Shallow Landslides: Retrospective Analysis of the Protective Effects of Forest and Conclusions for Prediction

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Abstract Landslides repeatedly cause damage in steep terrain and, therefore, the prediction of landslide susceptibility is important. In this context, comprehensive inventories with detailed information on shallow rainfall triggered landslides have been established in Switzerland. The present database includes information on more than 600 individual landslides. The data illustrate that slope inclination belongs to the most decisive parameters. Landslides occurred on slopes with inclinations from 20° to 50° with a majority on slopes of 35°–40°. The angles of internal friction of the landslide soil mostly range between 31° and 35°. Vegetation effects, particularly the existence of forest, are important reasons that slopes with inclinations of more than 35° were stable before the respective hazard events. This is supported by the fact that, in the majority of the event-inventories, landslide density is lower in forested areas than on open land. However, not only the presence of forest has an effect on slope stability but also its condition. Additionally, terrain morphology near the landslide seems to be relevant. A filtering procedure based on (i) soil mechanics and slope inclination, (ii) forest structure and (iii) terrain morphology explained more than 95% of 218 landslides in forested terrain. Additional case studies confirmed that forest structural characteristics do have an important influence on root reinforcement and shallow landslide susceptibility. For example a gap length of >20 m seems to be

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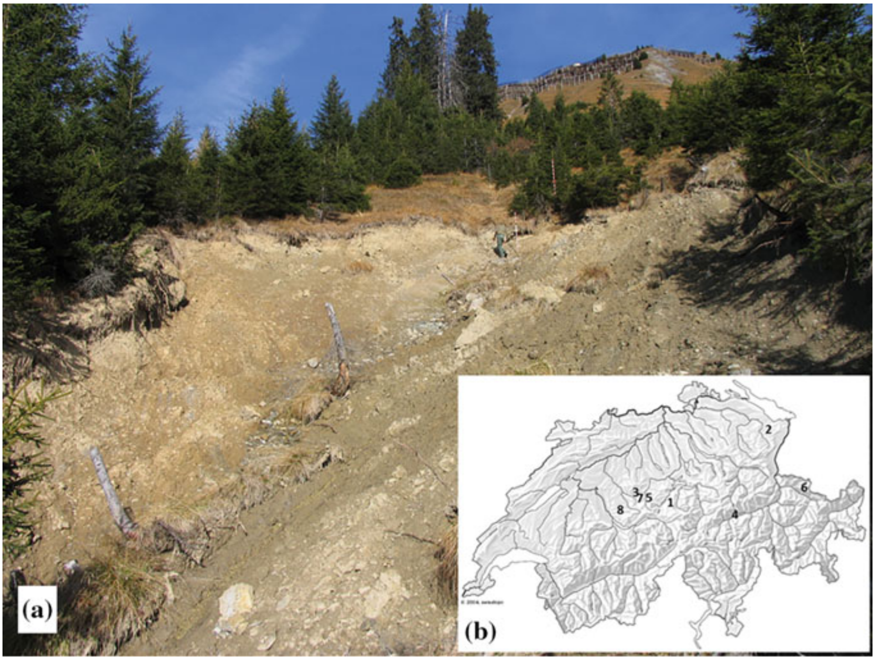

Fig. 1 **a** A shallow landslide near St. Antönien (no. 6 on the map). **b** Location of Swiss landslide inventories (cf. Table 1)

a critical threshold for landslide triggering. The study confirms that forest structure has—together with geomorphological and hydrological conditions—an important influence on shallow landslide susceptibility.

1 Introduction

Shallow landslides triggered by intensive rainfall are common hazards in alpine regions. They pose considerable danger to humans and infrastructure, particularly because they often evolve into hillslope debris flows with long runout and due to the difficulty of predicting/forecasting their spatial and temporal occurrence. The total damage sum due to landslides from 1972 to 2007 in Switzerland was estimated to 520 million Euros [7]. In 2005, one large devastating event (in Switzerland) triggered more than 5000 shallow landslides within only three days [2]. Although shallow landslides commonly occur both on areas with forest cover (Fig. 1) and on open land, the positive effect of forest due to tree roots as well as enhanced interception and evaporation on slope stability is well recognised [9, 18].

Landslide-event inventories contribute to a better understanding of the hazard processes and are, therefore, an important basis for hazard assessment and mitigation

Table 1 Landslide-event inventories by the WSL in Switzerland. More than 60 parameters including volume, inclination, and soil material were recorded per landslide

Location	No. of inventory*	Date of event	Precipitation		No. of landslides documented	Area of watershed (km^2)
			Cum. rainfall (mm)	Duration (h)		
Sachseln	1	15.8.1997	150	2	280	8.2
Appenzell	2	31.8.–1.9.2002	120	9	107	10.2
Napf	3	15.–16.7.2002	60	3	64	2.5
Surselva	4	14.–16.11.2002	252	63	35	3.2
Entlebuch	5	18.–23.8.2005	269	72	66	5.1
St. Antönien	6	18.–23.8.2005	185	72	63	4.7
Napf	7	18.–23.8.2005	241	72	54	1.6
Eriz	8	4.7.2012	60–100	2	25	9.5
Total					694	45.0

*Locations of the inventories are indicated in Fig. 1b

[e.g. 6, 8]. This article combines the analysis of landslide-event inventories with new field measurements in order to investigate relevant triggering factors and in particular the effect of forest structure on landslide susceptibility.

2 Data and Methods

The present study is mainly based on several comprehensive and field-based landslide-event inventories with detailed information on 694 shallow landslides (Table 1). The field surveys were performed with analogue protocols, covering many relevant parameters including the dimensions of the slides, and site characteristics such as vegetation, geomorphology, and topography as well as characteristics of the subsequent runout (see [16] for more details). Relating to soil mechanics, the soil of all landslides was assessed and classified according to VSS standard SN 670 008a [20] in the field. In addition, the correspondent angles of internal friction Φ' were derived following VSS standard SN 670 010 [21]. Forest condition near the landslides was assessed in two different ways: (1) based on guidelines that describe requirements for sustainable protection forests adapted to the site according to Frehner et al. [3] and (2) using a general forest stand code with assessments of forest layering, cover, development and mixture [13]. The underlying database currently includes information from landslide inventories with more than 600 individual landslides [17, Table 1].

The landslide data and some of the preliminary results of the inventories were used to establish an evaluation procedure of landslides triggered in forest areas [5]. This procedure ("filter") intends to retrospectively explain the occurrence of shallow landslides. The subsequent 3 fields were characterised by 6 parameters with the below mentioned values that explain failure:

1. Soil mechanics: slope inclination is more than 5° steeper than the angle of internal friction of the soil [4].
2. Forest characteristics:
   - layering is unstocked or mono-layered: layering according to portion of individuals in upper, medium, and lower layer (i.e. >2/3 of stand height, 1/3–2/3 of stand height, <1/3 of stand height)
   - tree cover is partial (~40%) or sparse (~20%): ratio of crown cover (canopy) projection (without multiple cover) to total cover (at the most 100%)
   - development is unstocked or a young stand up to thicket
   - forest condition: special case event-inventory Sachseln with forest condition "poor" [14] with gaps, signs of terrain movements, old landslides or wind throw, as well as inappropriate species mixture [3].
3. Terrain morphology: curvature line of slope-transverse profile is convex-flat, flat-concave, or convex-concave.

In addition to the aforementioned documentation of the landslides, further analyses on the effect of forest structure on landslide susceptibility were performed in two of the study areas (St. Antönien with 46 and Sachseln with 136 landslides in forested terrain). For each landslide plot as well as for a comparable set of control points (same number and range of forest cover and steepness), variables characterising forest structure, topography, geomorphology and hydrology were measured in the field (St. Antönien) and derived from LiDAR (light detection and ranging, 2 m resolution) based elevation data (St. Antönien and Sachseln) and from a stand classification (Sachseln). Subsequently, the data were analysed with univariate tests (Wilcoxon rank-sum tests for continuous and Chi-square tests for categorical variables) as well as multivariate statistics including logistic regression models and classification trees [11, 12]. For the case study of St. Antönien, the root distribution was additionally measured at regular distances from seven trees to calibrate a root bundle model and to quantify root reinforcement [10]. Based on this model, a proxy-variable for root reinforcement of the nearest tree was calculated [12].

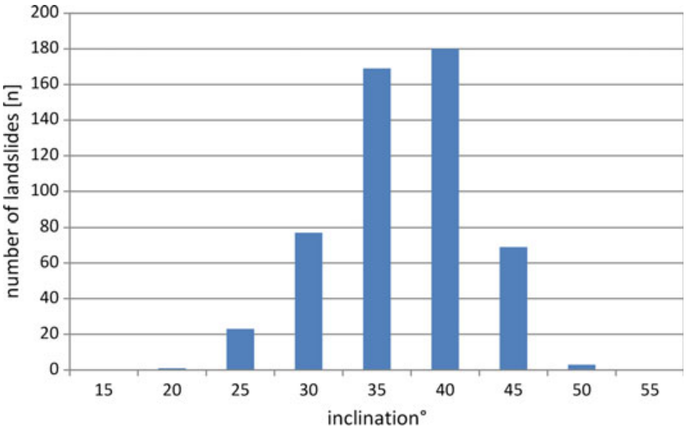

Fig. 2 Slope inclinations at the release areas of the landslides

3 Results and Discussion

3.1 Landslide Inventories

According to the landslide database the slope inclination at starting points is a decisive parameter for landslide occurrence, i.e. steep slopes are more prone to hillslope processes. All inventories (Table 1) show that landslide occurrence starts at slope inclinations of 20° and increases with steepening slope angel up to about 35°–40°. Roughly half of all landslides (48%) occurred on slopes with inclinations of more than 35° (Fig. 2).

Almost 80% of the soils were classified as lean clay, silt, clayey to silty gravel, silty gravel and silty sand (Fig. 3). The corresponding angles of internal friction Φ' ranged between 27° and 38° with the most frequent soil types materials found in the interval 31°–35°. In a simplified approach slopes of bare soil can be regarded stable up to inclinations equal to the angle of internal friction of the pure soil material. The reasons that steep terrain with inclinations between 35° and 50° was stable before the landslide triggering rainfall events can be found in parameters such as cohesion, compaction/compression and vegetation effects.

In the majority of the event-inventories, landslide density is lower in forested areas than on open land [15] demonstrating a considerable effect of forest on slope stability. Yet, landslide occurrence not only depends on the presence of forest but also on the forest stand characteristics at the release area [14]. The assessments of the forests near the landslides based on [3] identify high landslide density in forested areas with unfavourable stand characteristics, e.g. species and stand structure not suitable to site, many gaps, parts previously damaged, patchy stands. Vegetation assessment using the forest stand code showed that many landslides occurred in less favourable

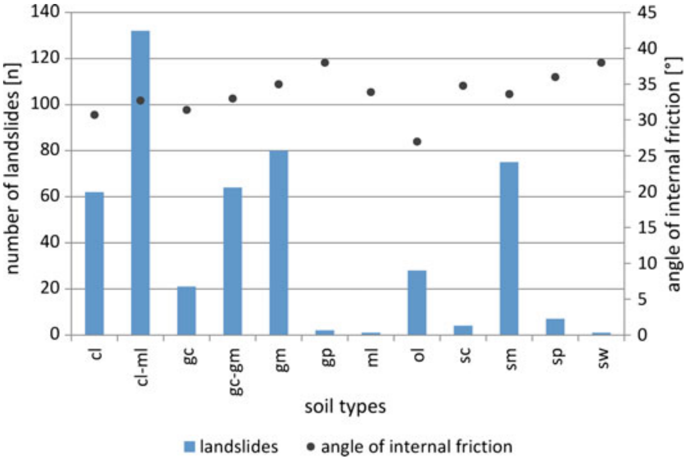

Fig. 3 Number of landslides (blue bars) related to the different soil types, including information for the angle of internal friction Φ′ (black dots) according to [21]

stands, e.g. unstocked, mono-layered, young stand/thicket, more than 80% needle trees, and partial (40%) or sparse (20%) tree coverage.

Terrain morphology is broadly considered relevant for landslide occurrence [e.g. 1, 19]. Our data show that a considerable proportion of all landslides (40%) was released in morphology types known to be susceptible to shallow landslides such as edges of terraces, hollows and gullies (curvatures line of slope—transverse profile convex-flat, flat-concave, or convex–concave).

3.2 *Filtering Procedure*

The serially applied filtering procedure of shallow landslides triggered during heavy rainfall events in forested areas, retrospectively explained 50% of the landslides by soil mechanics, 40% by forest characteristics and 7% by terrain morphology [5]. In total 97% of 218 landslides during the heavy rainfall events in 1997 (Sachseln), 2002 (Napf, Appenzell) and 2005 (Entlebuch, Napf, St. Antönien) were explained and only six (3%) of the 218 investigated landslides stayed unresolved. While new remote sensing data provide an increasing potential to deduce variables related to topography and forest structure on higher resolution, the assessment of the angle of internal friction Φ′ remains challenging. In order to characterise larger areas, e.g. catchments, in respect of soil mechanics, a conventionally applied approach is to assign fixed values of Φ′—and cohesion c′—to different geological units. However, this is not entirely satisfactory as is demonstrated for the Drusberg layers in Sachseln with 67 landslides. There, the assigned friction angle Φ′ is given with 36°. Yet, 95% of the events where triggered in soil with $\Phi' = [27°, 33°]$. Consequently, new approaches

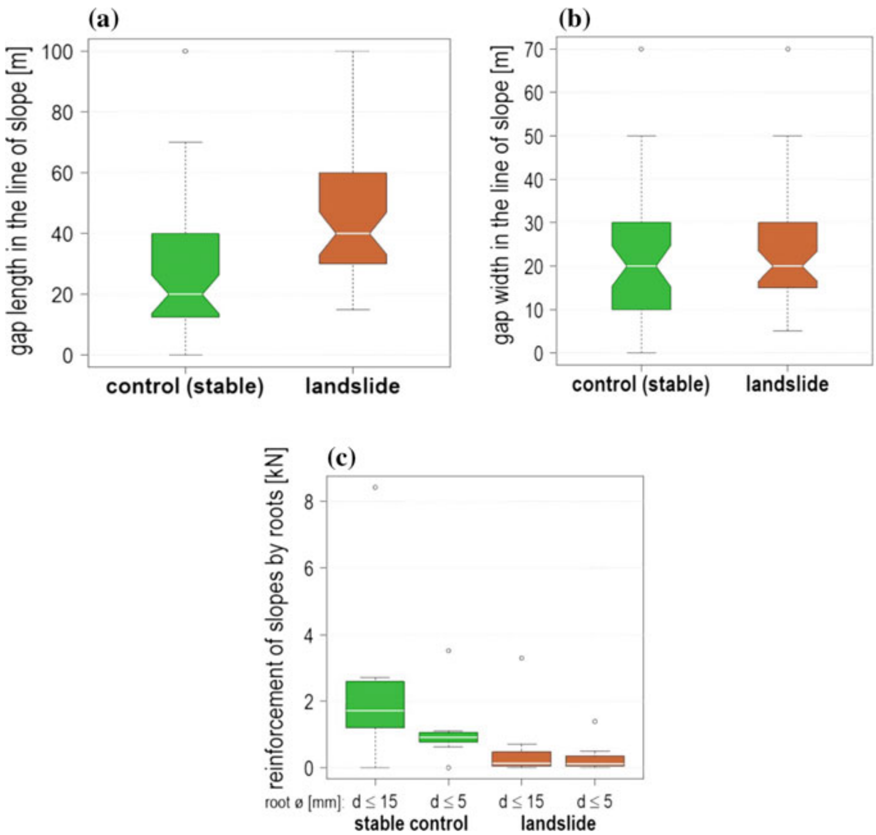

Fig. 4 **a** Distribution of gap lengths (significant) and **b** widths (not significant) of the largest gaps in control and landslide plots in St. Antönien and **c** root reinforcement by tree roots in a subset of plots for roots with a diameter <15 and <5 mm (significant) [12]

will be necessary to improve existing estimations for Φ′—possibly combined with other filtering parameters.

3.3 Influence of Forest Structure and Other Parameters on Landslide Susceptibility

In the study area St. Antönien, landslide and control plots were characterized by a relatively open forest structure (15–70% degree of forest cover). However, gap length measured in landslide plots was significantly larger compared to gap length of control plots ($p < 0.001$; Fig. 4a). In contrast, gap width in control and landslide plots did not differ significantly (Fig. 4b).

The distance from the (potential) release point to the nearest tree as well as the mean distance to the five nearest trees measured in the field were significantly higher in landslide plots compared to control plots ($p = 0.002$; $p = 0.001$). A similar result was obtained for the distance measured on the orthophoto of 2003 (before landslide event; $p < 0.001$). Moreover, the distances to the nearest tree on the orthophoto did not significantly differ from the distances measured in the field. The root reinforcement in a subset of landslide and control plots as well as the proxy-variable for root reinforcement of the nearest tree was significantly higher in control plots than in landslide plots ($p < 0.001$; Fig. 4c). Tree coverage calculated from the canopy height model (controlled variable), tree height, successional stage and layering of the forest did not significantly differ between landslide and control plots.

The classification tree model fitted with gap length and slope angle, first partitions the data based on a threshold of 20 m for gap length. In plots where the maximum gap is longer than 20 m, the probability of landslide occurrence is distinctly reduced, if the slope angle α is smaller than 36° (Fig. 5a). The distance to the nearest tree as explanatory variable, partitions the data set with a threshold of 6.2 m. In the case of smaller distances to the nearest tree, the probability of landslides is enhanced, given the slope angle α is larger than 38° (Fig. 5b) or, if there are signs of water logging (Fig. 5c).

In the study area of Sachseln (mixed forest with *Abies alba*, *Picea abies* and *Fagus silvatica*), tree height, standard deviation of tree height were significantly lower compared to the Study area of St. Antönien. Furthermore, stands affected by landslides were younger and less deciduous. Moos et al. [12] found that multivariate models integrating forest structure performed better than models solely based on terrain and hydrological variables, and models based on field variables performed much better than models based on LiDAR derived variables. Trees in Sachseln are on average taller and have bigger diameters at breast height (dbh) in control plots than in landslide plots, indicating enhanced reinforcement of the soil with increasing tree age. As the forest stands were affected by wind-throw and beetle calamity in the 1970s and again in 1990 (storm "Vivian"), we can assume that landslides occurred in a critical post-disturbance phase in which roots of dead trees did not reinforce the soil anymore and roots of the upcoming young growth were still too weak to stabilize the soil.

4 Conclusions

The study confirms that not only the presence of forest but also forest structural characteristics do have an important influence on shallow landslide susceptibility. It further turned out that the presented filtering procedure as well as landslide susceptibility maps may potentially consider additional criteria. In particular, gap length and distance between trees seem to be relevant variables to include in a further developed filter. However, the varying results between the two study sites make also evident that the influence of different forest structural characteristics depends on regional and

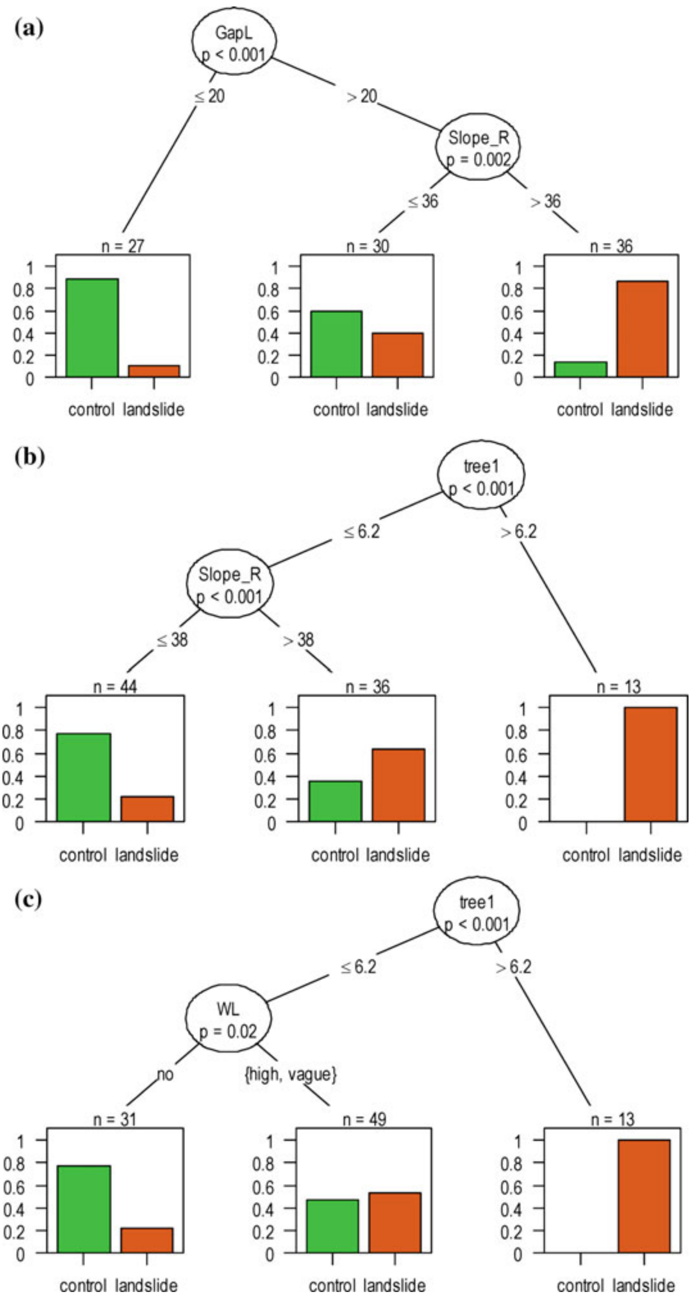

Fig. 5 Classification trees to predict landslide occurrence in St. Antönien based on significant forest structural variables and selected terrain variables. The models were fitted with the whole dataset (n = 93). The n-values exhibit the number of cases explained by the corresponding variables. GapL = length of the largest gap, Slope_R = slope of the release point, tree1 = distance to the nearest tree, WL = signs of water logging [12]

local conditions, such as vegetation zones, altitudinal range, disturbance history and the triggering rainfall event. The findings both confirm and complement the Swiss directives for the management of protection forests [3]. Such management activities include not only the regulation of the tree species composition but also the promotion of canopy openings which are large enough to provide sustainable regeneration on the one hand but are not too long (<20 m) to cause landslides on the other hand. In addition, the results help to quantitatively assess relevant spatial data for slope stability (in particular related to forest structure) and to identify possibilities and limitations for further development of tools for a better prediction of landslide susceptibility. Finally, the study indicates that landslide inventories are important components for improving hazard assessment tools to reduce damage due to shallow landslides and to establish recommendations for appropriate land use and forest management.

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