# Effects of forests on shallow landslides – case studies in Switzerland

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**Abstract**
Shallow landslides triggered off by heavy rainfall are recurrent phenomena on steep slopes. It is widely recognised that vegetation, particularly forest, can stabilize steep slopes. However, there is considerable argument about to what extent trees reduce hydro-geomorphic hazards. This article discusses the effects of forest on shallow landslides on the basis of detailed landslide inventories. A total of six study areas were investigated after different rainfall events in Switzerland. Within the boundary of these areas, all shallow landslides that occurred during the specific rainfall events were mapped and related to the site characteristics of the source area, such as its geomorphology and vegetation.

Only minor differences in dimensions were found between landslides in forest areas and those in open land. On the other hand, the field studies showed that landslide densities were lower in forested terrain than in open land. Furthermore, landslides mapped in forests occurred on steeper slopes than slides mapped in open land. The application of these results for predicting landslide occurrence is discussed.

Keywords: shallow landslides, slope stability, forest, open land, landslide inventory, land use

## 1 Introduction

Heavy rainstorms frequently not only cause floods and debris flows, but also trigger off many shallow landslides on steep slopes (Fig. 1). The danger due to these slope instabilities is considerable, as they often evolve into debris flows, which may damage cultivated land, buildings and infrastructure, and even cause fatalities (Moser 1980; Avanzi *et al.* 2004; Gorsevski *et al.* 2006; Raetzo and Rickli 2007). Furthermore, in many catchments shallow landslides are responsible for a substantial part of the total sediment delivery (Begueria 2006), which may increase the danger due to sediment transport during rainstorms.

Following Cruden and Varnes (1996) and Glade (2003), we use the term landslide for soil and debris travelling by sliding, flowing and complex movement. According to the Swiss recommendations (BRP, BWW, BUWAL 1997), landslides are classified as “shallow” if they are less than 2.0 m deep. Many landslide inventories agree that rainfall-triggered shallow landslides usually have dimensions with typical depths of 0.5 to 1.5 m, scar areas of 50 to 1000 m$^2$ and volumes ranging from a few to several hundred cubic metres (Moser and Schoger 1989; Aleotti *et al.* 1996; Avanzi *et al.* 2004; Markart *et al.* 2007; Raetzo and Rickli 2007). Shallow landslides can be triggered off by heavy rainfall of either short duration with high rainfall intensity, or long duration with low intensity (Ceriani *et al.* 1992; Crosta 1998; Guzzetti *et al.* 2004; Aleotti 2004).

Fig. 1. Shallow landslides triggered off by the August 2005 rainfall event in the Entlebuch region, central Switzerland.

Landslide-hazard maps contain information about the location, magnitude and frequency of the expected geomorphic processes and are therefore important instruments for land-use planning and hazard prevention. However, accurate information about the factors which influence slope stability is required to compile such maps. Although extensive research has been performed on shallow landslides, there is still little known about how and to what extent the effects of vegetation – particularly forests – should be taken into consideration when compiling hazard maps.

Vegetation and land use are widely recognised as important factors influencing the occurrence of rainfall-triggered landslides (SIDLE *et al.* 1985; BEGUERIA 2006). Many researchers have described the contribution of root systems to soil strength with an artificial cohesion term that can be added to effective soil cohesion (SIDLE *et al.* 1985). This effect can, however, also be described as an increase in the angle of internal friction or as a virtual increase in soil density (GRAF *et al.* this issue).

Although shallow landslides commonly occur both on areas with forest cover and on open land, numerous studies have shown the positive effects of forests and tree roots on slope stability (GREENWAY 1987; ABE and ZIEMER 1990; EKANAYAKE *et al.* 1997). Intensive harvesting activity and deforestation are generally considered to lead to an increase in landslide frequency (ZIEMER 1981; TANG *et al.* 1997; SIDLE and WU 1999; JAKOB 2000; SIDLE *et al.* 2006; CLAESSENS *et al.* 2007). This increase often occurs a few years after the deforestation, when the roots of the cut trees begin to decay.

As BORGA *et al.* (1998) describe, a variety of approaches has been proposed to evaluate landslide hazards: 1) stability rating with physically-based models, 2) multivariate analysis of the factors characterizing the sites of the slope instabilities, and 3) analysis of landslide scars and deposit inventories to delineate potentially hazardous areas. Regarding physically-based models, it has been suggested that the influence of trees on landsliding can be introduced as a reinforcing component into the calculation of slope stability (GUZZETTI *et al.* 2006; MEISINA and SCARABELLI 2007; TOSI 2007). However, physically-based stability rating models mostly suffer from having insufficiently accurate hydrological, vegetational, geological and topographical data. Furthermore, they often classify unreasonably large areas to be susceptible to landslides.

This article concentrates on the documentation and analysis of rainfall events, with a focus on evaluating the effects of forest on shallow landslides. It summarises the results of six landslide inventories after severe rainstorms in Switzerland during the last decade, concentrating on the question of the differences and similarities between forest and open land with respect to: 1) frequency and dimensions of landslides, and 2) the slope inclination of the release zones.

## 2 Material and methods

### Landslide inventories and study areas

According to MALAMUD *et al.* (2004), landslide inventories can be carried out in mainly two ways: 1) landslide-event inventories, and 2) historical (morphological) landslide inventories. An important quality of the first method is the fact that all slides of a certain limited perimeter are triggered off by a known and approximately similar amount of rainfall. The present study is based on the analysis of six landslide-event inventories carried out soon after rainfall events associated with numerous shallow landslides (RICKLI 2001; RICKLI *et al.* 2004; RAETZO and RICKLI 2007). The procedure for the documentation and data collection was the same in all six inventories. The first step was to define a study area within a region affected by a specific rainfall event where many shallow landslides had occurred. The second step involved mapping all the landslides within the defined study area and assessing various landslide parameters.

The six study areas of the landslide inventories described in this article are located in the Pre-Alps and the Alps of central and eastern Switzerland (Fig. 2). They range from 1.6 to 10.2 km$^2$ in size, with between 16 and 50 % covered by forest (Table 1). The size of the study area depended mainly on the time available for field investigations, and the exact boundaries

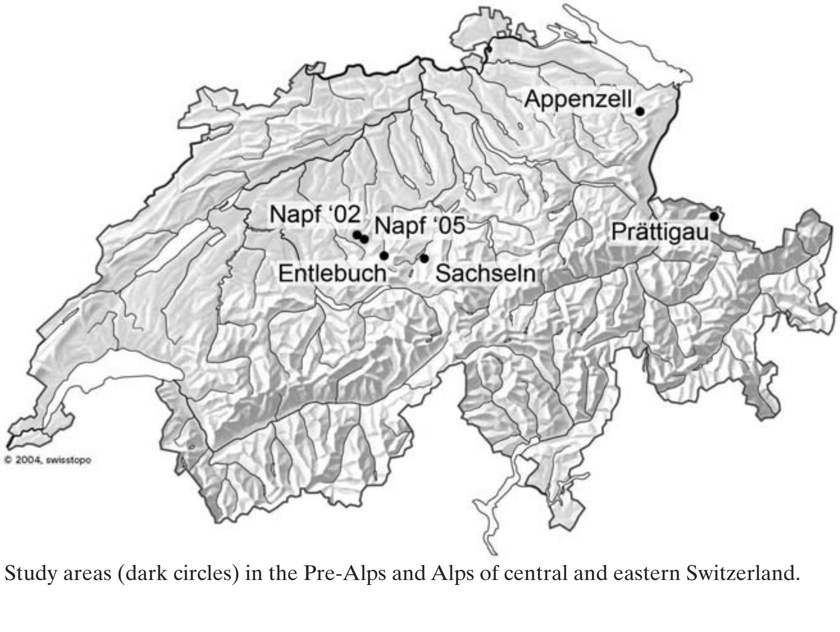


Fig. 2. Study areas (dark circles) in the Pre-Alps and Alps of central and eastern Switzerland.

followed the natural topography. The mean elevation of the study areas was between 900 and 1700 m asl, and the number of landslides investigated in each inventory varied between 36 and 256. In total, information on 522 slides were collected, of which 240 were in forest and 282 in open land.

On the basis of the location of the release line, each slide was assigned in the field to either forest or open land. The extent of the forest within the perimeters of the study site was derived from the Swiss National Map 1:25 000 (http://www.swisstopo.admin.ch), where areas with trees higher than 3.0 m and with a crown cover of more than 50 % are mapped as forest. The landslide densities (number of landslides per km$^2$) in forest and open land were calculated according to the number of slides that occurred and the surface areas of the corresponding vegetation types.

Table 1. Study areas and landslide parameters. * Geology (predominant): LFM = lower freshwater molasse (conglomerates, sandstones and marl); PF = Praettigau-Flysch (limestones, sandstones and marl); UFM = upper freshwater molasse (conglomerates, sandstones and marl); HN = helvetic nappes (limestones, marl and sandstones). ** RSR: surface area of steep slopes (i.e. with inclinations of 20° to 50°) within the study area; *** Slope inclinations: min. = observed minimum of slope inclinations, > 90 % = 90 % of all landslides were triggered off on slopes steeper than the indicated inclination.

| Study area | Entlebuch | Prättigau | Napf '05 | Napf '02 | Appenzell | Sachseln |
|---|---|---|---|---|---|---|
| Year / month of event | 2005 / 08 | 2005 / 08 | 2005 / 08 | 2002 / 06 | 2002 / 09 | 1997 / 08 |
| Event rainfall | | | | | | |
| sum | 236 mm | 145 mm | 236 mm | 60 mm | 150 mm | 150 mm |
| duration | 4 days | 3 days | 4 days | 3 h | 12 h | 2 h |
| Geology* | LFM | PF | UFM | UFM | LFM | HN |
| Mean elevation of study area (m asl.) | 1200 | 1700 | 900 | 1150 | 950 | 1250 |
| Surface area** | | | | | | |
| total (km$^2$) | 5.1 | 4.7 | 1.6 | 2.5 | 10.2 | 8.2 |
| forest (%) | 29 | 16 | 29 | 49 | 22 | 50 |
| total RSR(km$^2$/%) | 3.6 / 71 | 3.4 / 72 | 0.7 / 44 | 1.6 / 64 | 3.3 / 29 | 7.3 / 89 |
| forest RSR (km$^2$/%) | 1.3 / 36 | 0.7 / 21 | 0.4 / 57 | 1.0 / 63 | 1.5 / 45 | 3.8 / 52 |
| Number of shallow landslides | | | | | | |
| total | 47 | 50 | 36 | 51 | 82 | 256 |
| forest | 10 | 26 | 14 | 30 | 34 | 126 |
| open land | 37 | 24 | 22 | 21 | 48 | 130 |
| Median of landslide dimensions (forest/open land) | | | | | | |
| length (m) | 19.0 / 27.9 | 18.0 / 23.0 | 16.8 / 14.3 | 15.0 / 17.0 | 15.5 / 18.5 | 18.4 / 19.1 |
| width (m) | 12.0 / 13.6 | 13.8 / 13.5 | 17.3 / 15.0 | 13.5 / 12.0 | 14.8 / 11.8 | 12.4 / 13.1 |
| depth (m) | 1.2 / 1.3 | 1.4 / 1.1 | 1.0 / 0.9 | 0.8 / 0.8 | 1.0 / 1.0 | 1.0 / 1.2 |
| area (m$^2$) | 182 / 260 | 188 / 236 | 192 / 110 | 176 / 158 | 140 / 132 | 152 / 180 |
| volume (m$^3$) | 175 / 155 | 126 / 145 | 119 / 62 | 84 / 54 | 96 / 63 | 81 / 120 |
| Slope inclinations of landslides *** (min./> 90%/median) | | | | | | |
| forest (°) | 26 / 27 / 36 | 25 / 28 / 33 | 25 / 26 / 39 | 28 / 35 / 39 | 26 / 30 / 35 | 30 / 35 / 39 |
| open land (°) | 19 / 25 / 29 | 23 / 25 / 30 | 21 / 23 / 27 | 27 / 30 / 35 | 23 / 26 / 31 | 28 / 32 / 36 |

The first investigations of shallow landslides were conducted after an intense thunderstorm that occurred in August 1997 in Sachseln. Additional analyses were performed after two rainstorms in two regions of Switzerland in June 2002 (Napf '02) and September 2002 (Appenzell). Finally, three landslide inventories (Entelbuch, Prättigau and Napf '05) were carried out after a major rainfall event in August 2005, which affected extensive areas of Switzerland. When comparing the six landslide inventories, it is important to be aware of their different geological and topographical settings, as well as differences in the duration and total precipitation of the triggering rainfall events (Table 1).

**Field survey and data evaluation**

Following a standardised protocol (RICKLI 2001; RICKLI *et al.* 2008), a set of parameters was recorded for each landslide, including the dimensions of the slides and various site characteristics such as vegetation, geomorphology and topography. The landslide dimensions and the slope inclination of the release zones were measured as shown in Figure 3. Given the irregular shape of most landslide scars, both maximum and mean dimensions were recorded. Maximum values were used to specify the length, width and depth of the scars, whereas mean values of the parameters were used to compute the correct landslide areas and volumes.

Landslides with estimated volumes of less than 30 $m^3$ were not included in the landslide inventories. In all study areas several landslides were initiated by bank erosion along torrent channels or on steep cuts and fills or inappropriate drainage systems along roads. These landslides were not included in the present analysis because the study focuses on the effects of forest cover on rainfall-triggered slope processes. Air photographs were used to identify the location of the landslides. However, in general, a substantial part of all slides in forested areas cannot be identified by remote sensing (BRARDINONI *et al.* 2003; MILLS *et al.* 2003), and hence extensive field survey was essential to achieve a complete inventory.

As is generally known, in most regions shallow landslides are concentrated on steep slopes. When comparing landslide densities, gently inclined slopes within the study areas were excluded and only surfaces with slopes ranging from 20° to 50°, subsequently referred to as the relevant slope range (RSR), were taken into account for the calculation of landslide densities. This range of slope inclinations was defined taking into account our own field data (Fig. 6) and other landslide inventories (e.g. MOSER 1997; AVANZI *et al.* 2004; ANDRECS *et al.* 2002). Slope inclinations of the release zones of the slides were measured in the field according to Figure 3, whereas information on the inclinations of the study areas were

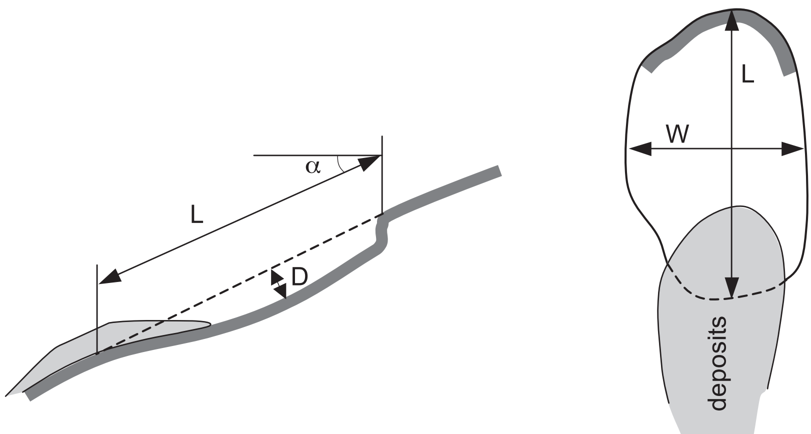


Fig. 3. Measurement of landslide dimensions (L = length, W = width, D = depth) and slope inclination α (°) at the release zone.

derived from digital elevation models with the highest precision available, namely a 10 × 10 m grid for the Sachseln study area derived from orthophotos, and a 2.5 × 2.5 m grid for all other areas derived from LIDAR-data (Swisstopo 2005). Robust statistical methods (Wilcoxon rank sum tests) were used to identify differences between the landslides in forests and in open land concerning their dimensions and inclinations of the release areas.

## 3 Results

**Landslide density**

Landslide densities (number of slides per $km^2$) can help to evaluate the effects of specific site characteristics, such as vegetation cover, on slope stability. Our calculations of landslide density are based on the relevant slope range RSR (inclinations from 20° to 50°), which varies widely between the six study areas. The lowest proportion of RSR was found in Appenzell (29 %) and the highest in Sachseln (89 %, Table 1). In all the study areas, the percentage of forest within RSR is higher than the percentage of forest in the entire study area, e.g. in Appenzell: 22 % of the entire study area, and 45 % of the RSR is forest. These patterns have to be considered when comparing the landslide densities of the different study areas, as well as of forest and open land.

In five of the six study areas the landslide density on steep slopes was greater in open land than in forested terrain (Fig. 4). In the areas Napf '02, Appenzell and Sachseln, the landslide density in forest areas amounted to about 80 to 90 % of the density in open land and in the two areas Entlebuch and Napf '05 about 50 %. We found, however, one exception: The landslide density in the Prättigau study area was markedly higher in the forested part. The total number of landslides per $km^2$ RSR (in forest and in open land) ranged from approximately 13 slides in Entlebuch to 51 slides in Napf '05.

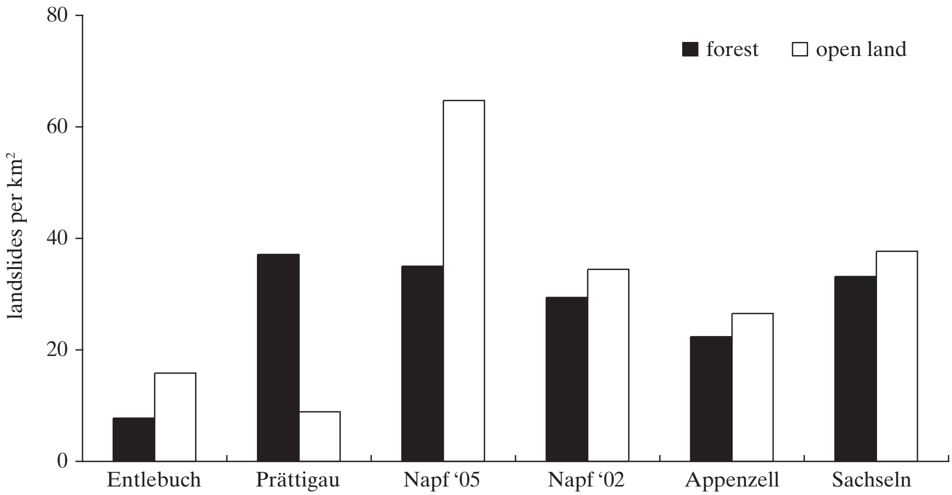


Fig. 4. Landslide density (number of landslides per $km^2$) in forests and in open land of the six study areas. Only surface areas with slope inclinations of 20° to 50° RSR were considered for the calculation of the landslide densities.

**Landslide dimensions**

Only a few significant differences (p-value < 0.05, Wilcoxon rank sum test) were discovered in landslide dimensions of landslides in open land and in forest areas. In three research sites (Napf '05, Napf '02, Appenzell), the volumes of open land slides exceeded those in forest (Fig. 5). In two study areas (Prättigau and Entlebuch), no significant differences were found, and in one area (Sachseln), the landslide volumes in forested areas were significantly larger than those in open land. In Prättigau the slides in open land were significantly deeper than those in forested areas, whereas the reverse applied in Sachseln. No differences in depth were found in the other four areas. Finally, concerning the width of the slides, the only significant differences occurred in Napf '02 and Appenzell, where the slides in open land were wider than in forest areas.

Considering the data from all the study areas (522 shallow landslides), depth was the only parameter that significantly differed between landslides in forest areas and those in open land, with on average deeper slides in forested terrain. For all other parameters such as length, width, scar area and volume, the null hypothesis (no difference between forested areas and open land) could not be rejected.

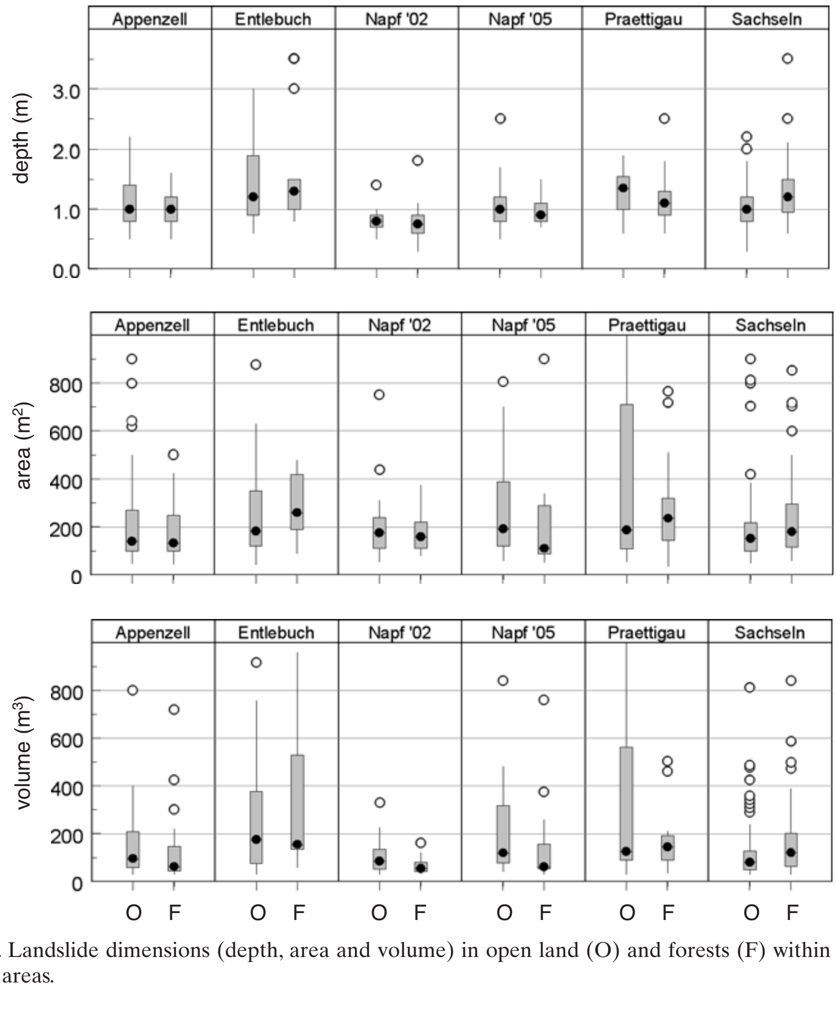


Fig. 5. Landslide dimensions (depth, area and volume) in open land (O) and forests (F) within the six study areas.

**Slope inclinations of the release zones**

Within the perimeters of the study areas, slides occurred on slopes with inclinations between 19° and 50°, predominantly between 25° and 45° (Fig. 6). Slides in forested terrain were triggered off in areas with steeper inclinations than slides on open land. In five of the six research areas, this difference was significant (p-value < 0.05, Wilcoxon rank sum test), and in one area (Prättigau) nearly significant (p-value = 0.058).

For each study area Table 1 gives both the lowest inclinations at the release zones of the landslides and the inclinations that are exceeded by 90% of all slides. The lowest observed slope inclinations in the six study areas range widely from 19° to 30°. In all study areas, the lowest inclinations were between 2° and 7° lower in open land than in forest areas. Furthermore, in all study areas, the inclinations that are exceeded by 90% of all slides were between 2° and 5° lower in open land.

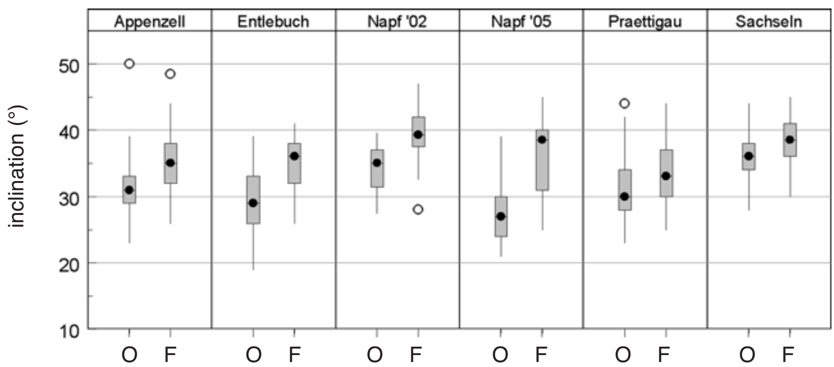


Fig. 6. Slope inclinations at the release zones of slides in open land (O) and forest (F) within the six study areas.

## 4 Discussion and conclusions

Shallow landslides may endanger both human life and infrastructure. Although extensive research has been conducted, forecasting landslides both temporally and spatially is still difficult. Among other things, there is considerable discussion about how and to what extent the effects of forests on slope stability should be considered in landslide hazard assessing. Field investigations shortly after rainfall events associated with numerous shallow landslides contribute to our understanding of the slope processes, and particularly to identifying the importance of certain parameters that affect soil stability. In this article we have focused on the questions: 1) whether – with comparable rain – landslide densities, the dimensions of the slides and certain site characteristics near the slides in forest areas are different from those in open land, and 2) whether such differences are relevant for hazard assessment and the compiling of hazard maps.

The initial impression after landslide triggering rainfall is that landsliding often seems to be markedly more pronounced in open land. However, landslide densities in forest areas are frequently underestimated because their scars and deposits are less visible. Furthermore, slides in open land attract more attention because they are the ones that tend to do most damage to infrastructure and buildings. The field inventories described in this paper demonstrate that the landslide density in a forest area can be substantial and – as in the particular case of Praettigau – may even be markedly higher than in open land. However, broadly considered and including all study areas, we found that landslide densities in forest areas are generally less pronounced than in open land, i.e. at five of the six research sites, the landslide density in forest areas amounted to only 50 to 90 % of that in open land.

When comparing geomorphic processes in forest areas and open land, it is important to take into account that human settlement and land use over centuries have affected the allocation of forests and open land. As a result, in most regions forests are actually on steeper slopes that are a priori more susceptible to landsliding. Although occasionally a forest may have destabilising effects due to the weight of the trees or unfavourable wind forces (GREENWAY 1987), forested slopes are mostly more stable than comparably steep slopes in open land. The reason for this probably has to do with the reinforcing effect on slope stability of the diverse root systems of the trees and the associated forest vegetation, as many authors have described. Several other landslide inventories have also found that shallow landslides are less frequent in forests than in open land (MOSER 1980; MOSER and SCHOGER 1989; FAZARINC and MIKOS 1992; MARKART *et al.* 2007).

The reason for the unexpectedly numerous slides in the forested part of the Prättigau study area is not clear. The unfavourable geological or hydrogeological conditions in the specific parts of the investigated area only partly explain this finding. It also raises the question of the relevance of the condition of the forest stand. TEMPERLI (2006) showed that a high percentage of the slides in the forest in the Prättigau study area originated from forest stands with many gaps. Earlier research in the Sachseln study area (RICKLI 2001) clearly points to the positive correlation between a forest's condition and the landslide density: During a heavy rainstorm in Sachseln, markedly more slides occurred in loose stands severely damaged by past wind-throw or bark beetles than in stands in better condition. Hardly any slides occurred on sites where the stands had well-adapted tree species, few gaps and a diverse stand structure. In the Sachseln study area, the landslide density in forest stands in poor condition was even higher than it was in open land, which was again observed in Praettigau. The described effect of a forest's condition on the frequency of landslides is confirmed by observations of SCHMIDT *et al.* (2001) and MARKART *et al.* (2007). We can conclude that landslide density within forests is generally less pronounced than in open land, however, strongly related to the condition of the forest. Therefore, both the distribution of forest and open land within a specific area as well as the condition of the forest should be taken into account when compiling hazard maps.

Concerning the dimensions of landslides, MOSER'S (1971) inventory shows that the largest slides occurred within forested areas, and MOSER and SCHOGER (1989) found that the surface areas of forest slides were larger than those in open land. We obtained similar findings in Sachseln, where forest slides were also larger in volume. Looking at the data from all six inventories in Switzerland, the distributions of the landslide dimensions vary widely and there is no evidence to clearly answer the question whether forest slides differ in dimension from those in open land. The results are clearest for the landslide volumes, as in three study areas, they were significantly larger in open land, in two study areas there was no clear difference and in one area the landslide volumes were larger in forests. Given the different findings and the lack of other studies addressing these questions, we conclude that, for hazard mapping, the dimensions of the landslides can be considered to be similar in forest and open land. Furthermore, the inconsistency of the results from the different study areas indicates once again the danger of generalizing when only limited data (e.g. only data from one study area) are available.

It is obvious that slope inclination is a crucial factor for slope stability. On slopes with an inclination of less than about 20°, the driving forces are normally low compared to soil strength. On slopes steeper than 45°, the landslide density decreases because in most areas only thin layers of till cover the bedrock, and the dominant denudation processes are erosion and rock fall (MOSER 1997). The evaluation of slope inclinations near the landslide scars showed significant differences between forest and open land. In all the research areas, the landslides within the forested areas occurred on steeper slopes than those in open land. Similar observations have been reported in other studies (MOSER and SCHOGER 1989; FAZARINC and MIKOS 1992). It can be assumed that, once again, the reinforcement of the soil provided by tree-roots is the main reason for this shift in the slope inclination of the release zones.

In all the study areas, the lower boundaries of the value-distributions of the inclinations in the release zones are some degrees higher in forests than in open land. It can be concluded that forested areas provide stability performance comparable to that provided by open land vegetation on gentler slopes. This may be relevant for susceptibility mapping as the critical inclination of slopes susceptible to landsliding can be determined according to the type of vegetation cover. That is, slopes in forested areas can be assessed as stable at inclinations several degrees higher than those of slopes covered by grass and herbaceous vegetation only. Given an infinite slope model, BÖLL and GRAF (2001) and GRAF *et al.* (this issue) propose expressing the effects of vegetation on slope stability as an increase in the angle of internal friction $\Phi'$ instead of as an additional cohesion coefficient (WU 1984). Following this approach, a higher angle $\Phi'$ could be introduced for forested slopes in landslide-susceptibility rating procedures which are based on the infinite slope model.

The present study demonstrates that landslide inventories and field experience can contribute to improving deterministic models and, in addition, serve as a complementary approach in the domain of susceptibility and hazard mapping. However, as field data tends to be very variable, its interpretation and extrapolation to other areas requires broad experience. Furthermore, it is important to take into consideration, where possible, data from different regions and from different rainfall events.

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## 5 References

ABE, K.; ZIEMER, R.R., 1990: Effect of tree roots on a shear zone: modeling reinforced shear stress. Can. J. For. Res. 21: 1012–1019.

ALEOTTI, P., 2004: A warning system for rainfall-induced shallow failures. Eng. Geol. 73: 247–265.

ALEOTTI, P.; BALDELLI, P.; POLLONI, G., 1996: Landsliding and flooding event triggered by heavy rains in the Tanaro basin (Italy). Proc. Int. Symp. Interpraevent 1996, Garmisch-Partenkirchen, Vol. 1: 435–446.

ANDRECS, P.; MARKART, G.; LANG, E.; HAGEN, K.; KOHL, B.; BAUER, W., 2002: Untersuchung der Rutschungsprozesse vom Mai 1999 im Laternsertal (Vorarlberg). Berichte Bundesamt und Forschungszentrum für Wald 127: 55–87.

AVANZI, G.D.; GIANNECCHINI, R.; PUCCINELLI, A., 2004: The influence of geological and geomorphological settings on shallow landslides. An example in temperate climate environment: the June 19, 1996 event in northwestern Tuscany (Italy). Eng. Geol. 73: 215–228.

BEGUERIA, S., 2006: Changes in land cover and shallow landslide activity: A case study in the Spanish Pyrenees. Geomorphology 74: 196–206.

Bundesamt für Raumplanung (BRP), Bundesamt für Wasserwirtschaft (BWW), Bundesamt für Umwelt, Wald und Landschaft (BUWAL), 1997: Berücksichtigung der Massenbewegungsgefahren bei raumwirksamen Tätigkeiten – Empfehlung. 42 pp.

BORGA, M.; DALLA FONTANA, G.; DA ROS D.; MARCHI, L., 1998: Shallow landslide hazard assessment using a physically based model and digital elevation data. Environ. Geol. 35, 2/3: 81–88.

BÖLL, A.; GRAF, F., 2001: Nachweis von Vegetationswirkungen bei oberflächennahen Bodenbewegungen – Grundlagen eines neuen Ansatzes. Schweiz. Z. Forstwes. 152: 1–11.

BRARDINONI, F.; SLAYMAKER, O.; HASSAN, M.A., 2003: Landslide inventory in a rugged forested watershed: a comparison between air-photo and field survey data. Geomorphology 54: 179–196.

CERIANI, M.; LAUZI, S.; PADOVAN, N., 1992: Rainfalls and landslides in the Alpine area of Lombardia region, central Alps Italy. In: Proc. Int. Symp. Interpraevent 1992, Bern. Vol. 2: 9–20.

CLAESSENS, L.; SCHOORL, J.M.; VELDKAMP, A., 2007: Modelling the location of shallow landslides and their effects on landscape dynamics in large watersheds: An application for Northern New Zealand. Geomorphology 87: 16–27.

CROSTA, G., 1998: Regionalization of rainfall thresholds: an aid to landslide hazard evaluation. Environ. Geol. 35, 2/3: 131–145.

CRUDEN, D.M.; VARNES, D.J., 1996: Landslide types and processes. In: TURNER, A.K; SCHUSTER. R.L (eds) Ladslides: Investigation and Mitigation. Special Report. Press, Wahington, DC, National Academ. 36–75.

EKANAYAKE, J.C.; MARDEN, M.; WATSON, A.J.; ROWAN, D., 1997: Tree roots and slope stability: a comparison between Pinus radiata and Kanuka. N. Z. J. For. Sci. 27, 2: 216–233.

FAZARINC, R.; MIKOŠ, M., 1992: Feststoffmobilisierung als Folge der extremen Niederschläge in Slowenien. Proc. Int. Symp. Interpraevent 1992, Bern. Vol. 1: 377–388.

GLADE, T., 2003: Landslide occurrence as response to land use change: a review of evidence from New Zealand. Catena 51: 297–314.

GORSEVSKI, P.V.; GESSLER, P.E.; BOLL, J.; ELLIOT, W.E.; FOLTZ, R.B., 2006: Spatially and temporally distributed modeling of landslide susceptibility. Geomorphology 80: 178–198.

GRAF, F.; FREI, M.; BÖLL, A., 2009: Effects of vegetation on the angle of internal friction of a moraine. For. Snow Landsc. Res. 82, 1: 61–77.

GREENWAY, D.R., 1987: Vegetation and slope stability. In: ANDERSON, M.G.; RICHARDS, K.S (eds) Slope Stability. Wiley. 187–230.

GUZZETTI, F.; CARDINALI, M.; REICHENBACH, P.; CIPOLLA, F.; SEBASTINI, C.; GALLI, M.; SALVATI, P., 2004: Landslides triggered by the 23 November 2000 rainfall event in the Imperia Provence, Western Liguria, Italy. Eng. Geol. 73: 229–245.

GUZZETTI, F.; REICHENBACH, P.; ARDIZZONE, M.; CARDINALI, M.; GALLI, M., 2006: Estimating the quality of landslides susceptibility models. Geomorphology 81: 166–184.

JAKOB, M., 2000: The impacts of logging on landslide activity at Clayoquot Sound, British Columbia. Catena 38: 279–390.

MALAMUD, B.D.; TURCOTTE, D.L.; GUZZETTI, F.; REICHENBACH, P., 2004: Landslide inventories and their statistical properties. Earth Surf. Process. Landf. 29: 687–711.

MARKART, G.; PERZL, F.; KOHL, B.; LUZIAN, R., KLEEMAYR, K.; ESS, B.; MAYERL, J., 2007: 22nd and 23rd august 2005 – Analysis of flooding events and mass movements in selected communities of Vorarlberg. BFW-Dokumentation 5/2007. 45pp.

MEISINA, C.; SCARABELLI, S., 2007: A comparative analysis of terrain stability models for predicting shallow landslides in colluvial soils. Geomorphology 87: 207–223.

MILLS, K.; PAUL, J.; HINKLE, J., 2003: Forest practices and mitigation of debris-flow risk in Oregon, USA. In: RICKENMANN, D.; CHEN, C.-I. (eds) Debris-Flow Hazards Mitigation: Mechanics, Prediction and Assessment. Rotterdam, Millpress. 1197–1207.

MOSER, M., 1971: Der Einfluss der Pflanzendecke bei Elementarereignissen auf Grösse und Anzahl der Anbruchsflächen im Bereich des mittleren Lesachtales, Kärnten. Cent.bl. gesamte Forstwes. 88: 164–176.

MOSER, M., 1980: Zur Analyse von Hangbewegungen in schwachbindigen bis rolligen Lockergesteinen im alpinen Raum anlässlich von Starkniederschlägen. Proc. Int. Symp. Interpraevent 1980, Bad Ischl. Vol. 1: 121–148.

MOSER, M., 1997: Zur Prognose von Massenbewegungen. Eclogae Geol. Helv. 90: 381–391.

MOSER, M.; SCHOGER, H., 1989: Die Analyse der Hangbewegungen im mittleren Inntal anlässlich der Unwetterkatastrophe 1985. Wildbach- Lawinenverbau 53, 110: 1–22.

RAETZO, H.; RICKLI, C., 2007: Rutschungen. In: BEZZOLA, G.R.; HEGG, C. (Ed.): Ereignisanalyse Hochwasser 2005. Teil 1 – Prozesse, Schäden und erste Einordnung. Bundesamt für Umwelt BAFU, Eidg. Forschungsanstalt WSL. Umwelt-Wissen Nr. 0707: 195–210.

RICKLI, C. (Red.) 2001: Vegetationswirkungen und Rutschungen – Untersuchung zum Einfluss der Vegetation auf oberflächennahe Rutschprozesse anhand der Unwetterereignisse in Sachseln OW am 15. August 1997. Birmensdorf, Bern; Eidg. Forschungsanstalt WSL, Bundesamt für Umwelt, Wald und Landschaft. 97 S.

RICKLI, C.; BUCHER, H.U.; BÖLL, A.; RAETZO, H., 2004: Untersuchungen zu oberflächennahen Rutschungen des Jahres 2002 im Napfgebiet und in der Region Appenzell. Bull. angew. Geol. 9, 1: 37–49.

RICKLI, C.; KAMM, S.; BUCHER, H.U., 2008: Flachgründige Rutschungen – Projektbericht im Rahmen der Ereignisanalyse Hochwasser 2005. 114 S. URL: http://www.wsl.ch/forschung/forschungsprojekte/oberflaechennahe_rutschungen

SCHMIDT, K.M.; ROERING, J.J.; STOCK, J.D.; DIETRICH, W.E.; MONTGOMERY, D.R.; SCHAUB, T., 2001: The variability of root cohesion as an influence on shallow landslide susceptibility in the Oregon Coast Range. Can. Geotech. J. 38: 995–1024.

SIDLE, R.C.; PEARCE, A.J.; O'LOUGHLIN, C.L., 1985: Hillslope stability and land use. American Geophysical Union. Water Resources Monograph 11: 140 pp.

SIDLE, R.C.; WU, W., 1999: Simulation effects of timber harvesting on the temporal and spatial distribution of shallow landslides. Z. Geomorphol. N.F. 43, 2: 185–201.

SIDLE, R.C.; ZIEGLER, A.D.; NEGISHI, J.N.; NIK, A.R.; SIEW, R.; TURKELBOOM, F., 2006: Erosion processes in steep terrain – Truths, myths, and uncertainties related to forest management in Southeast Asia. For. Ecol. Manage. 244: 199–225.

Swisstopo, 2005: DTM-AV. Das hochpräzise und informationsreiche digitale Terrainmodell. URL: http://www.swisstopo.admin.ch/internet/swisstopo/de/home/products/height/dom_dtm-av.html

TANG, S.M.; FRANKLIN, J.F.; MONTGOMERY, D.R., 1997: Forest harvest patterns and landscape disturbance processes. Landsc. Ecol. 12: 349–363.

TEMPERLI, R., 2006: Analyse der Rutschaktivität in Waldflächen in Bezug auf deren Zustand und Nutzung – Fallstudie in St. Antönien GR. Diplomarbeit Hochschule Wädenswil. 67 S.

TOSI, M., 2007: Root tensile strength relationships and their slope stability implications of three shrub species in the Northern Apennines (Italy). Geomorphology 87: 268–283.

ZIEMER, R.R., 1981: Roots and the stability of forested slopes. Erosion and sediment transport in the Pacific Rim steeplands. I.A.H.S. Publ. No. 132: 343–361.

WU, T.H.. 1984: Effect of vegetation on slope stability. Transportation research report 965:37–46.

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