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Soil erosion by snow gliding – a first quantification attempt in a sub-alpine area, Switzerland

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Abstract

Snow processes might be one important driver of soil erosion in Alpine grasslands and thus the unknown variable when erosion modelling is attempted. The aim of this study is to assess the importance of snow gliding as soil erosion agent for four different land use/land cover types in a sub-alpine area in Switzerland. We used three different approaches to estimate soil erosion rates: sediment yield measurements in snow glide deposits, the fallout radionuclide ^{137}Cs, and modelling with the Revised Universal Soil Loss Equation (RUSLE). The RUSLE model is suitable to estimate soil loss by water erosion, while the ^{137}Cs method integrates soil loss due to all erosion agents involved. Thus, we hypothesise that the soil erosion rates determined with the ^{137}Cs method are higher and that the observed discrepancy between the soil erosion rate of RUSLE and the ^{137}Cs method is related to snow gliding and sediment concentrations in the snow glide deposits. Cumulative snow glide distance was measured for the sites in the winter 2009/10 and modelled for the surrounding area with the Spatial Snow Glide Model (SSGM). Measured snow glide distance ranged from 2 to 189 cm, with lower values at the north facing slopes. We observed a reduction of snow glide distance with increasing surface roughness of the vegetation, which is important information with respect to conservation planning and expected land use changes in the Alps. Our hypothesis was confirmed: the difference of RUSLE and ^{137}Cs erosion rates was related to the measured snow glide distance ($R^2 = 0.64$; $p < 0.005$) and snow sediment yields ($R^2 = 0.39$; $p = 0.13$). A high difference (lower proportion of water erosion compared to total net erosion) was observed for high snow glide rates and vice versa. The SSGM reproduced the relative difference of the measured snow glide values under different land uses and land cover types. The resulting map highlighted the relevance of snow gliding for large parts of the investigated area. Based on these results, we conclude that snow gliding is a key process impacting soil erosion pattern and magnitude in sub-alpine areas with similar topographic and climatic conditions.

1 Introduction

While rainfall is a well-known agent of soil erosion, the erosive forces of snow movements are qualitatively recognized but quantification has not been achieved yet (Leitinger et al., 2008; Konz et al., 2012). Particularly wet avalanches can yield enormous erosive forces that are responsible for major soil loss (Gardner, 1983; Ackroyd, 1987; Bell et al., 1990; Jomelli and Bertran, 2001; Heckmann et al., 2005; Fuchs and Keiler, 2008; Freppaz et al., 2010) also in the avalanche release area (Ceaglio et al., 2012).

Besides avalanches another important process of snow movement affecting the soil surface is snow gliding (In der Gand and Zupancic, 1966). Snow gliding is the slow (mm–cm per day) downhill motion of a snowpack over the ground surface caused by the stress of its own weight (Parker, 2002). Snow gliding predominantly occurs on south-east to south-west facing slopes with slope angles between 30 and 40° (In der Gand and Zupancic, 1966; Leitinger et al., 2008). Two main factors that control snow glide rates are (i) the wetness of the boundary layer between the snow and soil cover and (ii) the ground surface roughness determined by the vegetation cover and rocks (McClung and Clarke, 1987; Newesely et al., 2000). So far, only few studies investigated the effect of snow gliding on soil erosion (Newesely et al., 2000; Leitinger et al., 2008). A major reason for this shortcoming is the difficulty to obtain soil erosion rates caused by snow processes. In steep sub-alpine areas soil erosion records (e.g. with sediment traps) are restricted to the vegetation period because avalanches and snow gliding can irreversibly damage the experimental design (Konz et al., 2012).

Recently, first physically based attempts to model the erosive force of wet avalanches were done (Confortola et al., 2012). No similar model exists for snow gliding. However, the potential maximum snow glide distance during a targeted period can be modelled with the empirical Spatial Snow Glide Model (SSGM) (Leitinger et al., 2008). The modelling of this process is crucial to evaluate the impact of the snow glide process on soil erosion at larger scale.

Soil erosion rates can be obtained by direct quantification of sediment transport in the field, by fallout radionuclides (FRN) based methods (e.g. Mabit et al., 1999; Benmansour et al., 2013; Meusburger et al., 2013) and by soil erosion models (Nearing et al., 1989; Merritt et al., 2003). Since the end of the 1970's empirical soil erosion models such as the Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1965; Wischmeier and Smith, 1978), and its refined versions the Revised USLE (RUSLE; Renard et al., 1997) and the Modified USLE (MUSLE; Smith et al., 1984), have been used worldwide to evaluate soil erosion magnitude under various conditions (Kinnell, 2010). These well-known models allow the assessment of sheet erosion and rill/inter-rill erosion under moderate topography. However, they do not integrate erosion processes associated with wind, mass movement, tillage, channel or gully erosion (Risse et al., 1993; Mabit et al., 2002; Kinnell, 2005) and also snow impact due to movement is not considered (Konz et al., 2009). Several models have been tested for steep alpine sites with the result that RUSLE reproduced the magnitude of soil erosion, the relative pattern and the effect of the vegetation cover most plausible (Konz et al., 2010; Meusburger et al., 2010b; Panagos et al., 2014). The erosion rate derived from RUSLE corresponds to water erosion induced by rainfall and surface runoff and hence in our site to the soil erosion processes during the summer season without significant influence of snow processes.

In contrast, the translocation of FRN reflects all erosion processes by water, wind and snow during summer and winter season and thus, is an integrated estimate of the total net soil redistribution rate since the time of the fallout in the 1950s (the start of the global fallout deposit) and in case of predominant Chernobyl ^{137}Cs input since 1986. Anthropogenic fallout radionuclides have been used worldwide since decades to assess the magnitude of soil erosion and sedimentation processes (Mabit and Bernard, 2007; Mabit et al., 2008; Matisoff and Whiting, 2011). The most well-known conservative and validated anthropogenic radioisotope used to investigate soil redistribution and degradation is ^{137}Cs (Mabit et al., 2013).

For (sub-) alpine areas the different soil erosion processes captured by RUSLE and the ^{137}Cs method result in different erosion rates (Konz et al., 2009; Juretzko, 2010; Alewell et al., 2014). However, this difference might also be due to several other reasons such as the error of both approaches, the non-suitability of the RUSLE model for this specific environment and/or the erroneous estimation of the initial fallout of ^{137}Cs.

In this study, we aim to investigate, whether the observed discrepancy between erosion rates estimated with RUSLE and the ones provided by the ^{137}Cs method can be at least partly attributed to snow gliding processes. Since vegetation cover affects snow gliding, four different sub-alpine land use/land cover types were investigated. A further objective of our research is to assess the relevance of snow gliding processes at catchment scale using the Spatial Snow Glide Model (SSGM).

2 Materials and methods

2.1 Site description

The study site is located in Central Switzerland (Canton Uri) in the Ursern Valley (Fig. 1). The elevation of the W–E extended alpine valley ranges from 1400 up to 2500 m a.s.l. At the valley bottom (1442 m a.s.l.), average annual air temperature for the years 1980–2012 is around 4.1 ± 0.7 °C and the mean annual precipitation is 1457 ± 290 mm, with 30 % falling as snow (MeteoSwiss, 2013). The valley is snow covered from November to April with a mean annual snow height of 67 cm in the period 1980–2012. Drainage of the basin is usually controlled by snowmelt from May to June. Important contribution to the flow regime takes place during early autumn floods. The land use is characterised by hayfields near the valley bottom (from 1450 to approximately 1650 m a.s.l.) and pasturing further upslope. Siliceous slope debris and moraine material is dominant at our sites, and forms Cambisols (Anthric) and Podzols (Anthric) classified after IUSS Working Group (2006).

Of the 14 experimental sites, 9 are located at the south facing slope and 5 at the northfacing slope at altitudes between 1476 and 1670 m a.s.l. Four different land use/cover types with 3–5 replicates each were investigated: hayfields (h), pastures (p), pastures with dwarf shrubs (pw), and abandoned grassland covered with *Alnus viridis* (A). Vegetation of hayfields is dominated by *Trifolium pratense*, *Festuca* sp., *Thymus serpyllum* and *Agrostis capillaries*. For the pastured grassland *Globularia cordifolia*, *Festuca* sp. and *Thymus serpyllum* dominate. Pastures with dwarf shrubs are dominated by *Calluna vullgaris*, *Vaccinium myrtillus*, *Festuca violacea*, *Agrostis capillaries* and *Thymus serpyllum*. At pasture sites of the south facing slope, which are stocked from June to September, cattle trails traverse to the main slope direction.

2.2 Snow glide measurement

We measured cumulative snow glide distances with snow glide shoes for the winter 2009/10. The snow glide shoe equipment was similar to the set-up used by In der Gand and Zupancic (1966), Newesely et al. (2000) and Leitinger et al. (2008). The set-up consisted of a glide shoe and a buried weather-proof box with a wire drum. Displacement of the glide shoe causes the drum to unroll the wire. The total unrolled distance was measured in spring after snowmelt. To prevent entanglement with the vegetation, the steel wire was protected by a flexible plastic tube. For each site, 3–5 snow glide shoes were installed to obtain representative values. A total of 60 devices were used.

2.3 Assessment of soil redistribution

Snow glide distance was measured with snow glide shoes for 14 sites. For 12 of the 14 sites (exclusive of the two *Alnus viridis* sites at the north facing slopes (AN)), RUSLE and ^{137}Cs based erosion rates were assessed. Seven of these sites were measured in 2007 (Konz et al., 2009). During a second field campaign performed in 2010, 5 additional sites were investigated using the same methods for soil erosion assessment with ^{137}Cs and RUSLE as in 2007 (Konz et al., 2009). The ^{137}Cs measurements were decay corrected to 2007 for comparison purpose.

2.3.1 Snow and sediment sampling in the snow glide deposition area

Sediment concentrations were estimated by measuring the amount of sediment in snow samples taken with a corer from the snow glide deposits in spring 2013 (Fig. 2). The corer allowed for the sampling of the entire depth of the snow deposit and thus the integration of the sediment yield over the depth of the deposit. For larger deposits, samples were collected along two transects across each deposit. For smaller deposits, we took three samples. The samples were melted and filtered through a 0.11 µm filter. The filtered material was dried at 40 °C and weighted to obtain the concentration of sediment per sample (M_S). The mean sediment values (and for deposits with several samples the interpolated mean sediment values) were used to estimate the total sediment load of the snow-glide deposit (M_A) according to:

$$M_\mathrm{A} = \frac{A_\mathrm{A} \cdot M_\mathrm{S}}{A_\mathrm{c}} \tag{1}$$

where A_c is the area of the corer and A_A is the area of the snow-glide deposit. The latter was mapped in the field by GPS and measuring tape. Sediment load was further converted to soil erosion rate (E) by:

$$E = \frac{M_\mathrm{A}}{A_\mathrm{S}} \tag{2}$$

where A_S is the source area of the snow and sediment deposit. Each snow glide was photo documented and the respective source area was mapped with GPS and transferred to ArcGIS for surface area estimation.

2.3.2 Assessment of soil redistribution by water erosion using the RUSLE

The USLE (Wischmeier and Smith, 1978) and its revised version the RUSLE (Renard et al., 1997) is an empirical erosion model originally developed in the United States. Several adapted versions for other regions as well as for different temporal resolutions have been developed and applied with more or less success (Kinnell, 2010). Despite its well-known limitation (highlighted in our introduction), we selected RUSLE because of the lack of simple soil erosion models specific for mountain areas and moreover because of its better performance when compared to the other existing models (Konz et al., 2010; Meusburger et al., 2010b). The RUSLE can be calculated using the following equation:

$$A = R \times K \cdot \mathrm{LS} \cdot C \cdot P \tag{3}$$

where A is the predicted average annual soil loss ($\mathrm{t\,ha^{-1}\,yr^{-1}}$). R is the rainfall–runoff-erosivity factor ($\mathrm{N\,h^{-1}}$) that quantifies the effect of raindrop impact and reflects the rate of runoff likely to be associated with the rain (Renard et al., 1997). The soil erodibility factor K ($\mathrm{N\,h\,kg\,m^{-2}}$) reflects the ease of soil detachment by splash or surface flow. The parameter LS (dimensionless) accounts for the effect of slope length (L) and slope gradient (S) on soil loss. The C-factor is the cover factor, which represents the effects of all interrelated cover and management variables (Renard et al., 1997).

For comparability between the RUSLE estimates of Konz et al. (2009) and the ones assessed in this study we used the same R-factor approximation of Rogler and Schwertmann (1981) adapted by Schuepp (1975). According to the USLE procedure, snowmelt can be integrated in erosivity calculation by multiplying snow precipitation by 1.5 and then adding the product to the kinetic energy times the maximum 30 min intensity. However, the latter procedure does not account for redistribution of snow by drifting, sublimation, and reduced sediment concentrations in snowmelt (Renard et al., 1997). Therefore, as suggested by Renard (1997) this adaption of the R-factor was not considered in this study. The K-factor was calculated with the K nomograph after

Wischmeier and Smith (1978) using grain-size analyses and carbon contents of the upper 15 cm of the soil profiles. Total C content of soils was measured with a Leco CHN analyzer 1000, and grain size-analyses were performed with sieves for grain sizes between 32 and 1000 µm and with a Sedigraph 5100 (Micromeritics) for grain sizes between 1 and 32 µm. L and S were calculated after Renard et al. (1997). The support and practice factor P (dimensionless) was set to 0.9 for some of the pasture sites because alpine pastures with cattle trails resemble small terrace structures, which are suggested to be considered in P (Foster and Highfill, 1983). For all other sites, P value was set to 1. The cover-and-management factor C was assessed for sites with and without dwarf shrubs separately using measured fractional vegetation cover (FVC) in the field.

For investigated sites without dwarf shrubs (US Department of Agriculture, 1977) the C-factor can be estimated with:

$$C = 0.45 \cdot e^{-0.0456 \cdot \mathrm{FVC}} \quad (4)$$

and for sites with dwarf shrubs the following equation was used:

$$C = 0.45 \cdot e^{-0.0324 \cdot \mathrm{FVC}} \quad (5)$$

The FVC was determined in April and September using a grid of 1 m^2 with a mesh width of 0.1 m^2. The visual estimate of each mesh was averaged for the entire square meter. This procedure was repeated four times for each plot. The maximum standard deviation was approx. 5 %. For the *Alnus viridis* sites we used the value provided by the US Department of Agriculture (1977) i.e. 0.003. This value assumes a fall height of 0.5 m and a ground cover of 95–100 %.

The uncertainty assessment of the RUSLE estimates is based on the measurement error of the plot steepness (±2 %) and slope length (±12.5 m). An error of ±2 % was assumed for the grain size analyses as well as for the organic carbon determination. These errors were propagated through the K-factor calculation. An error of ±20 % based on the observed variability of FVC on the plots, was used for the determination of the C-factor. For the R-factor an error of $\pm 5\,\mathrm{N\,h^{-1}}$, which corresponds to the observed variability between the sites was assumed. Finally error propagation for the multiplication of the single RUSLE factors was done.

2.3.3 ^{137}Cs to assess total net soil redistribution

A 2 inch × 2 inch NaI-scintillation detector (Sarad, Dresden, Germany) was used to measure the in situ ^{137}Cs activity. The detector was mounted perpendicular to the ground at a height of 25 cm to reduce the radius of the investigated area to 1 m. Measurement time was set at 3600 s and each site was measured three times.

The detector was successfully ($R^2 = 0.86$) calibrated against gamma spectroscopy laboratory measurements with a 20 % relative efficiency Li-drifted Ge detector (GeLi; Princeton Gamma-Tech, Princeton, NJ, USA) at the Department for Physics and Astronomy, University of Basel. For the GeLi detector the resulting measurement uncertainty on ^{137}Cs peak area (at 662 keV) was lower than 8 % (error of the measurement at 1-sigma) (Schaub et al., 2010). Gamma spectrometry calibration and quality control of the analysis were performed following the protocol proposed by Shakhashiro and Mabit (2009).

Soil moisture influences the measured ^{137}Cs activity. Thus, soil moisture measurements with an EC-5 sensor (DecagonDevices) were used to correct the in situ measurements. The NaI detector has the advantage of providing an integrated measurement over an area of $1\,\mathrm{m^2}$. The commonly observed intrinsic small scale variability (~ 30 %) for ^{137}Cs (Sutherland, 1996; Kirchner, 2013) is thus, smoothed. Nonetheless, around 10 % of the uncertainty of the ^{137}Cs-based soil erosion values can be attributed to the variability of replicated measurements on each single plot. The main error of the in situ measurement results from the peak area evaluation and was determined at 17 % (Schaub et al., 2010).

With the ^{137}Cs method soil redistribution rates are calculated by comparing the isotope inventory for an eroding point with a local reference inventory where neither erosion nor soil accumulation is expected. In the Urseren Valley, the initial reference ^{137}Cs fallout originated from thermonuclear weapon tests in the 1950s–1960s and the nuclear power plant accident of Chernobyl in 1986.

For the conversion of the ^{137}Cs inventories to soil erosion rates knowledge about the proportion of Chernobyl ^{137}Cs fallout is a key parameter for the estimation of erosion rates, however, only little data is available. Pre-Chernobyl (1986) ^{137}Cs activities of the top soil layers (0–5 cm) between 2 and 58 Bq kg^{-1} (one outlier of 188 Bq kg^{-1} in Ticino) were recorded for 12 sites distributed over Switzerland (Riesen et al., 1999). After radioactive decay, in 2007 only 1–35 Bq kg^{-1} are left. The ^{137}Cs activity for the flat reference sites near the valley bottom (1469–1616 m a.s.l.) was estimated as 146 ± 20 Bq kg^{-1} (Schaub et al., 2010). The investigated sites are located in close vicinity to the reference sites and at comparable altitude (1476–1670 m a.s.l.). Consequently, the maximum contribution of pre-Chernobyl ^{137}Cs might represent 20 % at reference sites.

Additionally, vertical migration must be considered. In literature migration values between 0.03 and 1.30 cm yr^{-1} are reported (Schimmack et al., 1989; Arapis and Karandinos, 2004; Schuller et al., 2004; Schimmack and Schultz, 2006; Ajayi et al., 2007). In the Urseren Valley, ^{137}Cs activity (Bq kg^{-1}) declines exponentially with depth. Therefore, for the conversion of ^{137}Cs measurements to soil erosion rates, the well-known profile distribution model (Walling et al., 2011) was adapted for the direct use with the ^{137}Cs activity profile (Konz et al., 2009, 2012). Moreover, since pre-Chernobyl ^{137}Cs is negligible the calculation of the erosion rates refers to the period 1986–2007. Due to the integrative and repeated measurement with the NaI detector, the errors associated with measurement precision are assumed to be largely cancelled out. However the error associated with the spatial variability of the reference inventory (±20 Bq kg^{-1}) were propagated through the conversion model in order to receive an upper and lower confidence interval for the resulting erosion estimates.

2.4 Spatial modelling of snow glide distances

We used the Spatial Snow Glide Model (SSGM, Leitinger et al., 2008) to predict potential snow glide distances for an area of approximately 30 km^2 surrounding our study sites. The SSGM is an experimental model, which includes the parameters: forest stand, slope angle, winter precipitation, slope aspect and the static friction coefficient μ_s (–). Slope angle and slope aspect were derived from the digital elevation models DHM25 and below 2000 m a.s.l. the DOM. The DOM is a high precision digital surface model with 2 m resolution and an accuracy of ±0.5 m at 1σ in open terrain and ±1.5 m at 1σ in terrain with vegetation. The DHM25 has a resolution of 25 m with an average error of 1.5 m for the Central Plateau and the Jura, 2 m for the Pre-Alps and the Ticino and 3–8 m for the Alps (Swisstopo). Winter precipitation was derived from the MeteoSwiss station located in Andermatt. We used the result from a QuickBird land cover classification with a resolution of 2.4 m (subsequently resampled to 5 m) as land cover input (Meusburger et al., 2010a). Combining this land cover map with a land use map (Meusburger and Alewell, 2009), it was possible to derive the parameter forest stand. To each of the 4 investigated land cover types a uniform static friction coefficient (μ_s) was assigned.

The static friction coefficient can be derived by:

$$\mu_\mathrm{s} = \frac{F_\mathrm{r}}{F_\mathrm{n}} \tag{6}$$

where F_n ($\mathrm{g\,m\,s^{-2}}$) is the normal force that can be calculated with

$$F_\mathrm{n} = m \cdot g \cdot \cos\alpha \tag{7}$$

where g is the standard gravity (9.81 $\mathrm{m\,s^{-2}}$), α is the slope angle (°) and m the weight of the snow glide shoe (in our study 202 g).

The initial force (F_r; with the unit $\mathrm{g\,m\,s^{-2}}$), which is needed to get the glide shoe moving on the vegetation surface, was measured with a spring balance (Pesola® Medio

1000 g) and multiplied with the standard gravity. To obtain representative values of F_r the measurement was replicated 10 times per sample site and subsequently averaged. The parameter estimates the surface roughness, which integrates the effect of different vegetation types and land uses on snow gliding. A detailed description of the model and its parameters has been provided by Leitinger et al. (2008).

Supplemented by snow glide measurements from this study, the SSGM (i.e. OLS regression equation) was refined to be valid also for north exposed sites and sites with *Alnus viridis*. Consequently, the revised SSGM is given by the equation:

$$\ln(\hat{y}) = -0.337 - 0.925x_1 + 0.095x_2 + 0.01x_3 + 1.006x_4 + 0.839x_5 + 0.076x_6 - 0.075x_7^2 \quad (8)$$

where $\hat{y}$ is the estimated snow-gliding distance (mm), x_1 is the forest stand (0; 1), x_2 is slope angle (°), x_3 is winter precipitation (mm), x_4 is slope aspect East (0; 1), x_5 is slope aspect South (0; 1), x_6 is slope aspect W (0; 1) and x_7 is the static friction coefficient. The revised SSGM was highly significant ($p < 0.001$) with a determination coefficient of 0.58 (adjusted R^2).

The model was then applied for the winter period 2009/10 (285 mm winter precipitation) and for the long-term average winter precipitation (430 mm winter precipitation, years 1959–2010).

3 Results and discussion

3.1 Snow glide measurements 2009/10

For each site the static friction coefficient as a measure for surface roughness was determined in autumn prior to the installation of the snow glide shoes. Lowest surface roughness was observed for the hayfields, followed by soil surface at sites covered with *Alnus viridis* on the north facing slope (Table 1). For the pastures without dwarf-shrubs, the two mean monitored values differed (μ_s = 0.37 and 0.68) but were similar to that of pastures with dwarf-shrubs (μ_s = 0.66–0.69). Slightly higher values were observed for

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the dense undergrowth of *Alnus viridis* sites on the south facing slope ($\mu_s = 0.70$ and 0.84). These static friction coefficients are within the range of 0.22–1.18 reported by Leitinger et al. (2008).

The mean measured snow glide distances (sgd) of the different sites varied from 2 to 189 cm (see Table 1). A main proportion of this variability can be explained by the slope aspect and the surface roughness (see Fig. 3). With increasing surface roughness (expressed as the static friction coefficient; μ_s) the snow glide distance declines. This decrease is more pronounced for the south facing slope ($\text{sgd} = -1547.2\mu_s + 172.93$; $R^2 = 0.50$; $p = 0.036$). For the north facing slope the snow glide distances and the variability are lower. Approximately 80 % of the observed variability on the north facing slope can be explained by the surface roughness ($\text{sgd} = -622.17\mu_s + 43.09$; $R^2 = 0.82$; $p = 0.033$). The identification of slope aspect and surface roughness as main causal factors for snow gliding, corresponds to the findings of other studies (In der Gand and Zupancic, 1966; Newesely et al., 2000; Hoeller et al., 2009). According to several studies on the seasonal snow–soil interface conditions (In der Gand and Zupancic, 1966; McClung and Clarke, 1987; Leitinger et al., 2008), snow gliding on south facing sites is preferential in spring, when high solar radiation leads to a high portion of melting water at the soil/snow interface. However, in autumn snow gliding primarily occurs when a huge amount of snow falls on the warm soil. In this case, north facing sites may be confronted with high snow gliding activity as well.

Our measured snow glide distances are comparable to those recorded by other researchers. For example Höller et al. (2009) monitored during a seven-year period in the Austrian Alps a snow glide distance of 10 cm within the forest, 170 cm in cleared forest sites and up to 320 cm for open fields. Margreth (2007) found total glide distances of 19–102 cm for an eleven-year observation period in the Swiss East Alps (south-east facing slope at 1540 m a.s.l.).

3.2 Soil erosion estimates

On the north facing slope an average RUSLE estimate of 1.8 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ with a maximum value of 3.8 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ was established (Table 2). The on average lower values as compared to the south facing slope (6.7 $\mathrm{t\,ha^{-1}\,yr^{-1}}$) are due to lower slope angles (thus lower LS-factor values) and C-factors (due to a higher fractional vegetation cover). This effect was not compensated by the on average higher K-factor of 0.40 $\mathrm{kg\,h\,N^{-1}\,m^{-2}}$ on the north facing slopes. The higher K-factor is caused by a 6 % higher proportion of very fine sand. The mean RUSLE based soil erosion rate for all sites was 4.6 $\mathrm{t\,ha^{-1}\,yr^{-1}}$.

The mean ^{137}Cs based soil erosion rates of 17.8 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ are approximately four times as high as the average RUSLE estimates. Congruent with RUSLE the ^{137}Cs-based average soil erosion rate on the north facing slopes is lower than on the south facing slopes (by 8.7 $\mathrm{t\,ha^{-1}\,yr^{-1}}$). The highest ^{137}Cs-based soil erosion estimates are found at two hayfield sites (h1 and h3) and the pasture sites at the south facing slope (p1 and p2). The higher RUSLE and ^{137}Cs estimates on the more intensely used, steeper and more snow glide affected south facing slope are reasonable. However, the high ^{137}Cs-based erosion rates (16.6 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ for A1N and 13.7 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ for A2N) at *Alnus viridis* sites are unexpected and will be discussed below.

In the winter 2012/13, for seven sites snow gliding, for one site a wet avalanche (pN) and for 4 sites no snow movement was observed (Table 3).The 4 sites without snow movement were all located at the north facing slope. The erosion rates estimated from the sediment yields of the snow glide deposit ranged from 0.03 to 22.9 $\mathrm{t\,ha^{-1}\,yr^{-1}}$. The maximum value was determined for the site h1 which is in agreement with the ^{137}Cs method. The winter 2012/13 was with 407 mm winter precipitation quite representative of the long-term average (i.e. 430 mm). On average, the pastured sites produced the highest measured sediment yields, followed by the hayfields and considerably lower values were observed for the pastures with dwarf shrub sites. Whether the observed difference is due to the different vegetation cover or due to site specific topography cannot be solved conclusively with the presented dataset. A wet avalanche was observed for the site pN. Interestingly, the estimated erosion rate of the wet avalanche deposit is with 1.97 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ smaller as most of the snow gliding related erosion rates. However, high erosion rates of 3.7 and 20.8 $\mathrm{t\,ha^{-1}}$ per winter due to wet avalanches have been reported in a study site located in the Aosta Valley, Italy (Ceaglio et al., 2012). There the snow-related soil erosion estimated from the deposit area were in a comparable range to the yearly total erosion rates assessed with the ^{137}Cs method (13.4 and 8.8 $\mathrm{t\,ha^{-1}\,yr^{-1}}$, Ceaglio et al., 2012).

3.3 Relation between soil redistribution and snow gliding

Our hypothesis was that the difference of the water soil erosion rate modelled with RUSLE and the total net erosion measured with the ^{137}Cs method correlates to a "winter soil erosion rate". This winter soil erosion rate comprises long-term soil removal by snow gliding and occasionally wet avalanches as well as snow melt. These "winter erosion rates" (difference of ^{137}Cs and RUSLE) ranged from sedimentation rates of 3.3 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ for a pasture with dwarf shrubs to erosion rates of 31 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ for the hayfield site h1.

Even though the sediment yield measurements in the snow glide deposit comprise only one winter, a relation ($p = 0.13$) between the snow glide erosion and the difference of ^{137}Cs and RUSLE could be observed ($R^2 = 0.39$; Fig. 4). The highest difference between ^{137}Cs and RUSLE based erosion could be observed for sites with high snow glide related sediment yield (except for the site h3). The resulting intercept might be either to a deviation of the weather conditions in the winter 2012/13 from the long-term average condition captured by the other methods or due to the impact of occasional wet avalanches and/or snow melt. For instance, following the USLE snow melt adaptation for R-factor would result in an on average 2.1 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ higher modelled erosion rate for all sites.

A further indication for the importance of snow gliding as soil erosion agent is given by the significant positive correlation between measured snow glide distance and the difference of ^{137}Cs and RUSLE, which we interpret as winter soil erosion rate (Fig. 5). The measured snow glide distance explained 64 % of the variability of the winter soil erosion rate ($p < 0.005$). However, this relation does not comprise the *Alnus viridis* sites that showed a high difference between RUSLE and ^{137}Cs based rates but a low snow glide distance. For the *Alnus viridis* sites, we have to expect that either one of the two approaches to determine soil erosion rates is erroneous and/or that we have another predominant erosion process not considered/or correctly parameterised in the RUSLE yet. A possible error related to the ^{137}Cs approach might be that ^{137}Cs was intercepted by leaf and litter material of *Alnus viridis*. Thus, a reference site with *Alnus viridis* stocking would be necessary which is difficult to find in our site because no flat areas exist with *Alnus viridis* stocking The observation of increasing soil erosion with increasing snow glide rates is congruent with the findings of Leitinger et al. (2008), who observed that the severity of erosion attributed to snow gliding (e.g. torn out trees, extensive areas of bare soil due to snow abrasion, landslides in topsoil) was high in areas with high snow glide distance and vice versa.

Even though all presented data are subject to high natural variability and methodological uncertainty the results imply that (i) the observed discrepancies between the RUSLE and ^{137}Cs based soil erosion rates are indeed related to snow gliding and (ii) snow gliding is an important agent of soil redistribution in the investigated sites and probably as well for other mountain sites with comparable topographic and climatic conditions

Further, it can be deduced that low surface roughness is correlated to high snow glide distances and these are again positively correlated to high observed differences between RUSLE and ^{137}Cs based soil erosion rates that we interpret as high winter soil erosion rates. Erosion estimates from sediment yield measurements of the snow glide deposit could confirm the partially high winter erosion rates. However, the presented relations might be highly variable, depending on soil temperature (whether the soil is frozen or not) during snow in, the occurrence of a water film that allows a transition of dry to wet gliding (Haefeli, 1948) and on the weather conditions of a specific winter. In addition, some of the investigated sites might also be affected by avalanches in other years.

3.4 Modelled snow glide distances

The modelled snow glide rates from the SSGM compared reasonably well with the snow glide measurements (Fig. 6). In agreement with the measured values all sites facing to the north revealed lower modelled snow glide distances. Largest discrepancies between the mean modelled and measured values of each site occur for the pastures on the south facing slopes (p and pw). The model overestimates the snow glide rates for these sites, which might be due to the effect of micro-relief in form of cattle trails at these sites. This small terraces (0.5 m in width) most likely reduce snow gliding but are not captured by the digital elevation model that is used for the SSGM. In general, modelled snow glide distances show smaller ranges than measured snow glide distances, due to the 5 m resolution of the model input data (Fig. 6). Interestingly, the occurrence of dwarf shrubs seems to reduce snow gliding to a larger extend as predicted by the model.

The modelled snow glide distance map (Fig. 7) is based on the long-term average of winter precipitation, which is with 430 mm clearly higher than the winter precipitation in 2009/10 with 285 mm (Fig. 6). The highest snow glide values were simulated on the steep, south facing slopes with predominate grassland and dwarf-shrub cover. Very high rates are also found on the lower parts of the south facing slopes that are used as pastures and hayfields. The smallest snow glide rates are located on the north facing slopes. The map clearly reproduces the effect of topography and aspect. Moreover, snow glide distances summarized for predominant land-use types also reproduce the impact of vegetation cover (Fig. 8). The highest potential snow glide distances were simulated by the SSGM for the south facing hayfield and pasture sites while the *Alnus viridis* has on average decisively smaller snow glide distances. In contrast, on the north facing slopes there is no difference observed between the *Alnus viridis* – and the hayfield category. Here the pasture sites show the highest average snow glide rate. The interpretation of the differences between land use types is, however, restricted since systematically different topographic conditions are involved.

The topographic and climatic conditions in our valley resemble the environment under which the SSGM was initially developed; nonetheless further regular yearly measurement would be needed to improve the performance of the model in this area. In conclusion, the application of the SSGM highlighted the relevance of the snow gliding process and the potentially related soil erosion for (sub-) alpine areas.

4 Conclusions

The presented absolute magnitude of the snow glide related soil erosion rate is subject to high uncertainties and inter-annual variability. However, snow glide erosion estimated from the snow glide deposit (0.03–22.9 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ in the winter 2012/13) and the significant correlation between snow glide distance and "winter" soil erosion rates (difference between RUSLE and ^{137}Cs based soil erosion) highlights the need to consider the process of snow gliding in steep, scarcely vegetated alpine areas.

The application of the RUSLE model showed that for an accurate soil erosion prediction in high mountain areas it is crucial to assess and quantify the erosivity of snow movement. The Spatial Snow Glide Model might serve as a tool to evaluate the spatial relevance of snow gliding for larger areas. However, it would be recommended to additionally estimate the kinetic energy that acts upon the soil during the snow movement. This would allow for a direct comparison of rainfall erosivity and snow movement erosivity, and moreover its insertion into soil erosion risk models like RUSLE. The impact of snow movement on soil removal should moreover, be evaluated in context of predicted changes in snow cover e.g. an increase of snow amount for elevated (> 2000 m a.s.l.) areas (Beniston, 2006).

Further, we demonstrated that surface roughness, which is determined by the vegetation type and the land use, reduces snow glide rates particularly on the in general more intensely used south facing slopes. In turn snow glide rates are positively related to increasing soil loss for grassland sites. This is an important result with respect to soil conservation strategy since surface roughness can be modified and adapted through an effective land use management.

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Table 1. Parameters related to measured snow glide distance (sgd, SD = standard deviation based on 3–5 replicate measurements) for the investigation sites in the Ursern Valley, Switzerland. N indicates the sites on the north facing slope.

site	vegetation	slope (°)	initial force F_r ($\mathrm{g\,m\,s^{-2}}$)	static friction coefficient μ_s (–)	measured sgd (cm)	SD sgd (cm)
h1	hayfield	39	569	0.37	189	117
h2	hayfield	38	510	0.33	50	40
h3	hayfield	35	392	0.24	126	49
pw1	pasture with dwarf-shrubs	38	1030	0.66	34	19
pw2	pasture with dwarf-shrubs	35	1118	0.69	28	15
p	pasture	38	579	0.37	89	37
p	pasture	35	1109	0.68	64	40
h1N	hayfield	28	343	0.20	30	14
h2N	hayfield	30	608	0.35	8	1
pN	pasture	18	628	0.33	17	23
A1N	*Alnus viridis*	25	1050	0.58	2	1
A2N	*Alnus viridis*	30	451	0.26	28	9
A1	*Alnus viridis*	22	1550	0.84	14	18
A2	*Alnus viridis*	31	1197	0.70	60	46

Table 2. Measured site characteristics (SOC = soil organic carbon; vfs = very fine sand fraction), resulting RUSLE factors and soil erosion rates and ^{137}Cs based erosion rates for the investigation sites in the Ursern Valley, Switzerland.

site	slope (°)	SOC (%)	vfs (%)	silt (%)	clay (%)	*K*-factor ($\mathrm{kg\,h\,N^{-1}\,m^{-2}}$)	*P*-factor (–)	LS-factor (–)	*R*-factor ($\mathrm{N\,h^{-1}}$)	*C*-factor (–)	RUSLE ($\mathrm{t\,ha^{-1}\,yr^{-1}}$)	^{137}Cs ($\mathrm{t\,ha^{-1}\,yr^{-1}}$)
h1*	39	7.7	12.9	47.3	12.5	0.280	1.00	22.2	97.2	0.010	6.0	37.0
h2*	38	7.2	9.7	58.8	17.3	0.290	1.00	8.8	94.5	0.006	1.5	11.0
h3*	35	7.4	12.3	43.8	16.9	0.230	1.00	20.7	93.6	0.010	4.5	33.0
pw1*	38	6.9	6.3	63.5	10.8	0.320	0.90	12.6	91.7	0.040	13.3	6.0
pw2*	35	7.1	11.2	40.9	14.2	0.230	0.90	11.8	94.8	0.040	9.3	13.0
p1*	38	7.6	11.2	50.5	11.6	0.270	0.90	11.8	97.6	0.020	5.6	20.0
p2*	35	7.2	12.4	45.6	15.0	0.250	0.90	15.3	96.4	0.020	6.6	30.0
h1N	28	4.8	18.5	41.0	5.8	0.416	1.00	7.0	93.6	0.012	3.2	18.3
h2N	30	4.3	13.7	48.0	8.5	0.419	1.00	8.4	91.7	0.012	3.8	7.5
pN	18	6.2	17.5	38.7	10.2	0.369	1.00	1.1	97.2	0.012	0.5	7.2
A1N	25	3.8	16.1	43.8	9.7	0.399	1.00	5.3	93.6	0.003	0.6	16.6
A2N	30	6.8	18.7	39.7	9.6	0.389	1.00	8.4	91.7	0.003	0.9	13.7
mean of N facing sites	37	7.3	10.9	50.1	14.0	0.267	0.94	14.7	95.1	0.021	6.7	21.4
mean of S facing sites	26	5.2	16.9	42.2	8.8	0.398	1.00	6.0	93.6	0.008	1.8	12.7
mean of all sites	32.4	6.4	13.4	46.8	11.8	0.3	1.0	11.1	94.5	0.0	4.6	17.8

* indicated the sites from Konz et al. (2009).

Table 3. Snow movement related soil erosion derived from the difference of ^{137}Cs-based and RUSLE-based erosion rates (diff.) and from field measured sediment in snow glide deposits (sg erosion). For each snow glide deposit, the mean sediment yield estimate is based on several samples (*n*). SD = is the standard deviation for the resulting erosion rates based on the individual sediment yield samples and * indicates the sediment yield of a wet avalanche. Uncertainty diff. provides the uncertainty of diff. resulting from both the ^{137}Cs and RUSLE method.

site	RUSLE ($\mathrm{t\,ha^{-1}\,yr^{-1}}$)	^{137}Cs ($\mathrm{t\,ha^{-1}\,yr^{-1}}$)	diff. ^{137}Cs – RUSLE ($\mathrm{t\,ha^{-1}\,yr^{-1}}$)	Uncertainty diff. ($\mathrm{t\,ha^{-1}\,yr^{-1}}$)	sg erosion ($\mathrm{t\,ha^{-1}\,yr^{-1}}$)	SD sg erosion ($\mathrm{t\,ha^{-1}\,yr^{-1}}$)	*n*
h1	6.0	37.0	31.0	8.5	22.9	81.5	16
h2	1.5	11.0	9.5	7.7	3.2	1.9	3
h3	4.5	33.0	28.5	8.2	1.1	1.9	10
pw1	13.3	13.0	−0.3	10.9	0.8	0.5	3
pw2	9.3	6.0	−3.3	9.8	0.0	0.1	7
p1	5.6	20.0	14.4	8.5	16.7	6.8	11
p2	6.6	30.0	23.4	8.6	14.0	44.9	13
h1N	3.2	18.3	15.1	7.6	no snow glide	–	–
h2N	3.8	7.5	3.7	8.4	no snow glide	–	–
pN	0.5	7.2	6.7	8.0	1.97*	3.8	18
A1N	0.6	16.6	16.0	7.2	no snow glide	–	–
A2N	0.9	13.7	12.8	7.6	no snow glide	–	–

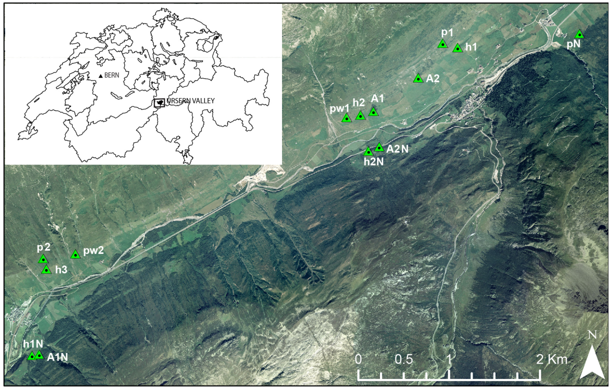

Fig. 1. The Ursern Valley in the Central Swiss Alps and the location of the 14 investigated sites – hayfields (h), pastures (p), pastures with dwarf shrubs (pw), and abandoned grassland covered with *Alnus viridis* (A), north facing slope (N).

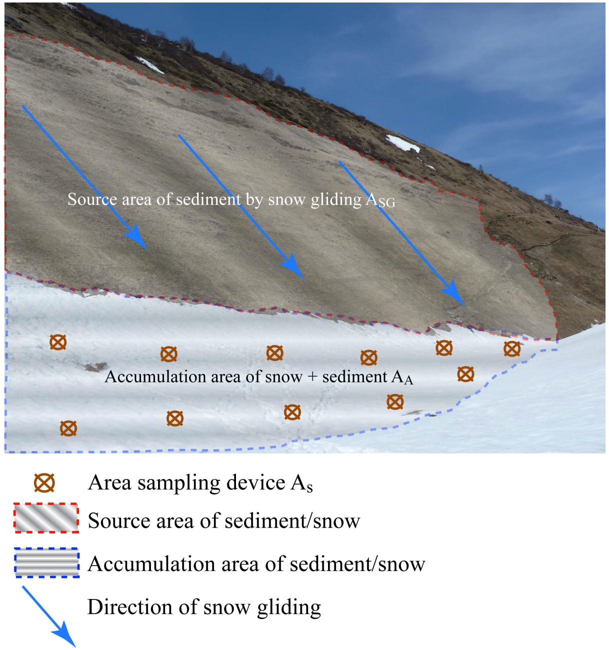

Fig. 2. Illustration of the procedure for snow glide related erosion rate assessment.

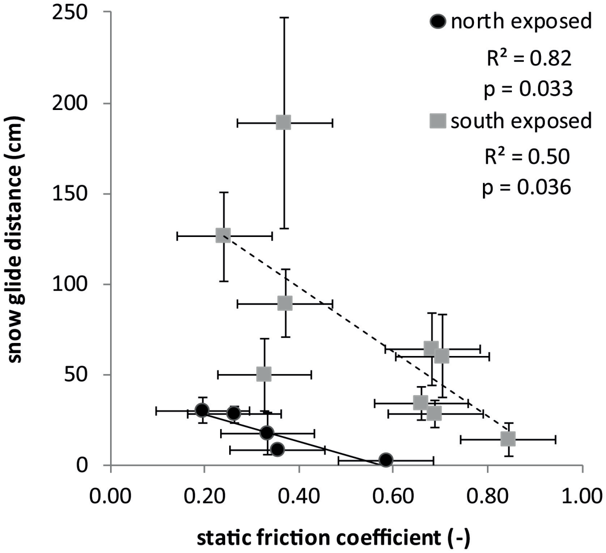

Fig. 3. Snow glide distance against the static friction coefficient for the south (squares) and north (dots) facing slope sites. *Y*-error bars represent the standard deviation of replicate measurements at one site. For the static friction coefficient an error of ±0.1 was assumed.

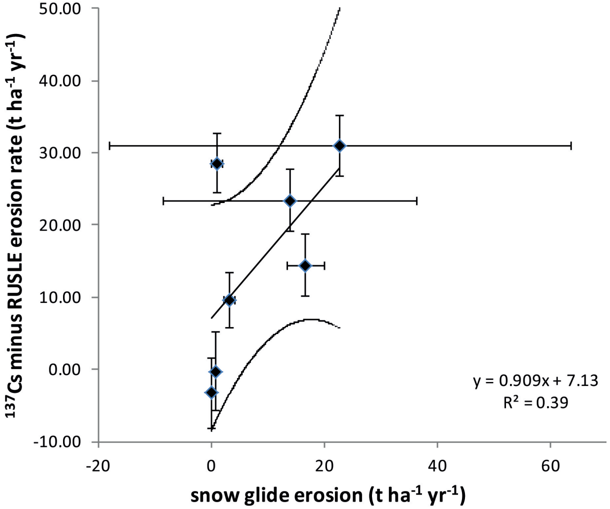

Fig. 4. Snow glide erosion estimated from the snow glide deposit sediment yield against the difference of the ^{137}Cs and RUSLE soil erosion rate (t ha^{-1} yr^{-1}). *Y*-error bars represent the uncertainty of both the ^{137}Cs and RUSLE estimates. *X*-error bars represent the standard deviation of erosion rates resulting from sediment several measurements within one snow glide deposit.

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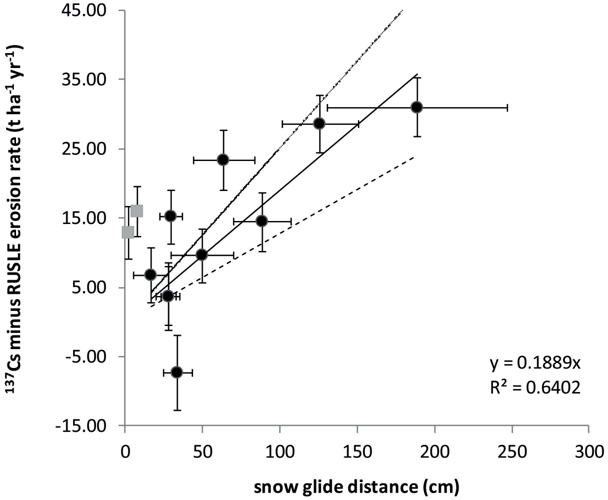

Fig. 5. Correlation of the cumulative snow glide distances (cm) measured for the winter 2009/10 vs. the difference of the ^{137}Cs and RUSLE soil erosion rate (t ha^{-1} yr^{-1}) for the grassland sites (dots, $n = 10$) and the *Alnus viridis* sites A1N, A2N (squares, $n = 2$). Y-error bars represent the error of both the ^{137}Cs and RUSLE estimates. X-error bars represent the standard deviation of replicate snow glide measurements at one site.

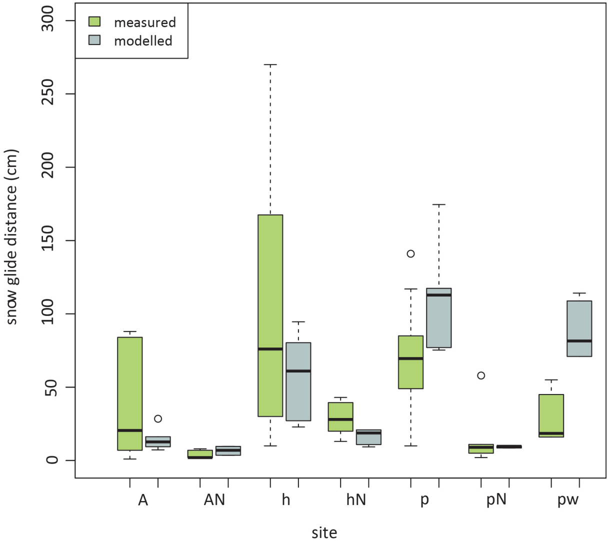

Fig. 6. Boxplot of measured snow glide distances and corresponding modelling results for different land use/cover types – hayfields (h), pastures (p), pastures with dwarf shrubs (pw), and abandoned grassland covered with *Alnus viridis* (A) – for the winter period 2009/10. N indicates the sites on the north facing slope.

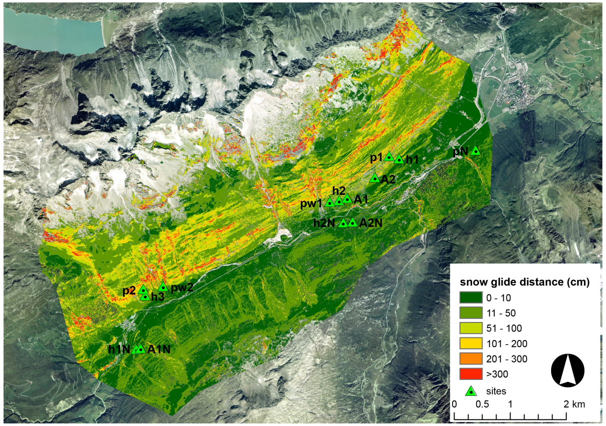

Fig. 7. Map of the potential snow glide distance (m) modelled by SSGM.

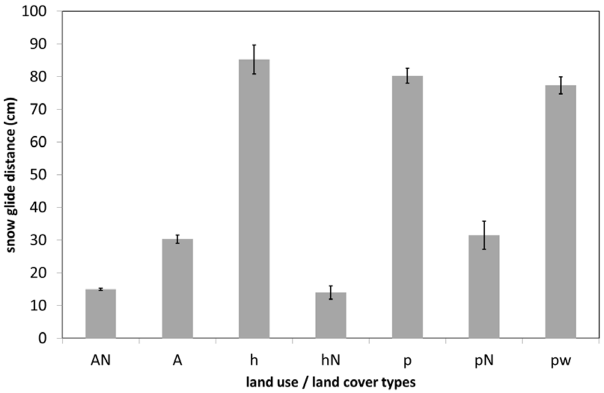

Fig. 8. Modelled potential snow glide distances (using long-term average winter precipitation) as mean for the whole catchment grouped by predominant land-use/cover types – hayfields (h), pastures (p), pastures with dwarf shrubs (pw), *Alnus viridis* sites (A). N indicates the sites on the north facing slope. Error bars indicate the standard error of the mean.