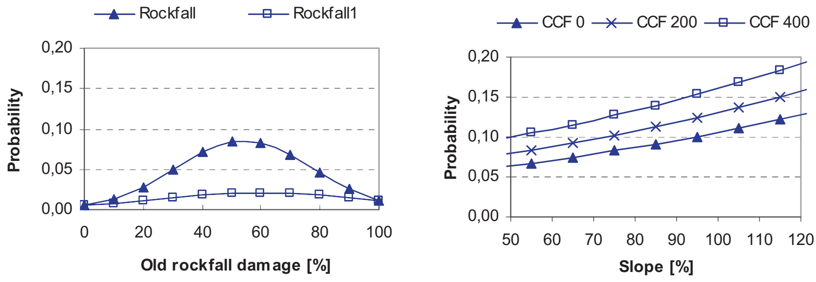

Fig. 2 Probability for new rockfall damage in a 6-year period for the percent of old rockfall damage, slope and CCF. Rockfall: the cause of damage was rockfall, Rockfall1: the cause of damage was either rockfall or logging.

The maximum of new rockfall damage was observed in stands where 50 % of the basal area had been previously damaged. The maximum was higher if rockfall was known to be the cause, but smaller if the cause of damage was only assumed to be rockfall (Fig. 2).

Further the probability for a new damage increased with slope and stand density (Fig. 2) and was 1.47 times more frequent on calcareous leptosol. Compared to all other species larch is less affected by rockfall and damage rate for larch is about a third of the overall rate.The discriminative ability of the model was good as is indicated by an area under the ROC-curve of 0.83.

Simulation

We simulated stand development in Finkenberg for 50 years and compared the increment predicted for the first 10 year period to the increment that was observed on the site in the past ten years. The average predicted increment of 5.5 $m^3a^{-1}ha^{-1}$ was similar to the average observed increment of 5.1 $m^3a^{-1}ha^{-1}$, deviations for individual stands ranged from 0 - 2.7 $m^3a^{-1}ha^{-1}$.

Tab. 2 Simulation results for the rockfall site Finkenberg

Stand	**Plots**	**N**		**G**		**dg**		**$MTFD_{30}$**	
	n	nha^{-1}		m^2ha^{-1}		cm		m	
		2001	***2051***	**2001**	***2051***	**2001**	***2051***	**2001**	***2051***
1	2	633	*448*	59	*69*	34.9	*44.8*	26.0	*32.5*
2	10	547	*374*	63	*67*	39.0	*48.4*	29.1	*37.8*
3	5	707	*528*	56	*68*	31.9	*41.9*	25.5	*29.6*
4	8	654	*462*	67	*71*	37.1	*46.4*	27.2	*33.8*
5	5	740	*498*	79	*82*	37.0	*46.3*	21.1	*28.0*
6	3	867	*593*	73	*81*	34.7	*43.7*	23.5	*28.5*
7	2	1100	*712*	79	*85*	30.2	*38.8*	15.8	*21.4*
8	3	745	*546*	57	*70*	31.4	*40.6*	23.1	*27.7*
9	5	767	*611*	53	*72*	29.3	*38.6*	23.5	*25.4*
10	5	667	*525*	50	*66*	30.6	*39.9*	27.2	*29.2*
11	4	683	*501*	58	*69*	34.5	*43.4*	28.2	*33.1*

The results of the simulation are shown in Table 2. For all stands in the next 50 years an increase in basal area can be observed, whereas stem number decreases. This means that basal area is concentrated on fewer individuals, which is also expressed in higher mean diameters. This situation seems to be less favourable for rockfall protection and thus the average tree free distance decreases. A detailed analysis revealed that towards the end of the simulation period all stands reach a point, where mortality is higher than basal area increment. This suggests that growth at Finkenberg is declining and that regeneration of the stands is necessary. This corresponds also to the field observations of Hösle (1997), who suggested that regeneration was necessary in all stands.

To demonstrate stand development under management we performed two simulation runs for stand number two. Stand number two is the stand where most plots were observed and it is also a stand with a high damage percent and a low current increment. For the first scenario no trees were removed and for the second scenario we mimicked strip felling. Strip felling perpendicular to the slopes, with strips exceeding no more than 20 m in the direction of the fall line was suggested as regeneration method for Finkenberg by Hösle (1997). Hösle also suggested that trees with the highest damage should be preferably used.

Thus we removed all trees with a dbh > 20 cm on three severely damaged plots. To create no large gaps in fall line the plots further had to be at least 40 m apart in fall line. The results of the two simulation scenarios are shown in Fig. 3. Compared to no management the mean tree free distance directly after the intervention increases, but as soon 2021 the tree free distance is shorter in the strip cutting scenario.

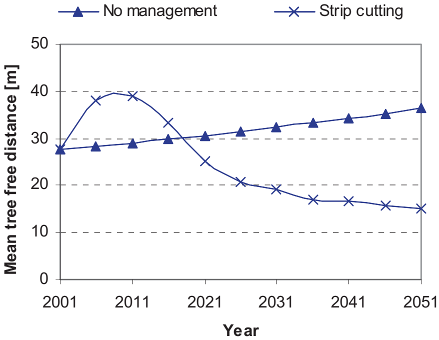

Fig. 3 Development of the mean tree free distance for Finkenberg for stand number two for no management and for strip cutting

DISCUSSION

Growth loss and mortality

Our results indicate a decreased growth and an increased mortality due to rockfall damage. Growth losses can be attributed to the production of defence and repair substances for wound healing. Other losses are caused by wound infection with wood decaying organisms which damage roots and sapwood and thereby restrict the uptake and transport of water and nutrients. Wound infection is probably also a major cause for increased spruce mortality. Annosum root disease, for example, is an important factor associated with conifer mortality. Trees eventually die from the stress or from attacks of scolytid beetles attracted to the stress (Preisler 1997).

Growth losses however were species specific and we found broadleaf trees to be more sensitive to damage than spruce, whereas for fir, larch and pine no influence on growth was detected. We assume that these differences are caused by different reactions to wounding and a different susceptibility to fungal attacks.
Reactions to wounding are described in detail by Dujesiefken et al. (1991) for wounding for spruce and various deciduous trees and by Knigge (1975) for spruce and beech. One important difference could be the fact that conifers do not suffer from air embolization, because they are able to close the bordered pits.
With respect to susceptibility to wound infection, the species that did not show a growth reduction due to damage, i.e. pine, larch and fir seem to be comparatively resistant (Mayer 1984). Beech, in contrast, is susceptible to various pathogens (Allinger-Csollich 2000).

Inferring that growth losses caused by rockfall damage are similar to those caused by other mechanical damages (logging, peeling) or butt rot, we were able to compare our results to those of other studies (Tab. 3). The annual growth reduction of 1.18 % we observed seems to be in line with other investigations, which report reductions 0.73-1.85 % for Norway spruce.

Tab. 3 Growth reduction due to different damage types

Author	Subject of study	Species	Annual basal area increment loss [%]
RockFor project	Rockfall damage	Norway spruce,	1.18
Hellgren and Stenlid (1995)	Butt rot	Norway spruce	0.73-1.85
Schimitschek (1939)	Peeling damage	Norway spruce	1.42

Although growth losses are considerable on an individual tree level we expect smaller growth reductions on a stand level. First in young stands where the increase in stand basal area is considerable the damage percent is very low. Further the growth of healthy trees may be positively affected by disease induced decreases in growth and vitality of their neighbours. This is called “compensatory growth“ and contributes to total stand growth. (Oren et al. 1985). Compensatory growth is particularly pronounced in stands where infected trees have died (Hellgren and Stenlid 1995). For example in Finkenberg, rockfall damage had little effect on stand growth.

Probably more important than growth losses are however a structural weakening in trees. Trees try to counteract this by allocating a disproportionally large amount of their growth to the lower part of their stem (Hellgren and Stenlid 1995). Nevertheless stem damage and subsequent infection with root rot makes trees more susceptible to wind throw (Whitney 1989).

New rockfall damage

New rockfall damage to trees is a rare phenomenon. Usually models for rare events are more difficult to fit than for more frequent events. Thus the good discriminative ability of the model is rather surprising.

The most important predictor in the model was the percentage of old rockfall damage, which is a variable describing rockfall activity on the site. Damage to trees was also used as an indicator for rockfall activity by Gsteiger (1989). He however used the number of injuries on a tree divided by the sum of breast height diameters. The percentage of damage is not a perfect measure of rockfall activity because (i) trees can have multiple damages, which was not recorded by the ANFI, (ii) at an inventory damage can not always be attributed to its correct cause, and (iii) not all wounds are visible. Allinger-Csollich (2000) observed, that small wounds (< 100 cm²), which were approximately 2/3 of his data, heal within few years (Aufsess 1978). Gsteiger (1989) found through stem analyses that 50 % of the damages did not show in a wound on the surface. In spite of these shortcomings damage percent was still the most important predictor in the model.

Other variables in the model related to the frequency of rockfall were slope and soil type. Slope is a factor initiating rockfall and an increase of rockfall with slope is commonly observed. Allinger-Csollich (2000), for example, found a damage percent of 6 %, 18 % and 33 % on plots with a slope <50 %, 50-75 % and >75 %, respectively. Also the data of Menéndez-Duarte and Marquínez (2001) indicated more rockfall on steeper sites.
Soil type is also an important factor and it is not surprising, that we found more rockfall on calcareous leptosols, because they are shallow sites. Generally, in Austria, also more rockfall damage is observed in the Limestone Alps, on calcareous parent material. In contrast Menéndez-Duarte and Marquínez (2001) found 22 % of rockfall active slope on calcareous

and 40 % of rockfall active slope on silicate material. This suggests, as hypothesized by Menéndez-Duarte and Marquínez (2001), that rockfall activity is often more related to the presence of discontinuities, stratification levels and other types of joints than to parent material.
A further variable often related to rockfall activity on the site is elevation, because more abrupt changes in temperature at high elevations cause more frequent freeze and thaw cycles. We did not find a confirmation of this in our data, probably because elevation and slope are highly correlated, thus steeper slopes are more frequent in higher elevations.

With respect to the forest stand the only variable included in our model was stand density (CCF). The same damage percent seems to indicate a higher rockfall activity in denser stands.
On an individual tree level larch was less susceptible to rockfall due to its thicker bark. Another factor often related to rockfall is dbh (e.g. Gsteiger 1989), because larger trees have a higher probability to be hit by falling boulders. It was however not significant in our model and we think this might be due to the fact that new damage in our model always refers to new damage of previously undamaged trees. Hence many of the large trees might already have been previously damaged.

Simulation at Finkenberg

Rockfall protection at the site in Finkenberg can be classified according to different criteria:
Zinggeler (1989) suggested that stands with a mean tree free distance of more than 30 m do not offer any protection against rockfall. Wasser (1996) classified mature stands with more than 400 stems per hectare as stands with sufficient protection, according to Kienholz and Krummenacher (1995) 300 stems per hectare are required. Thus the rockfall protection of all stands at the beginning of the simulation period is satisfactory, but during the simulation the protective function decreases. This is due to a concentration of growth on fewer individuals, and because of the high basal area there is also no regeneration. Strip cutting in stand number two encourages regeneration, and thus leads to an improvement in the protective function.

The newly developed models simulate stand growth in the spruce forests of Finkenberg reasonably well. Spruce however is a major species in Austria, and model performance for minor species might be less optimistic. Also the models assumes average browsing and mortality and stand development will differ, if browsing in Finkenberg were exceedingly high compared to the Austrian average or if a catastrophic event (wind throw, bark beetle attack) occured.

Additonally to a comparison of stands based on the tree free distance, forest growth simulation could be incorporated in rockfall models. Nowadays rockfall models increasingly incorporate forest parameters (Dorren 2002, Zingeller 1989) like stem number and dbh distribution.

CONCLUSIONS

We found that the individual tree growth model PROGNAUS is an adequate tool to simulate stand development in mountain forests. It allows to quantify growth processes in rockfall forests and to evaluate different management scenarios for stands. The model was improved for rockfall sites by including rockfall damage as independent variable. Changes in model performance compared to the original model were however small. Nevertheless we were able to show that rockfall damage also has an influence on tree growth and tree mortality.

The model was well describing growth at the rockfall site Finkenberg, results might however be less optimistic for less typical sites. To show the influence of forest management on rockfall protection additionally to the calculation of the tree free distance forest growth could be incorporated in rockfall models.

ACKNOWLEDGEMENTS

This study was financed by the EU-project RockFor QRLT-1999-31902 (Predicting the protection of forests against Rockfall.)

REFERENCES

Allinger-Csollich, W. (2000): "Waldbauliche Beurteilung der kiefernreichen Bestände des Bleiberger Erzberges (Steinschlagschutzwald)". Diplomarbeit. Universität für Bodenkultur. Wien 2000, 143 pp.

Aufsess, H. (1978): "Beobachtungen über die Auswirkungen moderner Durchforstungsverfahren auf die Entstehung von Wundfäulen in jungen Fichtenbeständen". Fw. Cbl. *97*,

Bitterlich, W. (1948): "Die Winkelzählprobe". Allgemeine Forst- und Holzwirtschaftszeitung. *59*, 4-5.

Dorren, L. K. A., Maier, B., Putters, U. S., and Seijmonsbergen, A. C. (2003): "Combining field and modelling techniques to assess rockfall dynamics on a protection forest hillslope in the European Alps". Geomorphology *1367*, 1-17.

Dujesiefken, D., Peylo, A., and Liese, W. (1991): "Einfluß der Verletzungszeit auf die Wundreaktionen verschiedener Laubbäume und der Fichte". Fw. Cbl. *110*, 371-380.

Forstliche Bundesversuchsanstalt (1981): "Instruktionen für die Feldarbeiten der Österreichischen Forstinventur 1981-1985". Forstliche Bundesversuchsanstalt. Wien 1981, 172 pp.

Forstliche Bundesversuchsanstalt (1994): "Instruktionen für die Feldarbeiten der Österreichischen Forstinventur 1992-1996. Fassung 1994". Forstliche Bundesversuchsanstalt. Wien 1994, 194 pp.

Gsteiger, P. (1989): "Steinschlag, Wald, Relief, Empirische Grundlagen zur Steinschlagmodellierung". Diplomarbeit. Universität Bern. 1989, 111 pp.

Hasenauer, H. (2000): "Die simultanen Eigenschaften von Waldwachstumsmodellen". Paul Parey Verlag. Berlin 2000, 131 pp.

Hasenauer, H. and Monserud, R. A. (1996): "A Crown Model for Austrian Forests". For. Ecol. and Manage. *84*, 49-60.

Heim, A. (1932): "Bergsturz und Menschenleben". Seperatdruck Vierteljahreszeitschrift d. nat. forsch. Ges. in Zürich *84*, 1-31.

Hellgren, M. B. and Stenlid, J. (1995): "Long-term reduction in the diameter growth of butt rot affected Norway spruce, Picea abies". For. Ecol. and Manage. *74*, 239-243.

Hösle, B. (1997): "Finkenberg-Einödseite. Aufbau und Realisierung eines Analysesystems zur standortsspezifischen Behandlung von sanierungsbedürftigen Wäldern im Bezug auf den Wirkungsbereich der Naturgefahr Steinschlag". Projektbericht 1997, 79 pp.

Hosmer, D. W. and Lemeshow, S. (2000): "Applied logistic regression". 2 nd edition. John Wiley & Sons. New York Chichester Brisbane Toronto Singapore 2000, 375 pp.

Jaeckli, H. (1957): "Gegenwartsgeologie des bündnerischen Rheingebietes. Beitrag zur Geologie der Schweiz". Geotechnische Serie *LG. 36*, Kümmerli & Frey. Bern 1957,

Jahn, J. (1988): Internationales Symposium Interprevent. Graz 185-198 pp.

John, K. W. and Spang, R. M. (1979): "Steinschläge und Felsstürze. Voraussetzungen - Mechanismen - Sicherungen". UIC Unterausschuss K7. Kandersteg 29 pp.

Knigge, W. (1975): "Die Auswirkung von Schälschäden auf die Rohholzeigenschaften von Fichte und Buche". Forstarchiv 32-38.

Krajicek, J. E., Brinkmann, K. E., and Gingrich, S. F. (1961): "Crown Competition - a Measure of Density". For. Sci. *7*, 35-42.

Kienholz, H. and Krummenacher, B. (1995): "Symbolbaukasten zur Kartierung der Phänomene". BUWAL, BWW.1995.

Ledermann, T. (2001): "Programmdokumentation und standardisierte Beschreibung des Waldwachstumssimulators Prognaus". Forschungsbericht. Institut für Waldwachstumsforschung 2001, 31 pp.

Ledermann, T. (2002a): "Ein Einwuchsmodell aus den Daten der Österreichischen Waldinventur 1981-1996". Cbl. ges. Forstwesen *119*, 40-76.

Ledermann, T. (2002b): In: von Gadow, K., Nagel, J., and Saborowski, J., Eds. (Editors): "Contiuous Cover Forestry. Assessment, Analysis, Scenarios". Kluwer Academic Publishers. Dordrecht 2002: 203-216 pp.

Mayer, H. (1984): "Waldbau auf soziologisch-ökologischer Grundlage". 3. Auflage. Verlag G. Fischer. Stuttgart, New York 1984, 522 pp.

Menéndez Duarte, R. and Marquínez, J. (2001): "The influence of environmental and lithologic factors on rockfall at a regional scale: an evaluation using GIS". Geomorphology *43*, 117-136.

Monserud, R. A. and Sterba, H. (1996): "A Basal Area Increment Model for Individual Trees Growing in Even- and Unevenaged Forest Stands in Austria". For. Ecol. and Manage. *80*, 57-80.

Monserud, R. A. and Sterba, H. (1999): "Modelling Individual Tree Mortality for Austrian Forest Species". For. Ecol. and Manage. *113*, 109-123.

Oren, R., Thies, W. G., and Waring, R. H. (1985): "Tree vigor and stand growth of Douglas-fir as influenced by laminated root rot". Can. J. For. Res. *15*, 985-988.

Ott, E., Frehner, M., Frey, H.-U., and Lüscher, P. (1997): "Gebirgsnadelwälder. Ein praxisorientierter Leitfaden für eine standortgerechte Waldbehandlung". Verlag Paul Haupt. Bern Stuttgart Wien 1997, 287 pp.

Preisler, H. K. and Slaughter. G. W. (1997): "A Stochastic Model for Tree Survival in Stands Affected by Annosum Root Disease". For. Sci. *43 (1)*, 79-86.

Schieler, K. (1997): "Methoden der Zuwachsberechung der Österreichischen Waldinventur". Dissertation. Universität für Bodenkultur. Wien 1997, 92 pp.

Schimitschek, E. (1939): “Untersuchungen über Rotwildschälschäden und deren Folgen. Cbl. ges. Forstwesen 65, 33-50, 65-82, 97-121.

Sterba, H., Golser, M., Moser, M., and Schadauer, K. (2000): "A timber harvesting model for Austria". Computers and Electronics in Agriculture *28*, 133-149.

Van Laar, A. (1991): "Forest Biometry". University of Stellenbosch. Stellenbosch, South Africa 1991, 590 pp.

Wasser, B. (1996): "Bundesamt für Umwelt, Wald und Landschaft - Wegleitung: Minimale Pflegemaßnahmen für Wälder mit Schutzfunktionen". Bundesamt für Umwelt, Wald und Landschaft. Bern 1996, 228 pp.

Whitney, R. D. (1989): "Root rot damage in naturally regenerated stands of spruce and balsam fir in Ontario". Can. J. For. Res. *19 (3)*, 295-307.

Zinggeler, A. (1989): "Steinschlagsimulation in Gebirgswäldern - Modellierung der relevanten Teilprozesse". Diplomarbeit. Universität Bern. Bern 1989, 113 pp.