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Parameterization of rockfall source areas and magnitudes with ecological recorders: When disturbances in trees serve the calibration and validation of simulation runs

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A B S T R A C T

On forested talus slopes which have been build up by rockfall, a strong interaction exists between the trees and the falling rocks. While the presence and density of vegetation have a profound influence on rockfall activity, the occurrence of the latter will also exert control on the presence, vitality, species composition, and age distribution of forest stands. This paper exploits the interactions between biotic (tree growth) and abiotic (rockfall) processes in a mountain forest to gather and obtain reliable input data on rockfall for the 3D process based simulation model RockyFor3D. We demonstrate that differences between the simulated and observed numbers of tree impacts can be minimized through (i) a careful definition of active source areas and (ii) a weighted distribution of block sizes as observed in the field. As a result of this field-based, optimized configuration, highly significant values can be obtained with RockyFor3D for the number of impacts per tree, so that results of the model runs can be converted with a high degree of certainty into real frequencies. The combination of the field-based dendrogeomorphic with the modeling approaches is seen as a significant advance for hazard mapping as it allows a reliable and highly-resolved spatial characterization of rockfall frequencies and a realistic representation of (past) rockfall dynamics at the slope scale.

1. Introduction

Rockfall is one of the most common geomorphic processes in mountain regions and potentially damages infrastructure or even causes loss of life (e.g. Porter and Orombelli, 1981; Erismann and Abele, 2001; Hantz et al., 2003). On forested slopes, falling rocks repeatedly interact with trees and therefore meet all the criteria to be considered as an agent of disturbance to forest dynamics (Seidl et al., 2011), since they typically disrupt forest ecosystem structure, composition and processes and ultimately cause the destruction of tree biomass (White and Pickett, 1985; Gunderson, 2000; Grime, 2001; White and Jentsch, 2001). At the forest stand level, rockfalls may (i) create patchiness or spatial heterogeneity (Veblen et al., 1994), thereby contributing largely to the existence of a wide range of ecological niches and (ii) favoring uneven-aged forests which are considered beneficial for plant diversity (Rixen et al., 2007). Through the impact of falling rocks, trees, may be uprooted, suffer from stem breakage, or decapitated if kinetic energy is transferred to the crown (Stokes, 2006). These disturbances to trees will cause immediate changes in their growth (e.g., Stoffel and Bollschweiler, 2008), thus allowing the retroactive assessment and reconstruction of past and contemporary rockfall activity (e.g., Stoffel et al., 2005a,b; Perret et al., 2006; Moya et al., 2010; Šilhán et al., 2011; Trappmann and Stoffel, 2013). Dendrogeomorphic approaches have also been demonstrated to yield in-situ information on rockfall parameters including source area, trajectories, frequency, magnitude, seasonality, or on triggers (Stoffel, 2006).

At the same time, forest structures have been shown to have physical effects on the dynamics of fallen boulders, namely on the (i) kinetic energy absorption through direct impact between a boulder and a trunk (Gsteiger, 1993; Brauner et al., 2005; Dorren et al., 2005; Stokes et al., 2005; Dorren et al., 2007; Lundström et al., 2007, 2009); (ii) energy dissipation (i.e. kinetic energy absorption) of rockfalls by coppice structures through the interaction between a rock and shrub vegetation (Ciabocco et al., 2009); as well as on the (iii) the positive effect of forest vegetation on geotechnical soil characteristics (Pfeiffer, 1989). Forests can thus act as protective shields for downslope reaches and prevent rockfall from affecting inhabited areas.

At locations where hazardous rockfall events have occurred in the past, 3D rockfall simulations are often used to determine runout distances, energies, preferential paths and bounce heights of rockfalls (Dorren, 2003), with some of these models explicitly simulating collisions with trees. The primary goal of performing model runs on forested slopes is for a realistic hazard assessment and secondly for a quantification of the role of forests in protecting human lives and their assests (Dorren et al., 2005). Crucial parameters for such an approach are the identification of source areas, determination of fall tracks, and the calculation of rockfall velocity (which depends on

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the interaction of rocks and boulders with the forest stand which will in turn determine runout distance (Dorren, 2003). Reliable model data can, however, only be obtained if a detailed database exists on the position of source areas, potential rock sizes, and slope properties. Such field information is crucial for a realistic calibration of model parameters, for verification of model results, and for the reduction of differences between model output and reality.

Model verification can be done through the study of orthophotos, field visits, and the analysis of archival records (Dorren and Berger, 2006). Yet, as a result of the sudden occurrence and unpredictable nature of rockfalls, such data are only rarely available. Real-time observations of rockfalls do not normally exist either since they are very time consuming and only available (if at all) for small sites and for a short period of time (Luckman, 1976; Douglas, 1980; Gardner, 1980; Matsuoka and Sakai, 1999). The perusal of archival data remains usually scarce and fragmentary as well (e.g. Dussauge-Peisser et al., 2002), and records usually contain information on events that caused fatalities or destruction of human assets, but will lack data on small-scale events and activity in less-densely inhabited areas (Stoffel, 2006).

This study therefore aims at (i) improving available data on rockfalls, (ii) enhancing delineation of source area and (iii) at better defining magnitude and frequency of rockfalls by calibrating the simulation model RockyFor3D with a dense set of dendrogeomorphic data. We also illustrate how differences between modeling and dendrogeomorphic reconstructions can be minimized through the use of a block size distribution in the model which is similar to the one measured in the field.

2. Study site

The east-facing Raaftgarte slope analyzed in this study is located in the Saas Valley, southern Swiss Alps (46°12′36″ N., 7°53′08″ E.), just above the main road (2,500 vehicles per day on average) connecting Stalden to Saas Fee (Fig. 1A, B). Rockfall is frequent at the site and fragments are normally detached from several release zones within a roughly 340-m high rock face (1140–1480 m asl). In the adjacent transit area (1020–1140 m asl, mean slope of 38°), Quaternary deposits are dominated by a mosaic of vegetated surfaces, intermittent scree slope deposits and an open forest stand composed of Silver birch (*Betula pendula* Roth) and European larch (*Larix decidua* Mill.) trees (Fig. 2A, B).

Bedrock in the release areas is composed of tectonized, fine grained gneisses (Bearth, 1978) belonging to penninic crystalline units. A major rockfall event (80 m^3) has been reported for the site on 14 November 2002, when a portion of the lower release area collapsed as a result of repeated freeze-thaw cycles of meltwater in the joint system. This event resulted in the partial destruction of the forest stand and road at and next to the southernmost segment of the study site. To protect the main road from the hazardous impacts of rockfalls, several rows of flexible rockfall nets have been installed in the northern part of the slope in 1990. The volume of rock fragments observed in the nets does not usually exceed 0.1 m^3 (99th percentile), and the largest individual block observed in the field has 2.4 m^3.

3. Material and methods

3.1. The dendrogeomorphic approach

Based on the geomorphic mapping, rockfall can be considered the only geomorphic process damaging trees at the study site. As a result, trees were selected randomly on the slope with special attention being paid to a regular distribution of sampled trees across the study perimeter. Coordinates of trees were recorded with a compass, inclinometer and measuring tape and imported into a GIS system.

Since the period during which rockfall scars remain visible on the tree bark primarily depends on the tree species (Stoffel and Perret, 2006), different strategies were applied to derive the number of rockfall events at the study site. The first species analyzed, *L. decidua*, is known to mask injuries efficiently, so that event histories at the level of individual trees were reconstructed with increment cores (max. 40×0.5 cm) and through the presence of tangential rows of resin ducts (TRD; Bannan, 1936; Stoffel, 2008) being formed next to and at some distance of the impact scar (Schneuwly, 2009; Schneuwly et al., 2009). In the case of *L. decidua*, sampling positions on the stem were therefore adapted to observed bounce heights which remain usually below 2 m at the study site. Increment cores were consequently extracted at 0.5, 1.0, and 1.5 m in case that signs of past injuries were not visible on the stem surface. One additional core was extracted on the undisturbed downslope side so as to determine tree age. In the case of visible scars, additional cores were extracted as close to the injury as possible following Schneuwly et al. (2009).

In the case of *B. pendula*, its non-peeling bark structure will leave mechanical impacts visible on the trunk surface over decades ., and past rockfall activity was assessed by simply counting visible scars on the stem surface (Trappmann and Stoffel, 2013). In addition, one increment core was extracted on the undisturbed downslope side of the tree as close to ground level as possible so as to determine tree age.

All cores were processed with fine grained sanding paper and tree rings were analyzed under a LINTAB positioning table following standard procedures as described in Stoffel and Bollschweiler (2008). As the accurate dating of events was not the primary goal of this study, we disclaimed the cross-dating procedure and derived tree age and number of impacts without measuring tree-ring widths. Events in *L. decidua* were dated through the identification of growth disturbances (GD) related to mechanical disturbances (Stoffel and Bollschweiler, 2008; Stoffel et al., 2010), but primarily through the presence of TRD and callus tissue (Stoffel and Hitz, 2008).

Return periods of rockfall were calculated for each individual tree by dividing its age with the number of impacts. As impacts in case of *L. decidua* were identified within a timeframe given by the tree-ring series, the longest record of a given tree was considered to represent its age. For *B. pendula*, in contrast, injuries were assumed to stay visible on the stem surface over the whole lifespan of the tree, and the real age (germination age) was used in the reconstruction. Rings missing from the inner end of the increment core to the pith were added using a transparent template of concentric rings. In addition, missing rings originating from sampling height above ground level were added following the approach described in Bollschweiler et al. (2008).

3.2. The Rockyfor3d modeling approach

In a subsequent step, rockfalls at Raaftgarte were simulated using RockyFor3D (Dorren, 2012), a probabilistic process-based rockfall trajectory model that combines physically-based, deterministic algorithms with stochastic approaches to simulate rockfall in its three dimensions. The model consists of three main modules.

The first module calculates rockfall trajectories by calculating sequences of classical parabolic free fall through the air and rebounds on the slope surface. During each rebound, the model allows the block to deviate from its direction before rebound toward the direction of the aspect of the raster cell in which the block rebounds. Hence, the model produces diverging rockfall trajectories. The second main module calculates energy loss due to impacts against single trees. The exact position of a falling rock and its current energy are modeled. If an impact against a tree takes place, part of the rock energy is dissipated as a function of the relative position between rock and tree center and the stem diameter of the corresponding tree. After a tree impact, the trajectory of a rock can be deviated laterally up to