INVESTIGATIONS INTO THE DISTRIBUTION AND DIVERSITY OF SHALLOW ERODED AREAS ON STEEP GRASSLANDS IN TYROL (AUSTRIA)

Christoph Wiegand and Clemens Geitner

With 12 figures, 1 table and 1 appendix
Received 13. May 2013· Accepted 27. November 2013

Summary: On many slopes in the Alps one can find small shallow eroded areas. In some areas an increase in such erosion forms has been documented and related to changes in land use in recent decades. Possible effects of changes in climatic conditions must also be taken into account in this context. The size of the eroded areas discussed in this paper ranges from 2 m² to 200 m² and their depth rarely exceeds a few decimetres. They also present clearly delineated scarps. The material transfer occurs in the unconsolidated material and may reach into the bedrock in individual cases. The eroded areas can occur as shallow landslides or as the result of erosion by snow movement. Key factors in these processes are the composition and layering of the unconsolidated material, the climatic framework, topography, land cover and land use. This paper discusses shallow eroded areas in Tyrol (Austria). Initially the distribution pattern of affected areas within Tyrol was studied on the basis of expert interviews and after analysing aerial photographs. Then 161 individual eroded areas in eight study areas were captured using a standardized documentation sheet and compared in terms of site and shape characteristics. From this it transpired that by far the regions with most eroded areas are found in the northern, limestone dominated regions of Tyrol. Moreover, the results indicate that the majority of all recorded shallow eroded areas seemed to be caused by snow movement what can be deduced from certain location parameters (e.g. aspect, inclination), shape and shallow depth of erosion. The comparison with results from other studies also suggests this conclusion. Nevertheless in individual cases there are uncertainties in concluding on the forming processes based on the mentioned properties of the shallow eroded areas.

Zusammenfassung: Das Auftreten kleinflächiger und flachgründiger Abtragserscheinungen kann an vielen Hängen der Alpen beobachtet werden. Für einige Gebiete lässt sich eine Zunahme dieser Abtragsformen innerhalb der letzten Jahrzehnte nachweisen, was mit Landnutzungsänderungen in Zusammenhang gebracht wird. Auch mögliche Folgen sich ändernder klimatischer Bedingungen müssen in diesem Zusammenhang berücksichtigt werden. Die hier behandelten Abtragserscheinungen sind in der Regel durch Flächengrößen zwischen 2 m² und 200 m² sowie durch Mächtigkeiten von wenigen Dezimetern gekennzeichnet. Außerdem besitzen sie klar abgrenzbare Anrissbereiche. Der Materialversatz findet im Lockermaterial statt und kann sich im Einzelfall bis zum anstehenden Gestein erstrecken. Die Abtragungen können als flachgründige Rutschungen oder in Folge von Schneeschurf entstehen. Maßgebliche Faktoren dabei sind Zusammensetzung und Aufbau des Lockermaterials, klimatische Rahmenbedingungen, Topographie sowie Vegetationsbedeckung und Landnutzung. Der vorliegende Beitrag beschäftigt sich mit dem Auftreten dieser flachgründigen Abtragserscheinungen in Tirol (Österreich). Zunächst wird anhand von Expertenbefragungen und Luftbildauswertungen das Verteilungsmuster von betroffenen Gebieten innerhalb Tirols untersucht. Anschließend werden aus acht Untersuchungsgebieten 161 Einzelformen unter Verwendung eines standardisierten Verfahrens erfasst und hinsichtlich Lage- und Formeigenschaften miteinander verglichen. Dabei zeigt sich u. a., dass die weitaus größten Flächen in den nördlichen, kalkdominierten Regionen Tirols vorkommen. Ferner deuten die Ergebnisse daraufhin, dass der größte Teil aller erfassten flachgründigen Abtragungen durch Schneeschurf entstanden sein dürfte, was sich aus bestimmten Lageparametern (z. B. Exposition, Neigung), Form und Tiefe der Abtragungen ableiten lässt. Der Vergleich mit anderen Studien bestätigt diesen Befund. Dennoch kann anhand der genannten Eigenschaften nicht in jedem Fall eindeutig auf den formenden Prozess geschlossen werden.

Keywords: Hill slope processes, shallow landslides, snow gliding, land-use change, steep grassland, Tyrol, Alps

1 Introduction

Numerous studies testify to the substantial impact of climate and land-use change on ecosystems in the Alps (MacDonald et al. 2000; Chemini and Rizzoli 2003; Beniston 2006; Tappeiner et al. 2008). In this context the increased occurrence of small and shallow erosion forms in recent years are also discussed. For some study areas there has been clear proof of the influence of changes in land use (Blechschmidt 1990; Tasser et al. 2005; Meusburger and Alewell 2008). While the influence of climate change cannot be excluded (Soldati et al. 2004; Crozier 2010), it is much

DOI: 10.3112/erdkunde.2013.04.03 ISSN 0014-0015 http://www.erdkunde.uni-bonn.de

harder to identify, all the more so as it is often concurrent with changes in land use.

Shallow eroded areas, also known in southern Germany and Austria as *Blaiken* (Wiegand and Geitner 2010), are phenomena where a loss of vegetation cover or the top soil has exposed the unconsolidated material (Karl 1961; Schauer 1975). With a size of between 2 m^2 and 200 m^2 and a depth of between a few decimetres and 2 m (Schauer 1975; Stahr 1997), these erosion forms are fairly small and shallow in dimension. Compared to other erosion processes in the Alps these eroded areas cause only minimal loss of material per single area. However, as a rule there are several, if not numerous, eroded areas in any one slope, which makes up for substantial material transfer in total. Most affected is the deeper range of the current soil formation with ensuing loss of soil, a severely threatened resource in mountain areas (Veit 2002; Geitner 2007). In addition to the loss of vegetation cover and soil and the accompanying destabilization of the slopes, another negative consequence is the impaired attractiveness of the landscape (Gobster et al. 2007), which plays a role especially in tourist regions. However, these shallow eroded areas can have a positive effect on the distribution of protected plant and animal species as investigations in Salzburg and Bavaria demonstrate (http://www.oekoteam.at/almakt.php; 10.09.2013).

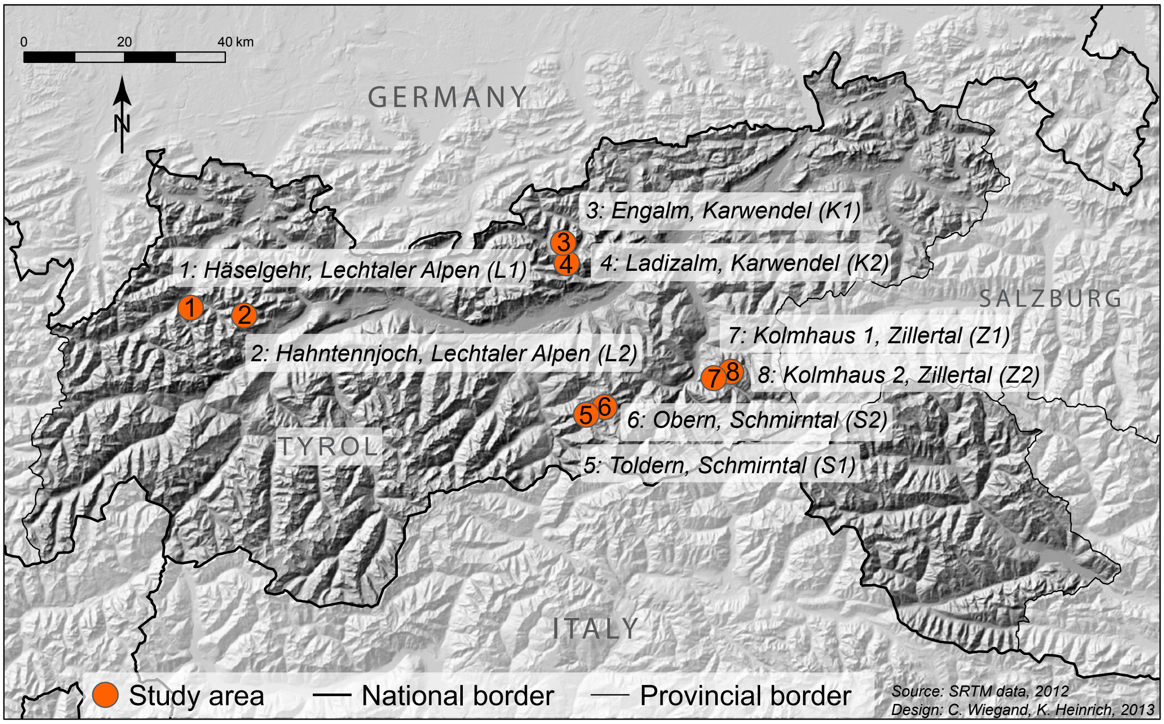
The shallow erosion forms investigated here can be the result of various processes. Such areas often result from shallow landslides which belong to gravitative mass movements (Tasser et al. 2005; Meusburger and Alewell 2008), but erosion by snow movements (esp. snow gliding) may also contribute to the emergence of such shallow eroded areas (Laatsch and Grottenthaler 1972; Ceaglio et al. 2012). If the trigger is unknown, the eroded areas cannot be clearly allocated to one or the other process type as both types result in highly similar erosion features. Once the unconsolidated material has been exposed, the areas suffer from a secondary impact of precipitation, wind and snow movement. The key factors for the occurrence of shallow eroded areas are the topography, the climatic framework, the type of unconsolidated material, soil composition, as well as land use and/or changes therein (Wiegand and Geitner 2010).

Most studies of this subject area concentrate on individual study areas and one or the other of these process types. Schauer (1975), Bernhaupt (1980) or Tasser et al. (2005) describe the eroded areas as shallow translational landslides, which belong to mass movements due to gravitative forces. Andrecs et al. (2002), Rickli et al. (2004), Markart et al. (2007) and Tarolli et al. (2011) have investigated shallow landslides that they were able to attribute to one triggering instance of heavy rain, which allows a clear definition of the process. The erosion forms studied by Mössmer (1985), Ammer et al. (1986), Dommermuth (1995) or Stahr (1997) fall into the category of erosion by snow. Newesely et al. (2000), Leitinger et al. (2008), Freppaz et al. (2010) and Ceaglio et al. (2012) also focused on the connection between snow movements and shallow eroded areas.

As in many cases it seems hardly possible to distinguish between the two types of processes from the appearance of the eroded areas, we are considering areas from both process types for the study reported here and we look at a larger total area. This allows us to make broader comparisons to differentiate the eroded areas better in spatial terms. In a further step one could investigate the genesis of these erosion forms. Our investigations are based on three research questions: (i) What are the distribution patterns of areas affected by shallow eroded areas in Tyrol? (ii) How do the eroded areas differ within the different study areas? (iii) Does the spatial differentiation allow conclusions about the processes involved and the dominant framework conditions for their occurrence?

2 Material, methods and study areas

The present analysis is based on 161 eroded areas in eight study areas within Tyrol (Fig. 1), captured using a standardized method. For an initial overview of the areas with many shallow eroded areas we interviewed 15 experts from several special units of the federal state authorities of Tyrol (Department of Agriculture, Department of Environmental Protection, Department of Forest Organization, Provincial Chamber of Agriculture, Nature Parks) and scientists working on this theme. The regions identified in this process were then explored in more detail using available aerial photographs from different years since the 1950s to obtain a clearer view of the eroded areas. After inspections in situ we selected eight typical slopes to study in further fieldwork. Main selection criteria were the existence of shallow eroded areas and a sufficient accessibility. To compare study areas with different geological settings and climatic properties, we choose four study areas in northern and four study areas in the central part of Tyrol (Fig. 1). The size of the investigated slopes ranged around 18 to 260 hectares.



Source: SRTM data, 2012
Design: C. Wiegand, K. Heinrich, 2013

Fig. 1: The eight study areas in Tyrol, Austria (c.f. Tab. 1)

A standardized documentation sheet was developed to capture the 161 individual eroded areas on the test slopes (see Appendix). It is based on our own mapping experience but also takes into account existing survey standards developed by Hübl et al. (2002) and PLANALP (2006) for natural hazards, by Andrecs et al. (2002) and Rickli and Bucher (2003) for documenting shallow landslides, or by Kienholz and Graf (2000) for capturing various geomorphologic phenomena. The survey scheme captures a wealth of quantitative and qualitative features that allow a differentiated identification of individual areas and their embeddedness in their surroundings as well as further calculations and comparisons between individual erosion sites and between study areas. We used GPS to locate the sites, inclinometers to measure slope inclination and a compass to determine aspect. Later we adjusted these measurements against digital terrain models (DTMs) (1 m resolution). We estimated the characteristics of the soil (skeleton content, bulk density and root penetration) in situ following the German manual for soil mapping (AD-HOC-ARBEITSGRUPPE BODEN 2005) at each shallow eroded area. Sketches and photographs were also added to the documentation of every recorded eroded area. For a larger section of the slope a soil profile was examined plus a rough inventory of the vegetation.

For the ensuing analyses of the field data we included the following secondary data: climate data from the Austrian digital climate atlas (1971–2000) (Auer et al. 2010), geological information from the geological map of Tyrol 1:300,000 (Brandner 1985), plus in some cases from geological maps 1:50,000 of the Geological Survey of Austria in Vienna, topographic information from DTMs (1 m resolution) (TIRIS 2010) and information about land cover from recent orthophotos (TIRIS 2010).

Four of the eight study areas are located in the northern part of Tyrol and four in the southern part (Fig. 1). The study areas in the northern part receive higher annual precipitation than those in the southern part. The underlying material is mainly calcareous, while the study areas in the southern part are dominated by the silicate material of the 'Tauern window' (Brandner 1985). All study areas are located below or just above the climatic tree line and have been kept free of trees for centuries through human land use. Depending on current land use intensity, the grassland may be mixed with dwarf shrubs, shrubs or saplings. With the exception of area S2 (Schmintal, Obern) and parts of area K1 (Karwendel, Engalm), which are used as extensive pastures, all slopes have been completely taken out of agricultural use by now. Until a few decades ago, however, they were used as hay meadows or as alpine pastures and maintained accordingly. Other characteristics of the study areas are put together in table 1.

3 Results and discussion

3.1 Spatial distribution of shallow eroded areas in Tyrol

What emerged from the expert interviews was that there are certain distribution patterns in Tyrol of regions with high appearance and regions with low appearance of shallow erosion forms. The main reasons mentioned were the geologic material, the distribution of precipitation and land use. Experts saw those parts of the northern Tyrolean Limestone Alps as particularly prone to this kind of erosion in which substrates with a higher clay content dominate, as is the case for instance in the Allgäu, Raibl or Reichenhall formations. There deep and fine-grained soils form, whose water retention capacity encourages gravitative processes. Blechschmidt (1990) has verified this for study areas in the Karwendel on the basis of the fact that shallow eroded areas were largely confined to clay-marly substrates. In contrast, Dommermuth (1995) and Stahr (1997) identified shallow eroded areas in Berchtesgaden National Park mainly in shallow, skeleton-rich Leptosols, but this may suggest that erosion by snow movements dominates in that area.

Apart from the geologic material the experts mentioned the relatively high precipitation on the northern rim of the Alps as a contributory factor to the increased shallow erosion there. As an additional factor the experts pointed to the relatively early abandonment of these slopes from 1950s in the course of a structural change in agriculture.

The northern district of Reutte is often cited as example of a highly affected area. Aerial photographs and our field work in the municipalities of Pfafflar, Häselgehr, Kaisers and in the valley of the river Lech confirmed these statements. Slopes there are dotted with shallow eroded areas.

Other areas greatly affected by shallow erosion forms are situated in the Tauern window, where easily eroded (Bündner) shist abut. They are usually badly disintegrated and rather unstable. Also in the region around Innsbruck (Nordkette) and the Stubai Valley (Kalkkögel) one can find strongly affected slopes. In an older work, Gall (1947) also mentions the Greywacke zone (esp. in the district of Kitzbühel) as a part of Tyrol affected by shallow erosion. The expert interviews and our own fieldwork did not confirm this assumption. Some substrate units of the Greywacke are indeed prone to shallow erosion, but many slopes which had been free of trees in the middle of the last century and had suffered repeated erosion events were abandoned and today are covered by forest, which makes them unlikely to suffer any more such erosion forms (own field survey).

Tyrolean districts dominated by erosion-resistant substrates such as granite or gneiss were considered less vulnerable to shallow erosion, which was confirmed by statements of the interviewed experts and our own fieldwork. As expected the distribution of highly and less affected areas within Tyrol is largely dominated by the geologic material, even if the concrete influence of the material is not completely clear in all cases. This may in part be due to the fact that the erosion occurs in the unconsolidated material while the geologic maps concentrate on the bedrock. We can assume that the grain size composition of the unconsolidated material exerts a stronger influence on shallow erosion than the mineral composition. There is no simple relationship between the distribution of precipitation and the occurrence of shallow erosion in Tyrol. Northern parts with high annual precipitation are just as much affected as southern areas with lower precipitation. Definitely more important is the occurrence of erosion trigger events such as enduring rainfall or a quick melt of large quantities of snow, both of which result in oversaturation with water in the slope material (Markart et al. 2007; Bovolo and Bathurst 2011). Land use is another factor that influences the occurrence of shallow eroded areas. Across large parts of Tyrol, at higher elevation, the abandonment of hay meadows and pastures has increased the occurrence of shallow eroded areas (Tasser et al. 2003). However, an intensification of agricultural use may also increase erosion, as Meusburger and Alewell (2008) proved for a study area in Switzerland. But these shallow erosions are often difficult to detect because the affected slope sites are redeveloped quickly after the occurrence (Andrecs and Hagen 2011).

3.2 Analyses on selected site and erosion characteristics

Below we compare the eight investigated slopes in terms of certain characteristics to determine regional differences and to discover pointers to the genesis of the eroded areas. Please note that not all eroded areas were captured on all eight slopes. In some study areas (except Z1 and Z2, Zillertal, Kolmhaus 1 and 2)

Tab.1: Characteristics of the eight study areas in Tyrol

Study area	Region	Elevation [m a.s.l.]	Mean slope [°]	Mean aspect [°]	T [°C]	P [mm]	Geological setting	Soils	Vegetation cover	Current land use	Sample areas
K1	Karwendel, Engalm	1350-1760	34	SE (130)	3.9	1880	Ammergau, Allgäu Formation: limestone, marl	Leptosol	Grassland, dwarf-shrubs	Fallow meadow	18
K2	Karwendel, Ladizalm	1680-1860	31	W (260)	3.0	2020	Reichenhall Formation: dolomite, graywacke	Leptosol	Grassland, dwarf-shrubs, shrubs	Fallow pasture	16
L1	Lechtaler Alpen; Häselgehr	1630-1880	36	E (90)	3.9	1640	Allgäuer Formation: dolomite	Leptosol	Grassland, dwarf-shrubs, shrubs	Fallow meadow	22
L2	Lechtaler Alpen, Hahntenn-joch	1830-2100	38	S (160)	2.1	1770	Raibler Formation: dolomite, argillaceous shale	Regosol, calc. Cambisol	Grassland, dwarf-shrubs, shrubs	Fallow pasture	19
S1	Schmirntal, Toldern (Tuxer Alpen)	1780-2070	38	SE (110)	2.4	1200	Bündner Shist	Cambisol	Grassland, dwarf-shrubs, shrubs	Fallow meadow	21
S2	Schmirntal, Obern (Tuxer Alpen)	2000-2260	35	E (100)	1.3	1270	Bündner Shist	Shallow Cambisol, Regosol	Grassland, dwarf-shrubs, shrubs	Sheep pasture	24
Z1	Zillertaler Alpen, Brandberg Kolmhaus 1	1740-1890	32	SW (260)	2.7	1510	Bündner Shist: limestone (Hochstegen-kalk), phyllite	Cambisol	Grassland, dwarf-shrubs	Fallow meadow	27
Z2	Zillertaler Alpen, Brandberg Kolmhaus 2	1800-1960	28	S (190)	3.2	1480	Bündner Shist: limestone (Hochstegen-kalk), phyllite	Cambisol	Grassland, dwarf-shrubs, shrubs	Fallow meadow	14

T = mean annual temperature, P = annual precipitation

we only explored a subset of eroded area for that site, due to the large number of eroded areas, we could not capture entirely. The selected eroded areas were chosen by random sampling. Neither a representative selection of eroded areas for whole Tyrol, yet a full coverage of all eroded areas within the test sites were intended. Nevertheless, this selection is a first overview on properties and frequency of occurrence of these shallow eroded areas.

3.2.1 Elevation and slope position

Elevation is a significant factor as the vertical distribution of temperature and precipitation affects the occurrence and spatial distribution of erosion triggers like heavy and prolonged rain, snow gliding and snow melt. However, elevation as a factor is significantly modified by inclination and aspect of the slope and must be considered in combination with these other factors (Mössmer 1985; Andrecs et al. 2002).

The slopes analysed in figure 2 range across altitudes from 1220 m to 2440 m a.s.l., i.e. in the montane, subalpine and alpine altitudinal zones (Veit 2002). The eroded areas occur at between 1440 m und 2140 m a.s.l. Eroded areas investigated in other studies are found at similar elevations, which results from the mountain contours (relief) and the land use. The climate also plays a certain role. Mössmer (1985) stresses that only above a certain altitude a sufficient amount of snow accumulates which consequently can cause erosion by snow movements. This is why the author only found shallow eroded areas above 1200 m a.s.l. Landslides are also more likely at higher elevations because of increased precipitation and less evaporation (Rickli et al. 2002).

As a rule the eroded areas we captured are situated above wooded areas within grasslands interspersed more or less with dwarf shrubs, shrubs or tree saplings (Fig. 2). The analyses indicate that the bulk of shallow eroded areas occur in the middle part of the slope but do spread to the higher sections. Here we must add that in most cases there are occasional eroded areas above the altitudinal range of our study, which we did not include (c.f. Sec. 3.2).

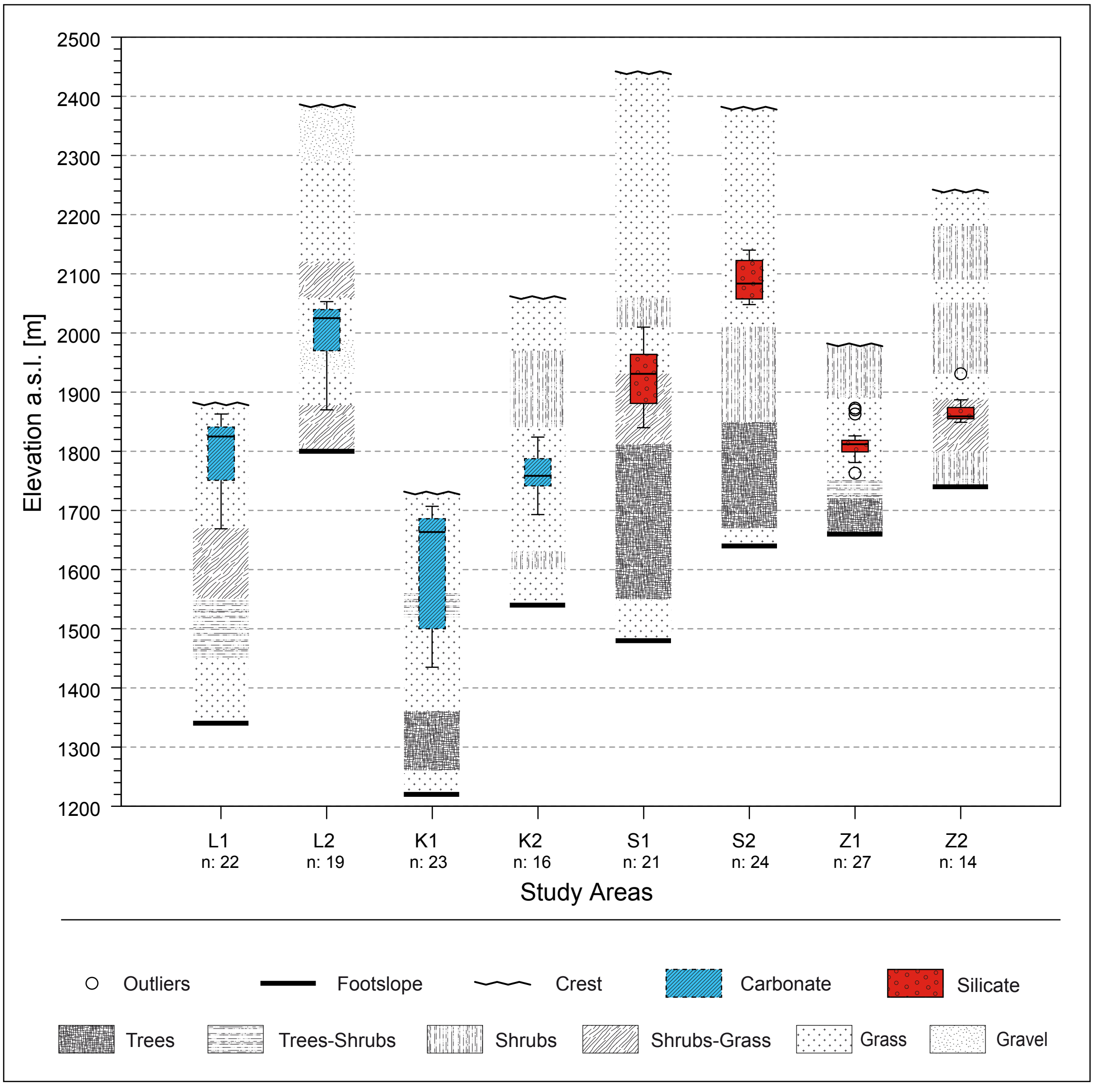
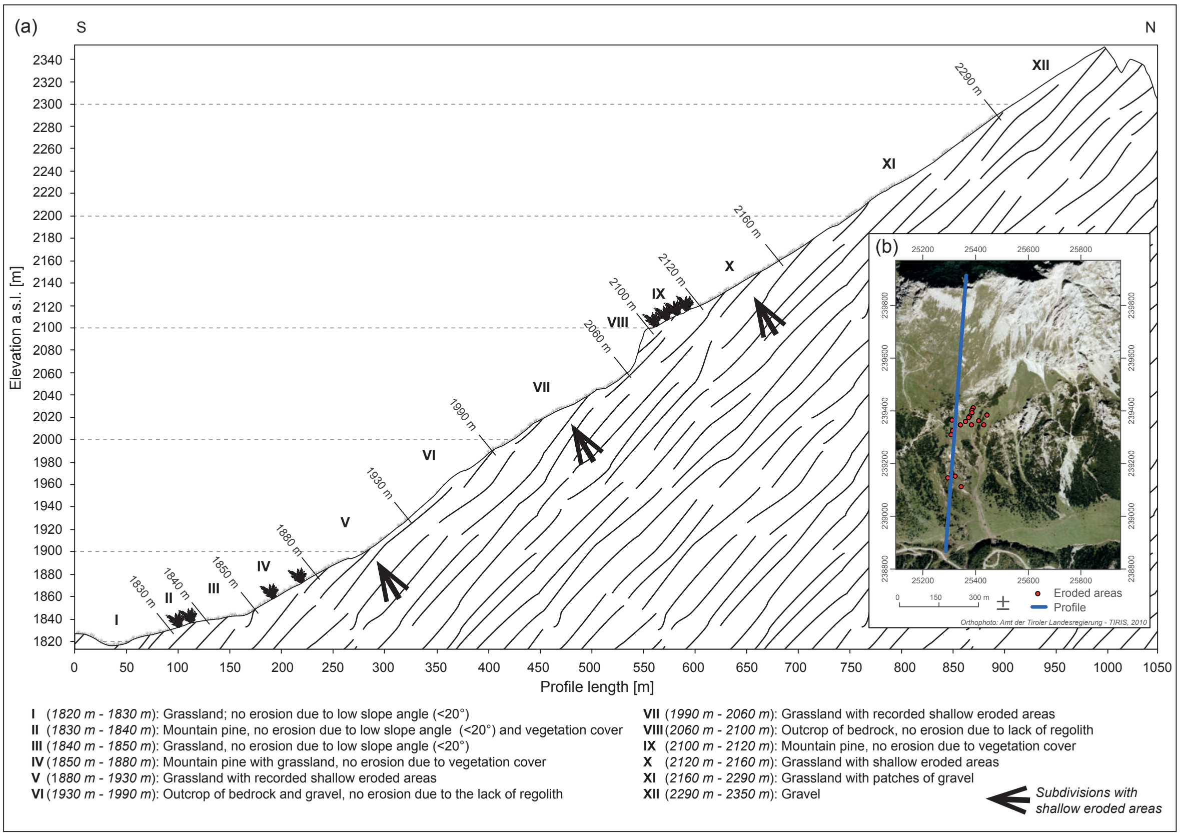


Fig. 2: Altitudinal distribution of shallow eroded areas within the slope profile (n = number of captured eroded areas). The study areas are listed by occurrence from West to East. The stated surface coverages describe the habitat types that exist along the slope profiles. Boxplot: shows the median, the 25% and 75% quartile, the smallest and largest distribution values (spread), plus outliers (o) (values that lie 1.5 and 3 box lengths outside the box) and extremes (*) (values that lie more than 3 box lengths outside the box). The presentation is the same for all box plots

The distribution of eroded areas across the slope is determined by various slope properties. Using the example of a slope profile from the study area L2 (Lechtaler Alpen, Hahntennjoch) the connection between the location of shallow eroded areas and slope properties can be demonstrated (Fig. 3). Especially the course of the slope inclination, the vegetation cover and the presence of unconsolidated material are crucial factors determining the location of shallow eroded areas. On shallower slope sections (Fig. 3, slope section: I – III) as well as on slope sections with stabilising vegetation cover (Fig. 3, slope section: II, IV, IX) no eroded areas occur. On slope sections where bedrock abut no eroded areas exist either (Fig. 3, slope section VI, VIII). In the study area S2 (Schmirntal, Obern) we found eroded areas clustered at or directly above segments of a different, flatter dip. Laatsch (1974) also described this phenomenon and assumed that erosion by snow movements finds a particularly effective starting point where the flatter slope staunches the snow.

3.2.2 Inclination

Slope inclination is one of the most significant factors triggering shallow erosion on Alpine slopes. In all study areas the captured eroded areas had mean inclinations of around 30°, the only exception being study area Z2 (Zillertal, Kolmhaus 2), where the eroded areas had a mean inclination of only 25° (Fig. 4a), even though the mean inclination of the studied slope was 28° (Tab. 1). Distribution across inclination classes reveals that the bulk (ca. 71%) of eroded areas occurs at inclinations between 30° and 40° (Fig. 4b). This matches studies from other parts of the Alps, both for shallow landslides (e.g. Tasser et al. 2003; 2005; D'Amato Avanzi et al. 2004; Rickli et al. 2004) and for erosion by snow movement (e.g. Blechschmidt 1990; Dommermuth 1995; Stahr 1997). The significant reduction in eroded areas at inclinations of less than 25° can be explained by the fact that it needs a minimum gradient for any mass movement, be it snow or slope material. The reduction at inclinations above 45° is due



I (*1820 m - 1830 m*): Grassland; no erosion due to low slope angle (<20°)
II (*1830 m - 1840 m*): Mountain pine, no erosion due to low slope angle (<20°) and vegetation cover
III (*1840 m - 1850 m*): Grassland, no erosion due to low slope angle (<20°)
IV (*1850 m - 1880 m*): Mountain pine with grassland, no erosion due to vegetation cover
V (*1880 m - 1930 m*): Grassland with recorded shallow eroded areas
VI (*1930 m - 1990 m*): Outcrop of bedrock and gravel, no erosion due to the lack of regolith
VII (*1990 m - 2060 m*): Grassland with recorded shallow eroded areas
VIII (*2060 m - 2100 m*): Outcrop of bedrock, no erosion due to lack of regolith
IX (*2100 m - 2120 m*): Mountain pine, no erosion due to vegetation cover
X (*2120 m - 2160 m*): Grassland with shallow eroded areas
XI (*2160 m - 2290 m*): Grassland with patches of gravel
XII (*2290 m - 2350 m*): Gravel

Subdivisions with shallow eroded areas

Fig. 3: Location of shallow eroded areas in the slope profile in study area L2 (Lechtaler Alpen, Hahntennjoch). (a) Subdivision of the slope profile and location of shallow eroded areas; (b) location of the slope profile within the study area. Vertical exaggeration: 0.52

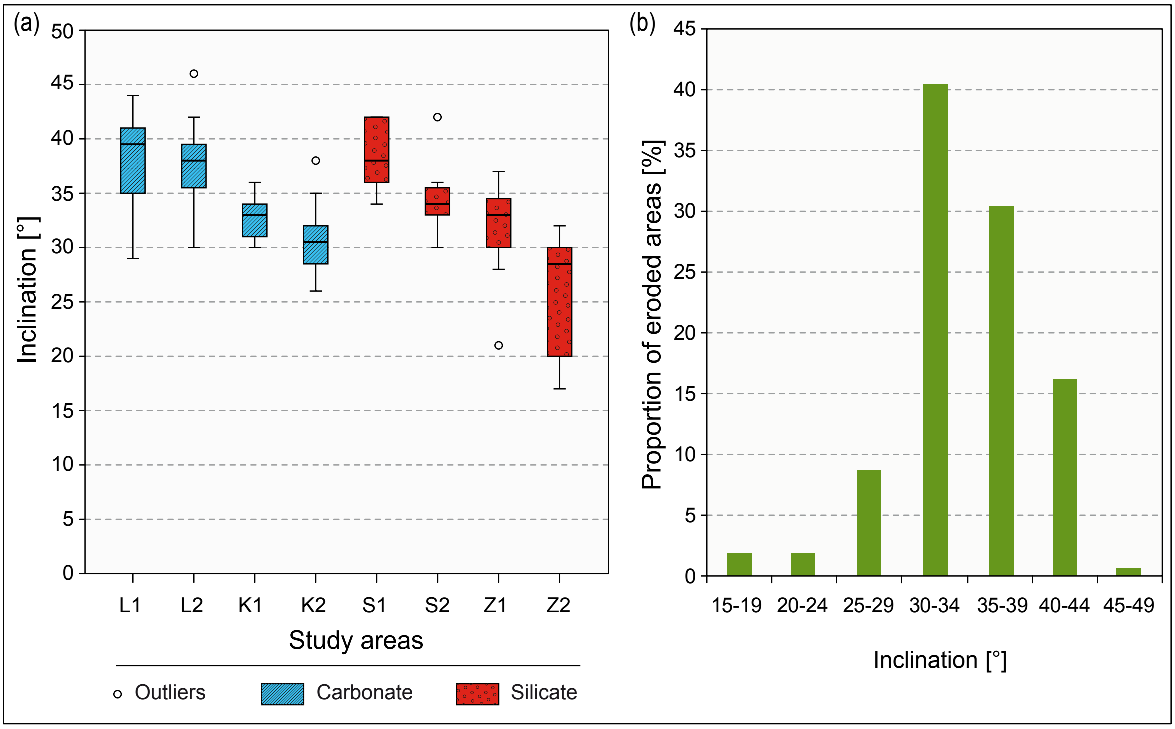


Fig. 4: Inclination of shallow eroded areas. (a) Distribution of the mean inclination of the eroded areas within the study areas and (b) subdivision of mean slope inclination of shallow eroded areas in inclination classes

to the reduced availability of unconsolidated material on such steep slopes (Blechschmidt 1990; Tasser et al. 2005). Based on comprehensive measurements of snow gliding, Leitinger et al. (2008) modeled smaller snow gliding distances on slopes >45° on the assumption that in such steep areas only thin snow cover can form.

The low median inclinations for the eroded areas in study area Z2 (Zillertal, Kolmhaus 2) may point to erosion by snow movement, which would match observations from other studies of erosion by snow movements at inclinations below 26° (Mössmer 1985; Zweckl and Spandau 1987). Field observations in study area Z2 also support such an assumption: in this slope we found smaller transposed soil clods with occasional shrubs (see Fig. 9d). Lesser inclinations might thus point to snow movement as the dominant erosion trigger, but do not exclude material movement in form of shallow landslides.

3.2.3 Aspect

The aspect of the slopes has an impact on duration, temperature and snow melt as well as soil humidity in relation to evaporation. This makes it highly relevant for both snow movements and the hydrologic balance of the unconsolidated material (Moser 1980; Tasser et al. 2005). The spread across the subdivision into 16 classes is partly due to the fact that the selected slopes are mainly E, S and W exposed (Tab. 1). Moreover, in Tyrol many NW to NE exposed slopes are covered in forest or similar wooded stands and were excluded from our survey. Therefore only 16% of eroded areas are found on slopes with a northerly aspect (Fig. 5).

Figure 5 shows E, S and W as the dominant aspects. Blechschmidt (1990) found a similar distribution for the Karwendel, and Laatsch and Baum (1976) for the Bavarian Alps. All of them describe a clustering of shallow eroded areas on E and SE aspect and relate it to snow accumulation in the lee of dominant winds from W and N. The results of our study largely match these findings, but in addition nearly 15% of eroded areas are exposed to the west (Fig. 5). The concentration of erosion in E, S and W exposed slopes might also be connected to erosion by snow movements, which is more common there due to the radiation angle and sunshine hours in these aspect. Studies by Zweckl and Spandau (1987), Tasser et al. (2005) and Leitinger et al. (2008) confirm this. Even though 83% of the areas captured by us are potentially within the sphere of impact of snow gliding, in single cases we cannot exclude landslides.

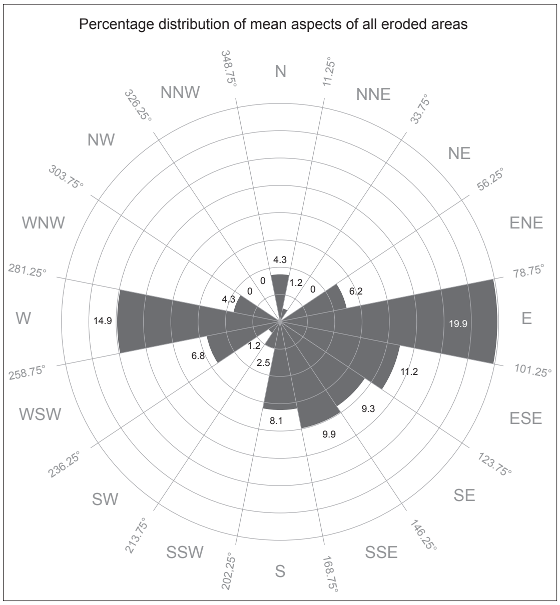


Fig. 5: Distribution of all shallow eroded areas by aspect (values in percent)

Studies of the aspect of shallow landslides return a rather inhomogeneous picture. Andrecs et al. (2002) found increased occurrence of shallow landslides in northern aspect and related it to the prolonged humidity of the unconsolidated material in shady locations. Other studies found clusters of shallow landslides in S to SW exposed slopes and related that to the intensified snow melt (Moser 1980).

3.2.4 Lengths and widths of the eroded areas

The mean maximal length of all eroded areas is 7 m, with individual areas up to 20 m long. The majority of areas (84%) only reaches maximal lengths of less than 10 m. Mean maximal width is 6 m, with a few areas more than 20 m wide. Here too, the vast majority of areas does not exceed 10 m in width. Overall the areas thus tend to be fairly small and a little longer in the direction of the slope than wide Significantly larger areas are mainly found in the northern study areas L1 and L2 (Lechtaler Alpen, Häselgehr and Hahntennjoch), occasionally in K1 and K2 (Karwendel, Engalm and Ladizalm) (Fig. 6). These are also the areas with the most noticeable deviations from the usual compact form, with elongated forms both along and against the slope. One reason for this might be that erosion processes there are so advanced that smaller eroded areas have grown together to form larger ones.

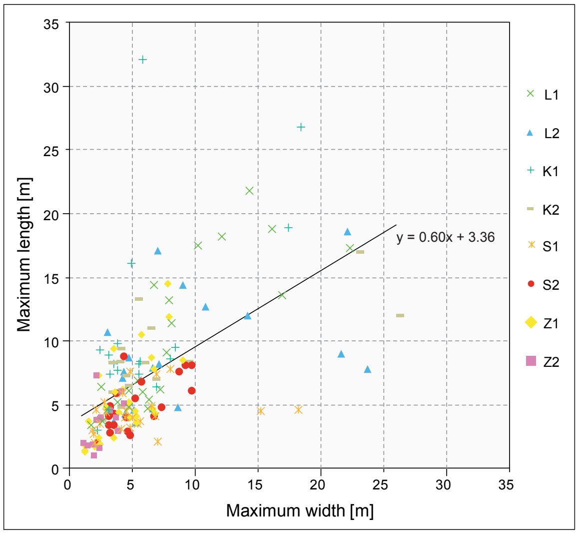


Fig. 6: Ration of maximum lengths and widths of shallow eroded areas by study area

3.2.5 Depth of eroded areas

Most of all measured depths were between 0.20 m and 0.40 m, with a few exceptional cases of 1 m depth (Fig. 7). Maximum depths were usually found near the centre of the eroded areas, in any case some distance from the scarp. The depths of the scarps (up to 0.4 m, mean 0.21 m) are much closer together than the maximum depths. In the study areas K1, K2 (Karwendel, Engalm and Ladizalm) and L1 (Lechtaler Alpen, Häselgehr) scarp depths differ more from the maximum depth than in the other study areas. This could be an indication of stronger secondary erosion, possibly related to the age of the forms, but certainly connected with the dense, marly substrate, which encourages surface flow and secondary erosion.

3.2.6 Size and volume of eroded areas

The distribution of mean area size and volume, calculated from the length, width and depth of the captured areas again reveals that the northern, calcareous study areas (L1, L2, K1, K2) show a greater range of values than the southern, siliceous ones (S1, S2, Z1, Z2) (Fig. 8). The means for area size and volume are significantly higher for the northern study areas. Area size falls largely into the range listed by Schauer (1975) of 2 m^2 to 200 m^2. Any significantly larger areas were only found in northern study ar-

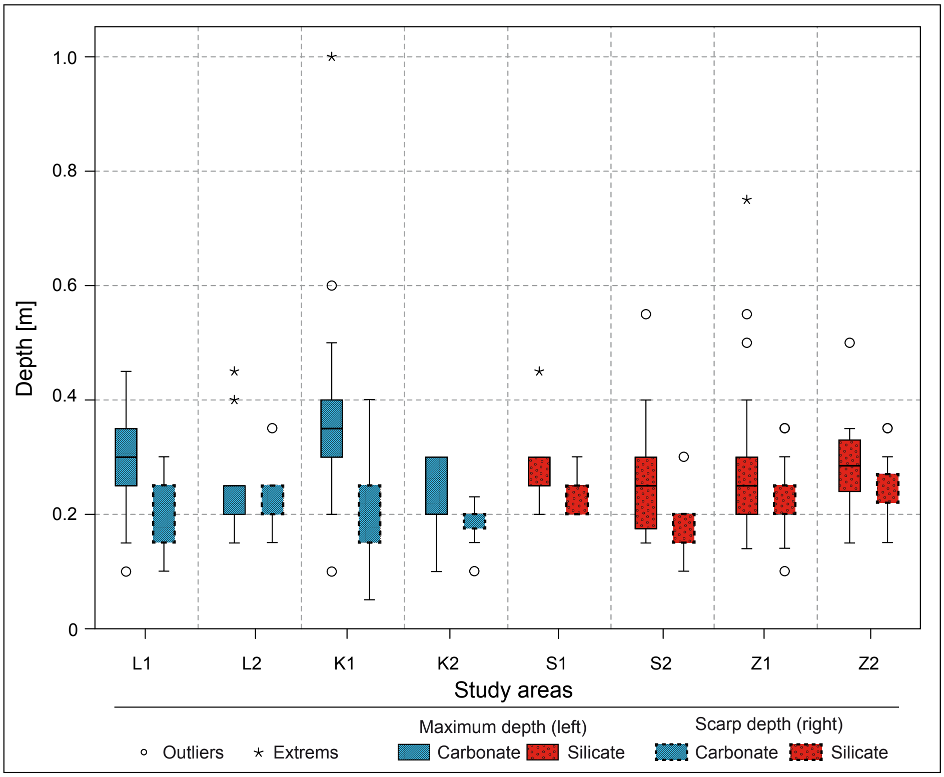


Fig. 7: Distribution of scarp and maximum depths of shallow eroded areas

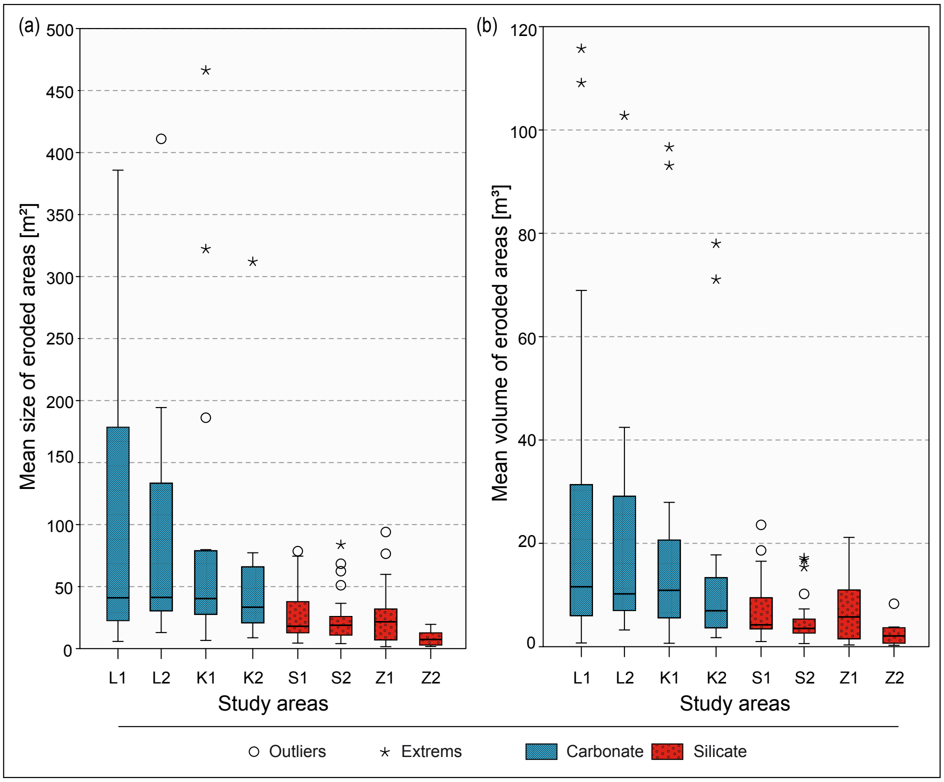


Fig. 8: Mean sizes and volumes of shallow eroded areas. (a) Distribution of area size and (b) mean volumes of shallow eroded areas

eas, particularly in L1 und L2 (Lechtaler Alpen, Häselgehr and Hahntennjoch).

The values for lengths, widths (c.f. Sec. 3.2.4) and depths (c.f. Sec. 3.2.5) determined by us, as well as the areas and volumes are significantly lower than the values described by e.g. Rickli and Graf (2009) for shallow landslides from different study areas in Switzerland. Here are the mean lengths between 14.3 m and 27.9 m, the mean widths between 11.8 m and 17.3 m and the mean depths between 0.8 m and 1.4 m (Rickli and Graf 2009, 36). The investigations of Markart et al. (2007) to shallow landslides due to extreme rainfall events from different communities in Vorarlberg (Austria) also show significantly larger values. The most frequent classes describe mean lengths of > 10 m and < 25 m, mean widths of > 5 m and < 15 m, and mean depths of > 0.5 m to < 1.5 m. The resulting volumes are thus also significantly larger, the most frequent classes show volumes between 50 m^3 and < 1000 m^3 (Markart et al. 2007, 25–27).

Investigations on shallow erosion by snow movements describe the superficial erosion of the uppermost decimetres resulting in small depths and volumes (Bunza 1976, cited by Zweckl and Standau 1987; Stahr 1997). From these comparisons, the conclusion can be drawn that most of our examined shallow eroded areas are likely caused by snow movement.

Compared to larger mass movements single shallow eroded areas only cause low volumes of displaced slope material. Thus a single eroded area generally provoke no risks for underlying slope areas. Affected slopes, however, usually show several eroded areas (e.g. > 30 eroded areas per ha in S2, Schmirntal, Obern), with considerable overall displacement of slope material. This causes loss of soil material and reduction of capability of slope water retention.

3.3 Vegetation and land use

We found that land cover clearly influences shallow erosion processes connected with snow gliding. Long-leaved, flattened grasses (e.g. *Deschampsia caespitose, Molinia arundinaceae, Carex sempervirens*) encourage snow gliding by lessening the surface roughness of the slope (Laatsch and Grottenthaler 1972; Ewald 1996) (Fig. 9a). The question remains how the forces

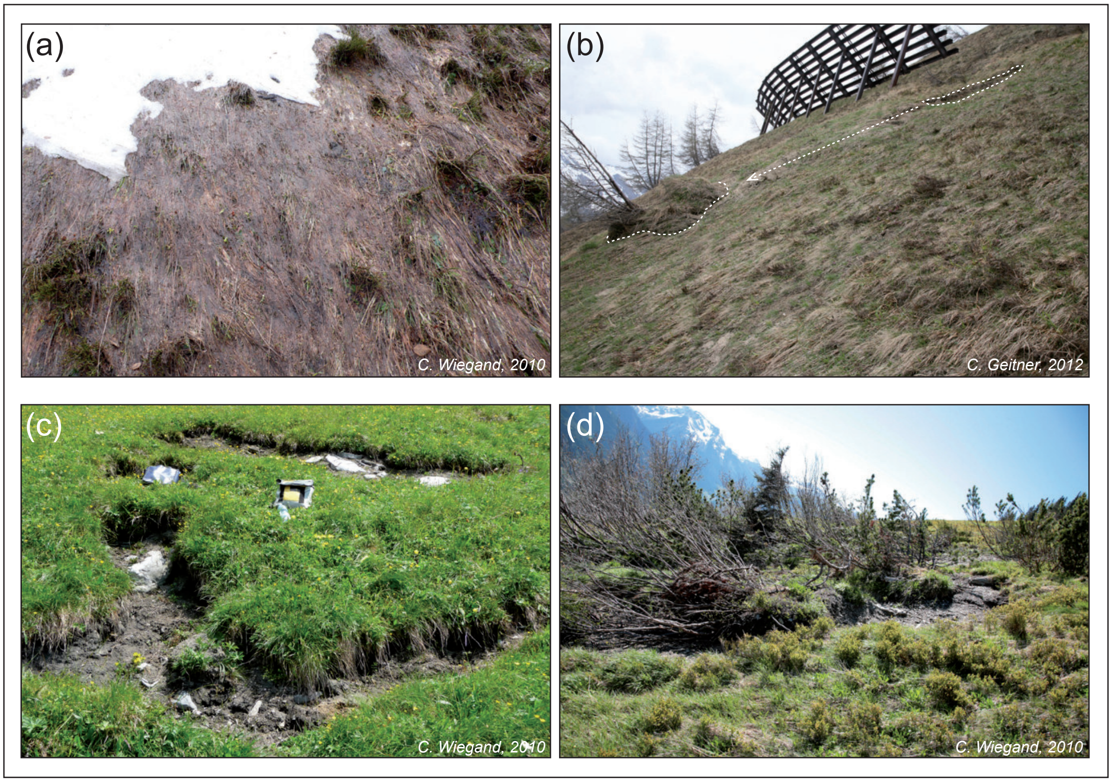


Fig. 9: Interrelation of vegetation on snow gliding and shallow erosion. (a) flattened grass in study area Z1 (Zillertal, Kolmhaus 1) offers little resistance to snow; (b) clod transfer with larch (*Larix*) in study area S2 (Schmirntal, Obern); (c) tension fissure in study area Z1; (d) material transfer by snow movement on green alder (*Alnus viridis*) and mountain pine (*Pinus mugo subsp. mugo*) in study area Z2 (Zillertal, Kolmhaus 2)

of the moving snow are transferred to the ground beneath the vegetation. This happens for instance in places where single young trees and shrubs have sprung up, which are then pushed away, often with the topsoil (Fig. 9b). We observed such phenomena in the study areas Z1, Z2 (Zillertal, Kolmhaus 1 and 2), S1 and S2 (Schmirntal, Toldern and Obern).

The impact of land use started in the studied slopes with the forest clearance, often several hundred years ago. It can be assumed that first shallow eroded areas developed with deforestation (Veit 2002). In recent decades most of the studied areas were abandoned, which led to a gradual change in land cover (Grabherr 1997; Tasser and Tappeiner 2002). Here we must also mention the abandonment of high mountain pasture maintenance. Detailed studies by Flöck (2012) on the area-explicit history of land use for the study areas K1 and K2 (Karwendel, Engalm and Ladizalm) revealed that abandonment results in increased shallow erosion on some abandoned areas, other abandoned areas experience no increase of shallow erosion. Thus, abandonment can lead to an increase of shallow erosion. But if other slope properties determine stable conditions shallow erosion can also be absent.

3.4 Discontinuities in the substrate near the surface

For the majority of studied areas we found a connection between scarp depth (Sec. 3.2.5) and a change in soil-physical characteristics. In all areas skeleton content (particularly coarse gravel and stones) increased significantly as did the grain size of the fine soil from topsoil to substrate (Fig. 10), which points to a multi-layered composition of the slope sediments. Bulk density also increased sharply at the relevant depth. In about 85% of the areas we found significantly reduced root penetration around the scarp depth. In most cases the change in the listed parameters goes hand in hand with a change in soil horizon. For the shallow Leptosols in the northern study areas and the Regosols in the southern study areas this change in horizon is found at the transition from the loose A horizon, very well penetrated by roots, to the denser C horizon with weak root penetration (Fig. 11). With the more deeply developed Cambisols of the southern study areas, the change is usually found at the transition from B to C horizons. These observations largely match the results of Dommermuth (1995) and Stahr (1997) for erosion by snow movement, with eroded areas always linked to a change in substrate below that also determines horizons and root penetration. Such changes have also been found for shallow landslides (Moser and Hohensinn 1983; D'Amato Avanzi 2004; Rickli et al. 2004) and reflect a reduced resistance against shearing towards the topsoil. This proves for both types of processes that the regularly occurring changes of substrate near the surface have a significant impact on erosion events. Wiegand et al. (2013a) were able to identify such an impact of discontinuities in the composition of the unconsolidated material on shallow landslides even for a site at a lower elevation in the study area Schmirntal.

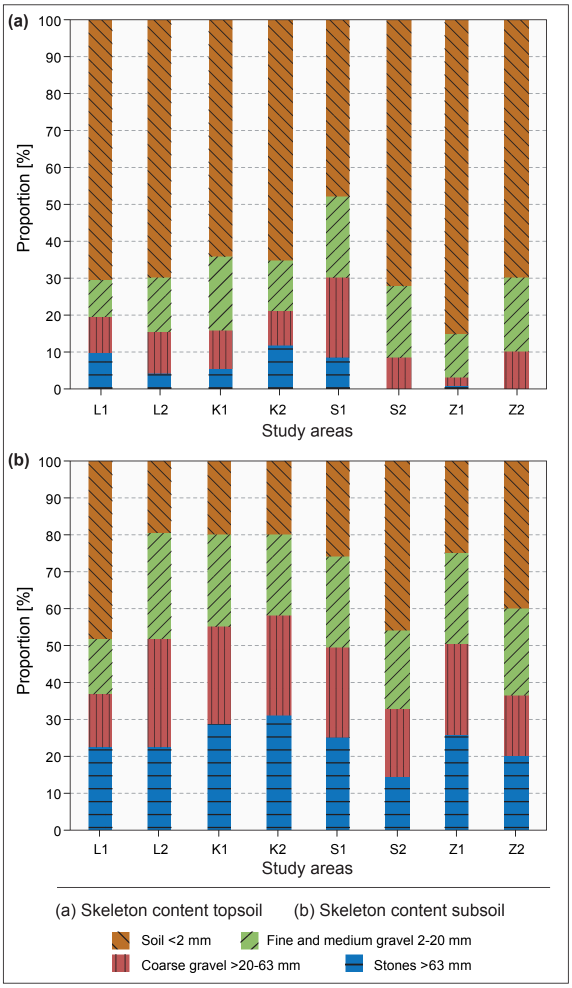


Fig. 10: Distribution of skeleton content in topsoil and substrate per study area. Skeleton content was estimated in the field

Thus the vertical structure of a soil can explain why the erosion takes place in such low depths. But as the whole test sites are covered by soil with similar structures, this information cannot explain the distribution patterns within the test sites.

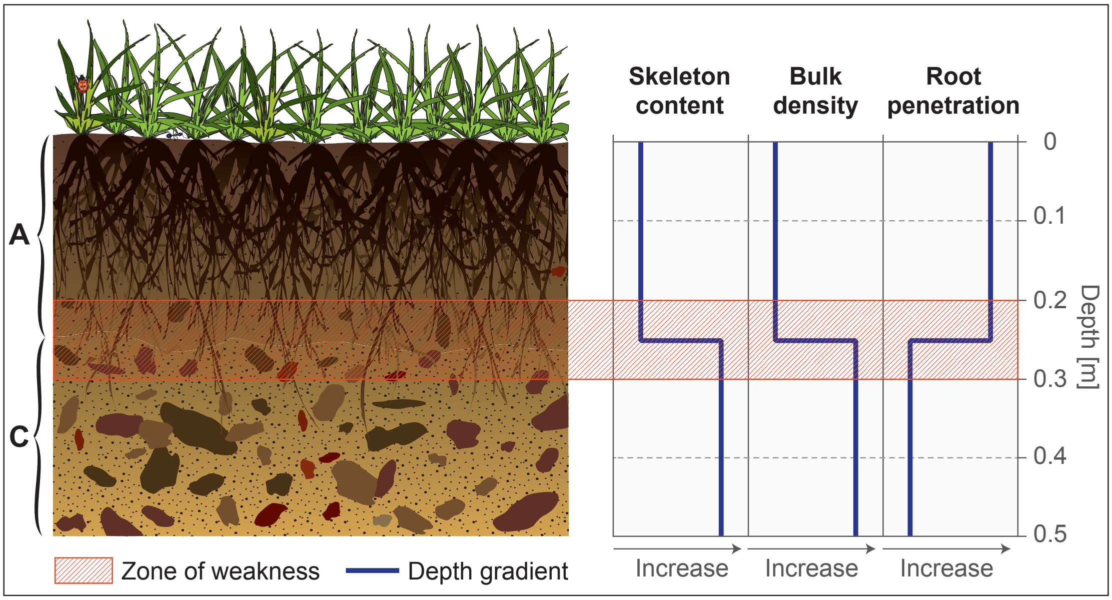


Fig. 11: Schematic presentation of a discontinuity for a sequence of A to C soil horizon, showing changes in skeleton content, bulk density and root penetration with increasing depth

3.5 Process types of shallow eroded areas

Our investigations revealed that in some cases neither observation in the field nor statistical comparisons of erosion forms (c.f. Sec. 3.2) yield clear indications for one or the other of the two process types. But compared to other investigations on shallow landslides and snow gliding, we can assume that the majority (> 90%) of our investigated eroded areas are caused by snow movements. Shallow landslides investigated in other studies show significantly larger amounts of displaced slope material (c.f. Sec. 3.2.6). Even where it was possible to observe current sliding processes in the transfer of smaller, compact clods of material (Fig. 12a), these only belong to a secondary further development of the scarp.

Most study areas present signs of erosion by snow movements (c.f. Sec. 3.3). After snow melt one can occasionally see considerable transfers of material in existing and new erosion areas (Fig. 12b). Other clear instances of erosion by snow movements are cases where shrubs or young trees have been moved by several metres or even tens of metres, often including the root-penetrated topsoil (Fig. 9b). Tension fissures, a few decimetres in width and up to several metres in length, also denote the impact of snow movement (Schauer 1975; Bernhaupt 1980) (Fig. 9c).

In addition, some location parameters may help to distinguish between the two process types. Eroded areas that regularly start at changes in the slope to flatter dips often clearly indicate the impact of erosion by snow movement. Eroded areas in flatter parts of the slope, particularly in E to W aspect may point to erosion by snow movements.

In individual cases both processes can interact. Where snow movement has created tension fissures in the surface of a slope, surface water can enter the subsoil in a concentrated manner and thus encourage landslides (Schauer 1975, Tasser et al. 2005).

4 Synthesis and outlook

Even if our available data do not always allow a definitive differentiation of the two process types the comparison with other studies show that the majority of the investigated shallow eroded areas are caused by snow movements. Furthermore the collected data provide an overview of the distribution and diversity of forms for shallow eroded areas in eight study areas in Tyrol. These data can also be used to estimate the total loss of soil arising from these processes. The results present a rough distribution pattern for Tyrol which is determined on a smaller spatial scale by the geological substrate and the occurrence of erosion triggering precipitation, and on a larger scale by the conditions for snow gliding and by historic and current land use. The presented results can also be relevant for other parts of the Alps as shallow eroded areas also occur. Looking at all 161 shallow eroded

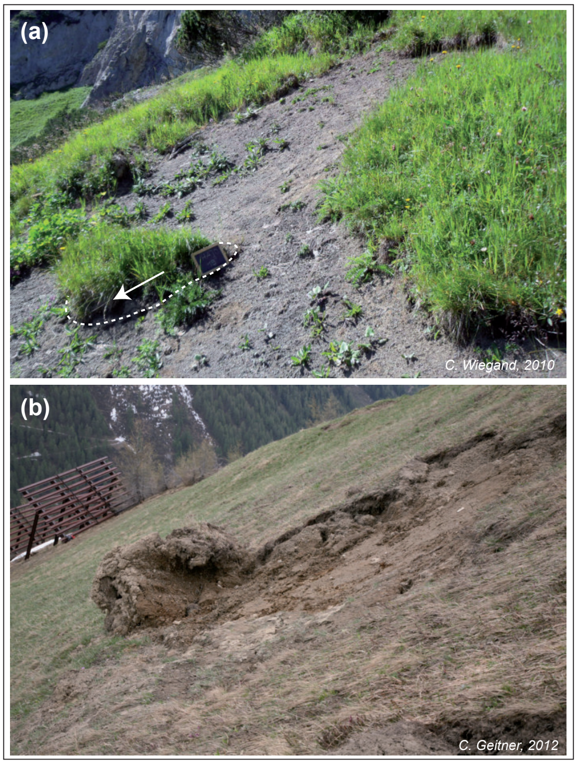


Fig. 12: Different forms of shallow eroded areas. (a) Gravitatively transferred material clod (study area L2, Hahntennjoch) and (b) shallow erosion by snow movement (study area S2, Obern, Schmirntal)

areas from eight Tyrolean study areas, we can see that the studied areas mostly occur above a closed forest belt and in slopes of ca. 25+° of inclination. The eroded areas are mainly exposed towards E, S and W. As a rule the shallow eroded areas develop compact forms of a size between 2 m^2 and 200 m^2, with certain dominance in length downslope. In the northern study areas larger and sometimes deeper eroded areas occur and this is why we also find the largest material transfers here. Secondary deeper erosion of already exposed areas may play a part in this. We found discontinuities within the upper layers of the substrate near the scarp for nearly all eroded areas. They are characterized by increases in skeleton content and bulk density as well as reduced root penetration. Land use has changed in recent decades and many areas have been abandoned or are only used extensively as pastures any more. A differentiated assessment of the impact of this change in land use would necessitate the multi-temporal reconstruction of land use history with exact mapping to individual plots.

In terms of differentiating between the two main process types, some questions remain. Even if the locational characteristics (e.g. inclination and aspect) and the comparison with other studies from the Alps point to erosion by snow movement, in most cases we cannot completely exclude landslides. Field work in situ can provide clear proof of snow impact, as has been shown for some concrete examples. Taken together, these indications suggest that erosion by snow movement is the dominant process in the study areas.

Despite numerous local studies more research is needed not just for identifying the process types but also for assessing the relevant impact factors and their critical combination. Multi-temporal studies as proposed by Wiegand et al. (2013b) could help differentiate processes and impact factors further. If the eroded areas are captured before and after the winter period, changes in size of the eroded area can be attributed more clearly to one or the other process type. Better data on the snow situation on the studied slopes would be helpful, not least to model snow gliding rates. Morphometric studies of the slopes would further help to discover the impact of certain terrain features, e.g. the changes in dip. Case studies with detailed plot-specific reconstructions of land use, as carried out by Flöck (2012) for one of our study areas, are needed to fully understand the impact of land-use change. Flöck's investigation revealed that areas with apparently very similar characteristics may react to the same land-use changes in a variety of ways when it comes to shallow erosion. It takes such time-consuming, multi-temporal surveys to pose new questions (Flöck et al. 2013).

Further research and a broader data basis is needed to account for the fact that the northern study areas presented significantly larger and differently shaped eroded areas than other study areas. Systematic multi-temporal analyses of aerial photographs are needed to find out whether certain characteristics of shape are connected with the age of the eroded areas. At the same time it would be possible to differentiate the extent of natural vegetation regrowth. To answer some of the questions it would be vital to analyse the unconsolidated substrate in more detail over a larger area. This would also be helpful in differentiating between erosion by snow movement or shallow landslides. A larger dataset would also serve to assess the loss of soil quantitatively in terms of erosion rates for different parts of Tyrol.

We need to understand the processes at work more fully if we want to assess potential changes in these processes under conditions of climate change. We would welcome any attempt at systematic monitoring in addition to the suggested detailed investigations.

Acknowledgements

We thank the Austrian Academy of Sciences and the University of Innsbruck for supporting this project and the federal authorities of Tyrol (Geoinformation Dept.) for providing the data. Our special thanks go to M.Sc. Felicitas Schöpf and M.Sc. Gerald Flöck for their help in capturing the erosion areas and Dr. Brigitte Scott for her help with the English editing. We also want to thank the interviewed experts for sharing their expertise and the two anonymous reviewers for their helpful suggestions.

References

AD-HOC-ARBEITSGRUPPE BODEN (2005): Bodenkundliche Kartieranleitung. 5. ed. (KA5), Hannover.

Ammer, U.; Pröbstl, U. and Mössmer, E.-M. (1986): Erosion auf Almen. Ein Beitrag zu aktuellen Fragen des Bodenschutzes. In: Forstwissenschaftliches Centralblatt 105, 48–59.

Andrecs, P. Markart, G.; Lang, E.; Hagen, K.; Kohl, B. and Bauer, W. (2002): Untersuchung der Rutschprozesse vom Mai 1999 im Laternsertal (Vorarlberg). In: Schriftenreihe des Bundesamtes und Forschungszentrum für Wald 127, 55–87.

Andrecs, P. and Hagen, K. (2011): Dokumentation von Lockersedimentrutschungen: Voraussetzungen, Nutzen und praktische Erfahrungen. Wildbach- und Lawinenverbau, Salzburg, 74 (166), 226–237.

Auer, I.; Hiebl, J.; Reisenhofer, S.; Böhm, R. and Schöner, W. (2010): ÖKLIM 1971–2000, Aktualisierung des digitalen Klimaatlas Österreich 1961–1990. Projektendbericht 2010, Wien.

Beniston, M. (2006): Mountain weather and climate: a general overview and a focus on climate change in the Alps. In: Hydrobiologia 562, 3–16. DOI: 10.1007/s10750-005-1802-0

Bernhaupt, P. (1980): Zum Problem der Bodenerosion in Almgebieten am Beispiel der Planneralm, Wölzer Tauern, Steiermark. In: Interpraevent 1980 Tagungspublikation 1, 291–308.

Blechschmidt, G. (1990): Die Blaikenbildung im Karwendel. In: Jahrbuch des Vereins zum Schutz der Bergwelt 55, 31–45.

Bovolo, C. I. and Bathurst, J. C. (2011): Modelling catchment-scale shallow landslide occurrence and sediment yield as a function of rainfall return period. In: Hydrological Processes 26 (4), 579–596. DOI: 10.1002/hyp.8158

Brandner, R. (1985): Geologie und Tektonik. Geologische und Tektonische Übersichtskarte von Tirol. Tirol-Atlas, Begleittexte IX, Innsbruck.

Ceaglio, E.; Meusburger, K.; Freppaz, M.; Zanini, E. and Alewell, C. (2012): Estimation of soil redistribution rates due to snow cover related processes in mountainous area (Valle d´Aosta, NW Italy). In: Hydrology and Earth System Sciences 16, 517–528. DOI: 10.5194/hess-16-517-2012

Chemini C. and Rizzoli, A. (2003): Land use change and biodiversity conservation in the Alps. In: Journal of Mountain Ecology (Suppl.) 7, 1–7.

Crozier, M. J. (2010): Deciphering the effect of climate change on landslide activity: a review. In: Geomorphology 124, 260–267. DOI: 10.1016/j.geomorph.2010.04.009

D'Amato Avanzi, G.; Giannecchini, R. and Puccinelli, A. (2004): The influence of the geological and geomorphological settings on shallow landslides. An example in a temperate climate environment: the June 19, 1996 event in northwestern Tuscany (Italy). In: Engineering Geology 73, 215–228. DOI: 10.1016/j.enggeo.2004.01.005

Dommermuth, C. (1995): Beschleunigte Bodenabtragungsvorgänge in der Kulturlandschaft des Nationalparks Berchtesgaden. In: Forstwissenschaftliches Centralblatt 114, 285–292.

Ewald, J. (1996): Graslahner – Rasengesellschaften in der montanen Waldstufe der Tegernseer Alpen. In: Berichte der Bayerischen Botanischen Gesellschaft 66/67, 115–133.

Flöck, G. (2012): Veränderung flachgründiger Abtragsflächen auf der Engalm (Karwendel/Tirol) über die Jahre 1953 bis heute. Ein Beitrag zum besseren Verständnis natürlicher Rahmenbedingungen und Landnutzungsänderungen. Master thesis. Innsbruck.

Flöck, G.; Geitner, C. and Wiegand, C. (2013 in print): Veränderungen flachgründiger Abtragsflächen auf der Engalm (Karwendel/Tirol) über die Jahre 1953 bis heute. Ein Beitrag zum besseren Verständnis natürlicher Rahmenbedingungen und Landnutzungsänderungen. In: Mitteilungen der Österreichischen Bodenkundlichen Gesellschaft.

Freppaz, M.; Godone, D.; Filippa, G.; Maggioni, M.; Lunardi, S.; Williams, M. W. and Zanini, E. (2010): Soil erosion by snow avalanches: a case study in the Aosta Valley (NW Italy). In: Arctic, Antarctic, and Alpine Research 42 (4), 412–421. DOI: 10.1657/1938-4246-42.4.412

Gall, H. (1947, published and provided with a gleaning 1985): Bodenerosion und Bodenerhaltung im Gebirgsland am besonderen Beispiel Nordtirols. PhD thesis. Innsbruck.

GEITNER, C. (2007): Böden in den Alpen – Ausgewählte Aspekte zur Vielfalt und Bedeutung einer wenig beachteten Ressource. In: BORSDORF, A. and GRABHERR, G. (eds.): Internationale Gebirgsforschung. IGF-Forschungsberichte 1, 56–67.

GOBSTER, P. H.; NASSAUER, J. I.; DANIEL, T. C. and FRY, G. (2007): The shared landscape: what does aesthetics have to do with ecology? In: Landscape Ecology 22, 959–972. DOI: 10.1007/s10980-007-9110-x

GRABHERR, G. (1997): The high-mountain ecosystems of the Alps. In: WIELGOLASKI, F. E. (ed.): Ecosystems of the world 3. Polar and alpine Tundra, 97–121.

HÜBL, J.; KIENHOLZ, H. and LOIPERSBERGER, A. (eds.) (2002): DOMODIS – Documentation of Mountain Desasters. Internationale Forschungsgesellschaft Interpraevent, Schriftenreihe 1. Klagenfurt.

KARL, J. (1961): Blaikenbildung auf Allgäuer Blumenbergen. In: Jahrbuch des Vereins zum Schutze der Alpenpflanzen und -tiere 26. München, 55–62.

KIENHOLZ, H. and GRAF, C. (2000): Vom Gelände zur Karte der Phänomene. Nationale Plattform Naturgefahren (PLANAT). Bern.

LAATSCH, W. (1974): Hangabtrag durch Schnee in den oberbayerischen Alpen und seine Begünstigung durch unpflegliche Almwirtschaft und Wildverbiß. In: Forstwissenschaftliches Centralblatt 93, 23–34.

LAATSCH, W. and BAUM, U. (1976): Faktoren der Wald- und Bodenzerstörung durch Schnee in den Alpen. In: Agrochimica 10, 324–338.

LAATSCH, W. and GROTTENTHALER, W. (1972): Typen der Massenverlagerung in den Alpen und ihre Klassifikation. Forstwissen. In: Forstwissenschaftliches Centralblatt 91, 309–339.

LEITINGER, G.; HÖLLER, P.; TASSER, E. and TAPPEINER, U. (2008): Development and validation of a spatial snow-gliding model. In: Ecological Modelling 211, 363–374. DOI: 10.1016/j.ecolmodel.2007.09.015

MACDONALD, D.; CRABTREE, J. R.; WIESINGER, G.; DAX, T.; STAMOU, N.; FLEURY, P.; GUTIERREZ LAZPITA, J. and GIBON, A. (2000): Agricultural abandonment in mountain areas of Europe: environmental consequences and policy response. In: Journal of Environmental Management 59, 47–69. DOI: 10.1006/jema.1999.0335

MARKART, G.; PERZL, F.; KOHL, B.; LUZIAN, R.; KLEEMAYR, K.; ESS, B. and MAYERL, J. (2007): 22. und 23. August 2005 – Analyse von Hochwasser- und Rutschungsereignissen in ausgewählten Gemeinden Vorarlbergs. Schriftenreihe des Bundesforschungs- und Ausbildungszentrums für Wald, Naturgefahren und Landschaft 5. Wien.

MEUSBURGER, K. and ALEWELL, C. (2008): Impacts of anthropogenic and environmental factors on the occurrence of shallow landslides in an alpine catchment (Urseren Valley, Switzerland). In: Natural Hazards and Earth System Sciences 8, 509–520.

MOSER, M. (1980): Zur Analyse von Hangbewegungen in schwachbindigen bis rolligen Lockergesteinen im alpinen Raum anlässlich von Starkniederschlägen. In: Interpraevent 1980 Tagungspublikation 1, 121–148.

MOSER, M. and HOHENSINN, F. (1983): Geotechnical aspects of soil slips in alpine regions. In: Engineering Geology 19, 185–211.

MÖSSMER, E. (1985): Einflussfaktoren für die Blaikenerosion auf beweideten und aufgelassenen Almflächen im kalkalpinen Bereich der Landkreise Miesbach und Rosenheim. Forstliche Forschungsberichte München 63.

NEWESELY, C.; TASSER, E.; SPADINGER, P. and CERNUSCA, A. (2000): Effects of land-use changes on snow gliding processes in alpine ecosystems. In: Basic and Applied Ecology 1, 61–67. DOI: 10.1078/1439-1791-00009

PLANALP – Plattform Naturgefahren der Alpenkonvention (ed.) (2006): Dokumentation von Naturereignissen – Feldanleitung. Innsbruck, Bern.

RICKLI, C. and BUCHER, H. (2003): Oberflächennahe Rutschungen, ausgelöst durch die Unwetter vom 15.–16.7.2002 im Napfgebiet und vom 31.–1.9.2002 im Gebiet Appenzell. Projektbericht BWG. Bern.

RICKLI, C. and GRAF F. (2009): Effects of forests on shallow landslides - case studies in Switzerland. In: Forest Snow and Landscape Research 82 (1), 33–44.

RICKLI, C.; ZÜRICHER, K.; FREY, W.; LÜSCHER, P. (2002): Wirkung des Waldes auf oberflächennahe Rutschprozesse. In: Schweizerische Zeitschrift für Forstwesen 153 (11), 437–445.

RICKLI, C.; BUCHER, H.; BÖLL, A. and RAETZO, H. (2004): Untersuchungen zu oberflächennahen Rutschungen des Jahres 2002 im Napfgebiet und in der Region Appenzell. In: Bulletin für Angewandte Geologie 9 (1), 37–49.

SCHAUER, T. (1975): Die Blaikenbildung in den Alpen. Schriftenreihe des Bayerischen Landesamtes für Wasserwirtschaft 1. München.

SOLDATI, M.; CORSINI, A. and PASUTO, A. (2004): Landslides and climate change in the Italian Dolomites since the Late glacial. In: Catena 55, 141–161. DOI: 10.1016/S0341-8162(03)00113-9

STAHR, A. (1997): Bodenkundliche Aspekte der Blaikenbildung auf Almen. Nationalpark Berchtesgaden Forschungsberichte 39. Berchtesgaden.

TAPPEINER, U.; BORSDORF, A. and TASSER, E. (eds.) (2008): Alpenatlas – Atlas des Alps – Atlante delle Alpie – Atlas Alp – Mapping the Alps. Society – Economy – Environment. Heidelberg.

TAROLLI, P.; BORGA, M.; KANG-TSUNG, C. and SHOU-HAO, C. (2011): Modelling shallow landsliding susceptibility by incorporating heavy rainfall statistical properties.

In: Geomorphology 133, 199–211. DOI: 10.1016/j.geomorph.2011.02.033

Tasser, E. and Tappeiner, U. (2002): Impact of land use changes on mountain vegetation. In: Applied Vegetation Science 5 (2), 173–184. DOI: 10.1111/j.1654-109X.2002.tb00547.x

Tasser, E.; Mader, M. and Tappeiner, U. (2003): Effects of land use in alpine grasslands on the probability of landslides. In: Basic and Applied Ecology 4, 271–280. DOI: 10.1078/1439-1791-00153

– (2005): Auswirkungen von Bewirtschaftungsänderungen auf die Blaikenbildung im Gebirge. In: Mitteilungen der Österreichischen Bodenkundlichen Gesellschaft 72, 193–217.

TIRIS (2010): Land Tirol, Amt der Tiroler Landesregierung.

Veit, H. (2002): Die Alpen – Geoökologie und Landschaftsentwicklung. Stuttgart.

Wiegand, C. and Geitner, C. (2010): Flachgründiger Abtrag auf Wiesen- und Weideflächen in den Alpen (Blaiken). Wissenstand, Datenbasis und Forschungsbedarf. In: Mitteilungen der Österreichischen Geographischen Gesellschaft 152, 130–162.

Wiegand, C.; Kringer, K.; Geitner, C. and Rutzinger, M. (2013a): Regolith structure analysis – a contribution for understanding the local occurrence of shallow landslides (Austrian Tyrol). In: Geomorphology 183, 5–13. DOI: 10.1016/j.geomorph.2012.06.027

Wiegand, C.; Rutzinger, M.; Heinrich, K. and Geitner, C. (2013b): Automated extraction of shallow erosion areas based on multi-temporal Ortho-Imagery. In: Remote Sensing 5 (5), 2292-2307. DOI: 10.3390/rs5052292

Zweckl, J. and Spandau, L. (1987): Untersuchungen zur Blaikenerosion im Jennergebiet des Alpenparks Berchtesgaden. In: Landschaft und Stadt 19, 122–128.

Authors:

Dr. Christoph Wiegand
Institute of Geography
University of Innsbruck
Innrain 52f
A-6020 Innsbruck
Austria
email: wiegand.chr@web.de

Assoz. Prof. Dr. Clemens Geitner
Institute of Geography
University of Innsbruck
Innrain 52f
A-6020 Innsbruck
Austria
clemens.geitner@uibk.ac.at

Appendix

Documentation of shallow eroded areas

Event No.: Date: Person: Location:

Map sheet:

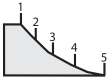
Bedrock:
(reference in km)
- ☐ intrusive rock
- ☐ extrusive rock
- ☐ metamorphice rock
- ☐ sedimentary rock
- ☐ not specified

Macro relief:
(reference 500 m)
- ☐ terrace
- ☐ depression
- ☐ trench
- ☐ slope
- ☐ crest
- ☐ alluvial fan
- ☐ debris cone
- ☐ others

Meso relief:
(reference 50 m)
- ☐ plain
- ☐ slope steepening
- ☐ slope flattening
- ☐ crest
- ☐ slope toe
- ☐ depression
- ☐ not specified

Micro relief:
(reference 5 m)
- ☐ smooth
- ☐ gullies
- ☐ scree landscape
- ☐ fissures
- ☐ rippled
- ☐ humpy
- ☐ not specified

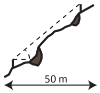
Total slope:



- ☐ upper slope edge (1)
- ☐ upper slope (2)
- ☐ middle slope (3)
- ☐ lower slope (4)
- ☐ slope toe (5)

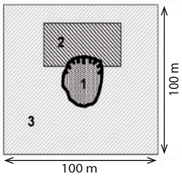
Remarks to the slope:

mean inclination:



Description of regolith:

Distance to point of culmination: m



Land use (3):
- ☐ grassland
- ☐ pasture
- ☐ forest
- ☐ fallow
- ☐ ski runway
- ☐ field

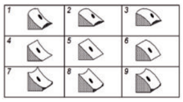
Pasture (3):
- ☐ none
- ☐ low
- ☐ medium
- ☐ high

Surface cover (3):

sealing %
vegetation %
moss %
weed %
shrubs %
trees %
vegetation free %
bedrock %
boulders and stones %
open soil %

Vegetation (3):
- ☐ deciduous forest
- ☐ coniferous forest
- ☐ mixed forest
- ☐ larch meadow
- ☐ forest edge
- ☐ mountain pine
- ☐ green elder
- ☐ clear cutting, windfall
- ☐ meadow
- ☐ pasture
- ☐ dwarf shrubs
- ☐ rock and debris vegetation

Slope curvature (3):



Strength of curvature (3):

horizontal	vertical
☐ none	☐ none
☐ very low	☐ very low
☐ low	☐ low
☐ medium	☐ medium
☐ intense	☐ intense
☐ very intense	☐ very intense
☐ not specified	☐ not specified

Hydrological Conditions (3):
- ☐ drain > inflow
- ☐ drain = inflow
- ☐ drain < inflow
- ☐ influence of groundwater
- ☐ backwater: dry
- ☐ backwater: moist
- ☐ backwater: wet
- ☐ influence of slope water

Degree of humidity (3):
- ☐ very dry
- ☐ dry
- ☐ moderate dry
- ☐ well supplied
- ☐ moderate moist
- ☐ moist
- ☐ wet
- ☐ periodically wet

Hydrol. local characteristics (indicator species) (2):
- ☐ wet
- ☐ fresh/moist
- ☐ dry

Compaction (3):

actual	endangering
☐ non	☐ low
☐ medium	☐ medium
☐ high	☐ high

Signs of older events (3):

Initial forms (3):

Land use (3):

Vegetation (species):

coverage & distribution of dominant species

Suitable as monitoring location: ☐ no ☐ yes:

Distinctive points: ☐ no ☐ yes:

Arrangements: ☐ non ☐ repaired others:

Soil record: ☐ no ☐ yes record no.: Soil type:

Photographs No.:

Protection work: ☐ no ☐ yes ☐ not recorded Type of protection work:

Damage to protection work: ☐ no ☐ yes ☐ not recorded

Technical arrangements:
- ☐ paths/embankment
- ☐ linear (channels)
- ☐ others:

Process:
- ☐ translational slide
- ☐ rotational slide
- ☐ debris flow
- ☐ depression
- ☐ river bank damage
- ☐ denudation by snow
- ☐ others:

Persumed trigger:
- ☐ slope water
- ☐ lateral erosion
- ☐ vertical erosion
- ☐ livestock trampling
- ☐ anthropogen (road works, etc.)
- ☐ others:

Rooting (10x10 cm):

0-10 cm:	11-20 cm:	21-30 cm:	31-40 cm:	41-50 cm:
☐ non	☐ non	☐ non	☐ non	☐ non
☐ low	☐ low	☐ low	☐ low	☐ low
☐ medium	☐ medium	☐ medium	☐ medium	☐ medium
☐ intense	☐ intense	☐ intense	☐ intense	☐ intense
☐ very intense	☐ very intense	☐ very intense	☐ very intense	☐ very intense
☐ root felt	☐ root felt	☐ root felt	☐ root felt	☐ root felt

Coord. scarp: N E

Measurement error (GPS): m

Altitude a.s.l.: m

Aspect: °

D. max: m

Inclination max: °

Width scarp: m

W. max: m

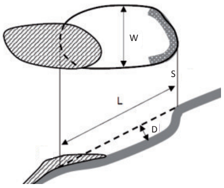
Inclination Ø: °

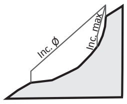
Depth scarp: m

L. max: m

Discontinuity noticeable ☐ yes ☐ no ☐ unclear

Remarks to discontinuity:





Accumulation area noticeable: yes ☐ no ☐

Inclination: ° W. max : m L. max : m

L: max. length
W: max. width
D: max. depth
S: scarp

Skeleton content

topsoil:
- stones (<63 mm) ______%
- gravel (>20-63 mm) ______%
- gravel (2-20 mm) ______%
- soil (<2 mm) ______%

subsoil:
- stones (<63 mm) ______%
- gravel (>20-63 mm) ______%
- gravel (2-20 mm) ______%
- soil (<2 mm) ______%

Bulk density

topsoil:
- ☐ very low
- ☐ low
- ☐ medium
- ☐ high
- ☐ very high

subsoil:
- ☐ very low
- ☐ low
- ☐ medium
- ☐ high
- ☐ very high

Date of event: (yyyy-mm-dd)

Information:

sketches:

longitudinal profil:

cross profile:

additional remarks: