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Estimation of soil redistribution rates due to snow cover related processes in a mountainous area (Valle d'Aosta, NW Italy)

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Abstract

Mountain areas are widely affected by soil erosion, which is commonly linked to runoff processes. Also winter processes, like snow gliding and full-depth avalanches, may be important factors that can enhance soil erosion, however the role and importance of snow movements as agents of soil redistribution are not well understood yet. The aim of this study is to provide information on the relative importance of snow related soil erosion processes in comparison to runoff processes. In the study area, which is an avalanche path characterized by intense snow movements and soil erosion, soil redistribution rates were quantified with two methods: (i) by field measurements of sediment yield in an avalanche deposition area during 2009 and 2010 winter seasons; (ii) by Caesium-137 method, which supplies the cumulative net soil loss/gain since 1986, including winter and summer soil erosion processes. The soil erosion rates estimated from the sediment yield at the avalanche deposit area (3.2 and 20.8 Mg ha^{-1} event^{-1}) is comparable to the yearly erosion rates (averaged since 1986) estimated with the Cs-137 method (8.8–13.4 Mg ha^{-1} yr^{-1}). The soil accumulation rate estimated with data from the avalanche deposition area (28.2 and 160.7 Mg ha^{-1} event^{-1}) is even more intense than the yearly deposition rates estimated with Cs-137 (8.9–12.6 Mg ha^{-1} yr^{-1}). This might be due to the high relevance of the two investigated avalanche events and/or to the discrepancy between the long-term (since 1986) signal of the Cs-137 method compared to rates of 2009 and 2010. Even though the comparability is limited by the different time scale of the applied methods, both methods yielded similar magnitudes of soil redistribution rates indicating that soil erosion due to snow movements is the main driving force of soil redistribution in the area. Therefore winter processes have to be taken into account when assessing soil erosion as they significantly contribute to soil redistribution in mountainous areas.

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Estimation of soil redistribution rates due to snow cover related processes

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1 Introduction

Soils in mountain areas are fragile and often scarcely developed, mainly because of slope steepness and extreme climate conditions, and they are widely affected by erosion processes and soil slip involving mainly superficial horizons. Main drivers for soil erosion are topography, land cover, soil texture, rainfall patterns and land use (Wischmeier and Smith, 1978). Soil erosion is mainly linked to runoff processes, but, in mountain areas, also snow cover related processes, like snow gliding and full-depth avalanches, may be important factors that can enhance soil erosion (Konz et al., 2009). However, the role and importance of snow as a soil erosion agent are not well understood yet. In fact, the snow movements can exert considerable erosive forces on soils; in particular avalanches can transport consistent amounts of debris, especially when they involve the whole depth of snow or run onto snow-free areas (Luckman, 1978; Freppaz et al., 2006; Freppaz et al., 2010; Confortola et al., 2011). The rock and soil material, transported by snow movements, origins from the erosion of the underlying soil and bedrock in the release zone and along the track area (Gardner, 1983; Jomelli and Bertran, 2001). Deposits of debris from snow avalanches are common in mountain environments indicating the importance of avalanches as specific geomorphic agents.

Mapping and quantification of soil erosion under different land-use conditions have been evaluated in many projects for agricultural soils in lowlands. However, only few studies exist on soil erosion measurement and quantification in low-mountain ranges (e.g. Nearing et al., 1999; Leser et al., 2002; Gabriels et al., 2003; Prasuhn et al., 2007) or in alpine environments characterized by specific climatic and topographic conditions (Felix and Johannes, 1995; Descroix and Mathys, 2003; Isselin-Nondedeu and Bedecarrats, 2007; Konz et al., 2009, 2010, 2011; Meusburger et al., 2010). Moreover, most of the studies focus on soil-erosion measurement during the vegetation period, while only few works deal with soil erosion caused by snow related winter processes (Ackroyd, 1987; Bell et al., 1990; Kohl et al., 2001; Heckmann et al., 2005; Konz et al., 2009, 2011; Freppaz et al,, 2010). Hence, more data on soil erosion in alpine

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regions, for longer time periods and including also winter season, are needed (Konz et al., 2009).

Taking into account the soil redistribution process related to winter season, conventionally, it can be assessed by the measurement of sediments transported in the runout zones by snow movements (snow gliding and full-depth avalanches), considering both the debris and the fine material (e.g. Ackroyd, 1987; Bell et al., 1990; Kohl et al., 2001; Heckmann et al., 2005; Freppaz et al., 2010). On the other side the yearly soil erosion in mountain areas can be measured by isotopic techniques based on the use of fallout radionuclides "FRNs" such as ^{137}Cs, ^{7}Be and ^{210}Pb (Zapata, 2002; Mabit et al., 2008a). FRNs, in particular ^{137}Cs, have proven to be very powerful tracers of soil movements within the landscape, and this methodology can complement conventional approaches (Mabit and Fulajtar, 2007). The presence of ^{137}Cs in the soil is either due to nuclear weapon testing ('60s) and/or to the Chernobyl reactor accident in 1986. Input of ^{137}Cs through the Chernobyl reactor accident was highly dependent on the rainfall pattern which caused high (kilometre to regional scale) heterogeneity in ^{137}Cs distribution (Higgitt et al., 1992; Renaud et al., 2003). For a small catchment or single hill slopes an homogeneous rainfall pattern can be assumed. After deposition, ^{137}Cs is rapidly and tightly bound to fine soil particles and its redistribution is mainly caused by soil erosion as it moves with soil particles (e.g. Bonnett, 1990; Ritchie and McHenry, 1990). The use of ^{137}Cs measurements to estimate rates of erosion and deposition is based on comparison of the inventories at individual sampling points with a reference inventory, representing the local fallout input. The reference site is expected to show neither erosion nor deposition. A measured inventory for an individual sampling point less than the reference value is indicative of erosion, whereas an inventory greater than reference value is indicative of deposition (Walling and He, 1999). To convert ^{137}Cs measurements to quantitative estimates of erosion and deposition rates, many different methods exist, including both empirical relationships, and theoretical models and accounting procedures (Walling and He, 1999).

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The aim of this study is to quantify soil erosion and deposition rates due to snow related winter processes (snow gliding and full-depth avalanches) by conventional field measurements in a snow deposition area. Moreover the yearly soil redistribution rates in different sites of the study area will be assessed with the Cs-137 method, which yields the cumulative net soil loss/gain since 1986, including winter and summer erosion processes. Our hypothesis is that the combination of the two approaches will provide information on the relative importance of soil erosion related to snow movements in comparison to runoff processes.

2 Materials and methods

2.1 Study area

The watershed investigated (24.6 ha) is located in the north-western part of the Valle d'Aosta Region (NW-Italy), very close to the Mont Blanc Massif (4810 m a.s.l.) in the municipality of Courmayeur. The study area is an avalanche site called "Torrent des Marais", running on a west exposed slope, from 2115 m to 1250 m a.s.l. (Fig. 1). In this site full-depth, wet snow avalanches are frequent during the spring time, and sometimes also in late autumn, and the release and track areas are often characterized by intense snow gliding and glide cracks formation. All these processes are related with soil erosion. Avalanches in particular often involve the soil surface with the removal, subsequent transport and accumulation, in the deposition areas, of the upper horizons mixed with rocks and plant material. The avalanche release area (RA) is characterized by mean steepness of 30° and is covered by abandoned pastures. The track area (TA) becomes very channelled (>35° of inclination) and its coverage is composed mainly by grass. In the steepest areas, rocks and bare soil are frequent. However, the main deposition area (LDA) has a decreasing steepness and ends on an avalanche shed, constructed in the 70's to protect a regional road. Besides this main deposition area, there's a secondary smaller deposition area which is located at upper elevation (UDA)

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at 2015 m a.s.l., just below the release zone. A portion of the release area is covered with snow bridges (active avalanche defence structures) since 1974, and in this area (SB) the vegetation cover is mainly characterized by dwarf shrubs (*Vaccinium Myrtillus* and *Rhodondendron Ferrugineum*) and several larch (*Larix decidua*) seedlings. Just above the snow bridge, at 2110 m a.s.l., there's a flat area (ASB), where the inclination gently decreases, and then the slope above is again steep up to the top. Meteorological data are continuously recorded by an automatic weather station (2076 m a.s.l.) of the Ufficio Centro Funzionale (UCF) – Valle d'Aosta Region (VDA), located very close to the study area. The long-term yearly mean precipitation recorded at this station is 840 mm yr^{-1} (period 1995–2010) and the mean annual air temperature is +2.8 °C (period 1993–2010) (Source: UCF-VDA). The average cumulative annual snowfall is 275 cm at 1250 m a.s.l. (period 1937–1995) and about 450 cm at 2000 m a.s.l. (Source: SMS, 2003). The bedrock is constituted mainly by black argillic schists and calcareous sandstones and, in some places, by porphyritic granites.

During the first decade of May, 1986 (Chernobyl accident), north-western Italy was disturbed by both wet and dry radioactive fallout and the study area was affected by a precipitation estimated in 5–10 mm of rain. After a sampling campaign conducted in the Valle d'Aosta Region in 2001–2004 by ARPA Valle d'Aosta (Regional Environmental Agency), the ^{137}Cs concentration in the soil was estimated to be in the range 0–6000 Bq m^{-2} (Agnesod et al., 2006). Moreover in the close Piemonte Region, it was estimated that the contribution of Chernobyl wet deposition was the major part of the global inventory (84 %), while 9 % was attributable to pre-Chernobyl caesium (derived from atomic bomb testing in the atmosphere) and 7 % to Chernobyl dry deposition (Facchinelli et al., 2002). Because of the proximity between the two Regions, we can consider these data most likely attributable also to our study area. This is an important assumption because if the Chernobyl input is considerably greater than the input of ^{137}Cs associated with "60's bomb fallout", then the ^{137}Cs measurements will primarily reflect erosion occurring after 1986.

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2.2 Methodology

2.2.1 Snow sampling in the avalanche deposition area

Two full-depth gliding avalanche events were considered in this work: (a) one during winter season 2008–2009 (1 March 2009) and (b) the other in winter 2009–2010 (17 March 2010). Both snow avalanches caused soil erosion, with the formation of very dirty snow accumulations in the deposition zones (LDA-UDA) (Fig. 2). The release and track areas were calculated with GIS, on the basis of the georeferenced pictures taken after the avalanche events. The deposit area, by GPS measurements, and the snow depth, for calculating the volume, were determined in the field as soon as the safety of the area was judged adequate. For the purpose of sediment estimation, each avalanche deposit was surveyed two times: 17 March and 19 May during winter 2009; 2 April and 17 May during winter 2010.

Snow in the main avalanche deposition zone (LDA) was sampled according to a gridded design. During winter 2009 the sampling points were distributed on a 7 × 7 m grid square during the first sampling campaign (17 March ($n = 58$)) then on a 15 × 15 m grid square during the second campaign (19 May ($n = 10$)). Sampling in 2010 was conducted at a lower spatial resolution, using a 20 × 20 m grid square in both sampling events (2 April ($n = 16$), 17 May ($n = 6$)). The sampling points were mapped by GPS (accuracy <5 m). Surface samples (0.02 m depth) were collected on a constant area using a wooden made rectangular mask (0.15×0.15 m) and snow samples were collected at 0.20 m below the surface using a plastic core (0.15 dm^3). Moreover a snow pit was dug down to the ground in the avalanche deposit during spring 2009, in order to analyze the debris distribution at greater depth (Fig. 2).

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2.2.2 Estimates of snow related soil redistribution rates by avalanche deposit data

The samples were melted and filtered through a 0.45 µm filter, using a vacuum pump. The filtered material was dried (40 °C) and weighted to obtain the concentration of sediment (C) that was used to estimate the total amount of sediment in the avalanche deposit by multiplying with the avalanche volume (V). The sediment amount was calculated for both the avalanche surface layer (V = avalanche surface area × snow depth of the superficial layer (0.02 m)) and for the rest of the snow deposit (V = avalanche surface area × estimated mean avalanche depth in the field (2 m)). The average soil deposition rate was calculated dividing the total sediment load of each event by the deposition area. This mass accumulation rate was converted into a rate of soil accretion dividing the soil deposition rate by the unconsolidated debris density of 1200 kg m^{-3} (Freppaz et al., 2010). The average soil erosion rate for each event was calculated dividing the total sediment load by the sum of avalanche release and track areas.

2.2.3 Soil sampling along the avalanche path

Soil samples were collected during summer season 2010, using a 72 mm diameter soil core sampler, (Giddings Machine Company, Windsor, CO, USA). The site for the reference inventory (RS), that represents the original ^{137}Cs activity without soil redistribution processes, was selected very close to the study area in a flat and undisturbed position at 2000 m a.s.l. We took 11 soil profiles from the reference site: three soil samples, which were a bulk of three replicates taken within 1 m^2, were used to determine average profile distribution and maximum depth of ^{137}Cs, while eight samples were used to investigate its spatial variability and to determine the caesium-137 base line. For estimating soil redistribution rates, soil cores were collected in three sites (SB, RA, TA) along one altitudinal transect, except for the track area (TA) where we chose to sample two transects (TA1 and TA2) because of the wider extension of this area compared to the others. For each transect 5 cores were taken every 15 m of distance. From these

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cores the upper 9 cm were separated from the lower soil profile, in order to differentiate the physico-chemical properties of topsoil from the subsoil.

In the lower main avalanche deposition area (LDA) 7 samples were collected and bulked together every 5 cm, while three sites were sampled in the upper deposition area (UDA) and other three in the flat area above the snow bridge (ASB) (Fig. 1).

2.2.4 Soil samples pre-treatment and laboratory analyses

In total 62 soil cores were sampled, and from them 136 sub-samples were oven-dried at 40 °C, lightly ground and sieved (<2 mm). An aliquot of each sample was put into a 25-mL container (6.5 cm diameter; Semadeni25) and analyzed for 8 h with a Li-drifted Ge detector (GeLi; PrincetonGamma-Tech, Princeton, NJ, USA) at the Department for Physics and Astronomy, University of Basel. The size of the detector was 48 mm in diameter and 50 mm in length. The relative efficiency was 18.7 %. In order to reduce the amount of radiation from background sources into the environment, the samples were shielded by 4-cm-thick lead during measurement. The ^{137}Cs activity concentrations were determined using the Inter Winner 5 gamma spectroscopy software (Ortec, Oak Ridge, TN, USA). The energy calibration of the GeLi detector was done using a Eu-152 multi-source with peak line positions at 117.6, 347.6, 773.5, 1108.0 and 1408.9 keV. For efficiency calibration, three reference-samples provided by H. Surbeck (University of Neuchâtel) enriched with known activities of U-238, Th-232 and K-40, were used. These calibration samples were of the same geometry and a comparable density as our analysed soil samples. The resulting measurement uncertainty on ^{137}Cs peak area (at 661 keV) was lower than 15 % (error of the measurement at 2-sigma). The minimum detection activity for ^{137}Cs was 0.1 Bq kg^{-1}. In order to make sure that the gamma spectroscopy system is working correctly and yields reliable results, the reference material IAEA-375 was measured every second week.

Soil cores from each sampling site were roughly described during the sample preparation and 17 of them (for 46 sub-samples in total) were analyzed for the determination of the main physical and chemical properties. The measured physical parameters

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were: skeleton content (%), bulk density ($kg\,m^{-3}$), particle size distribution (%) measured by the wet sieving method for sand fractions and by the sedimentation method (using the SediGraph 5100 Particle size Analysis System) for the silt and clay fractions. The chemical parameters analyzed were: pH_{H_2O}, total organic (TOC) carbon content (%) measured by the RC612 Multiphase Carbon and Hydrogen/Moisture Analyzer, total nitrogen content (TN %) measured by the LECOCHN-1000 Carbon, Hydrogen and Nitrogen Analyser.

2.2.5 Conversion of ^{137}Cs measurements in estimates of soil redistribution rates

The profile distribution model is the most used for undisturbed stable soils, where the depth distribution of ^{137}Cs shows an exponential decline with depth that may be described by the following function (Walling and Quine, 1990; Zhang et al., 1990):

$$A'(x) = A_{\text{ref}}(1 - e^{x/h_o}) \quad (1)$$

where: $A'(x)$ = amount of ^{137}Cs above the depth x ($Bq\,m^{-2}$)
x = depth from soil surface expressed as mass between top and actual depth ($Kg\,m^{-2}$)
A_{ref} = ^{137}Cs reference inventory ($Bq\,m^{-2}$)
h_o = coefficient describing profile shape ($Kg\,m^{-2}$)

If it is assumed that the total ^{137}Cs fallout occurred in 1986 and that the depth distribution of the ^{137}Cs in the soil profile is independent of time, the erosion rate Y for an eroding point (with total ^{137}Cs inventory A_u ($Bq\,m^{-2}$) less than the local reference inventory A_{ref} ($Bq\,m^{-2}$)) can be expressed as (Walling and Quine, 1990; Zhang et al., 1990):

$$Y = 10/(t - 1986) \times \ln(1 - X/100) \times h_o \quad (2)$$

Y = erosion rate ($Mg\,ha^{-1}\,yr^{-1}$)
t = year of sampling

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1986 = because in Valle d'Aosta Region the contribution of Chernobyl wet deposition was the major part of the global inventory (84 %)
X = % reduction of ^{137}Cs total inventory in respect to the local ^{137}Cs reference value (defined as: $(A_{ref} - A_u)/A_{ref} \times 100$)

The profile distribution model is simple and easy to use. However, this model involves a number of simplifying assumptions and does not take into account the time-dependent nature of the ^{137}Cs fallout migration in the soil and the progressive evolution of the depth distribution of the ^{137}Cs within the soil profile after deposition from the atmosphere. Consequently, it is likely to overestimate rates of soil loss if long time periods are investigated (Walling and He, 1999). However, in our study area with ^{137}Cs input predominantly (>80 %) from Chernobyl (1986), the application of this model is most suitable because we can assume that the time span for migration of ^{137}Cs is too short. Statistical analysis of the data was carried out using SPSS 17.0 (SPSS Inc., Chicago, IL).

3 Results and discussion

3.1 Assessment of snow related soil deposition rates using the conventional approach

The frequency of ground avalanches in the investigated area seems to have increased: for each of the last four winters we had one documented event, while previous data recorded in the Regional Avalanche Cadastre, within the last four decades, indicate only few full-depth, wet snow avalanches. The last events took place during winter seasons with differing snow conditions (2007/2008: low snowfall; 2008/2009 and 2009/2010: high snowfall; 2010/2011: low snowfall).

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In the two considered events (2008/2009 and 2009/2010) the measured volumes and areas of the avalanche deposits were comparable (Table 1) and most part of the sediments was concentrated in the upper centimeters of the snow deposit (Fig. 2).

The snow related soil deposition rates, estimated by the avalanche deposit data, ranged between 28.2 and 160.7 Mg ha^{-1} event^{-1}; these values were comparable to data (9.7–240.8 Mg ha^{-1} event^{-1}) referred to an avalanche path located close to the study area (Freppaz et al., 2010). The mean soil accretion, resulting from the sediment accumulation was in the range 2.4–13.4 mm event^{-1} (Table 1). And considering that just one avalanche event occurred per season, we can assume that these data are rates of snow related soil deposition per year.

3.2 Assessment of snow related soil erosion rates using the conventional approach

In the considered events (2008/2009 and 2009/2010) the avalanche release and track areas had almost the same shape and the total area was considered as equal (Fig. 1, Table 1). The soil erosion rates, estimated by data from the avalanche deposits ranged between 3.2 and 20.8 Mg ha^{-1} event^{-1} corresponding to a soil layer of about 0.3–1.7 mm (Table 1). It was comprised into the wide range (1–100 Mg ha^{-1} yr^{-1}) reported by Bozhinskiy and Losev (1998) and referred to the annual removal of mineral material caused by avalanches in areas of Russia at different elevation zones. As for the deposition rates we can consider these data as yearly rates of snow related soil erosion.

3.3 Soil characterization of reference site and evaluation of the ^{137}Cs baseline level

In the reference site (RS) the upper horizons showed a well developed polyhedral and granular structure, while the subsoil had a weaker structure and a higher skeleton content (Table 2).

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The mass activity in the first 3 cm ranged between 28.8 and 72.0 Bq kg^{-1} and exponentially decreased to 8.7–16.1 Bq kg^{-1} in the 9–12 cm soil increment. No caesium was detected below the 12 cm layer. The reference site had a total mean ^{137}Cs activity equal to 141.6 Bq kg^{-1}.

Considering the average areal activity density, calculated on the bases of the soil density, most of ^{137}Cs (87 %) was accumulated in the upper 9 cm (Fig. 3). The total ^{137}Cs areal activity of the reference inventory points ranged from 2.62 to 4.45 kBq m^{-2}, and the average value of 3.59 kBq m^{-2} corresponded to the caesium baseline level, that was the residual amount left from the historical ^{137}Cs fallout inputs, in absence of erosion or deposition. This data was within the range (0–6000 Bq m^{-2}) of caesium concentrations in the soil, reported for the study area after a measuring campaign conducted by ARPA Valle d'Aosta between 2001 and 2004 (Agnesod et al., 2006). The coefficient of variation (22.3 %) for the reference inventory was within the range of results reported in other studies carried out on reference sites (Sutherland, 1991, 1996; Owens and Walling, 1996).

3.4 Assessment of soil deposition rates using ^{137}Cs approach

The deposition areas (UDA and LDA) and the site above snow bridge (ASB), compared with the reference area, showed a clear sedimentation process; the average deposition rate in ASB (8.9 Mg ha^{-1} yr^{-1}), even if not significantly ($p = 0.094$), was globally lower than the deposition areas (average of 11.7 Mg ha^{-1} yr^{-1}) (Fig. 4). In UDA the average total areal activity was 12.76 kBq m^{-2} with a maximum activity in the 3–6 and 21–24 cm soil layers (Fig. 5). In LDA the total areal activity was 13.33 kBq m^{-2} with a greater activity in the upper soil horizons (0–15 cm), and the maximum in the 10–15 cm soil layer, equivalent to 2.70 kBq m^{-2}. In ASB the ^{137}Cs activity was maximum in the upper soil layer, with an exponential decrease towards depth and a total average areal activity of 9.37 kBq m^{-2} (Fig. 6).

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The sedimentation rates in the avalanche deposition sites were estimated equal to 12.1 Mg ha^{-1} yr^{-1} (UDA) and 12.6 Mg ha^{-1} yr^{-1} (LDA) (Fig. 4). Taking into account the average bulk density of the different soil layers, the soil accretion was estimated at 1.0 mm yr^{-1} and 0.9 mm yr^{-1}, equivalent to a total deposition during the 24-year period (1986–2010) of 25.1 and 22.4 mm, in UDA and LDA, respectively. The yearly sedimentation rates measured by cesium were lower but comparable with the estimates done using data from the avalanche deposit area (28.2 and 160.7 Mg ha^{-1} event^{-1} with an estimated soil accretion ranging between 2.4 and 13.4 mm event^{-1}). In particular in LDA the effective ^{137}Cs value could be likely higher as the sampling points were chosen in a rather steep area in the deposition zone (greater than 15°), but not disturbed by human activity. In ASB the associated soil accretion rate was 0.8 mm yr^{-1}, equivalent to a total deposition during the 24-year period (1986–2010) of 20.2 mm. In the upper (UDA) and lower (LDA) deposition areas the soils, compared to all the other sites, were characterized by the highest skeleton content (52 %) and bulk density (1277 kg m^{-3}), while in the area above the snow bridges (ASB) soils had lower skeleton content (average of 19 %) and bulk density (average of 1003 kg m^{-3}) (Table 2). Considering the even lower amount of skeleton (12 %) found in the upper soil horizons of ASB, it seems that here mainly fine particles accumulate; therefore in this area, besides the runoff processes, snow gliding (and not avalanche activity), without enough force to transport stones, actively contributes to the total soil erosion, as shown also by the particle sedimentation visible after the snow melt (Fig. 7).

3.5 Assessment of soil erosion rates using ^{137}Cs approach

In the avalanche release (RA) and track areas (TA) the soils were frequently disturbed with the removal of the upper horizons and the exposure of the subsoil, while in the snow bridges area (SB) no evident erosion was present. Looking at the properties of the upper horizons in RS, RA, TA and SB, the soil density ranged between 659 kg m^{-3} in SB and 1073 kg m^{-3} in RA and the skeleton content is the highest in RA (41 %) and the lowest in RS (5 %). The high percentage of skeleton content, except for RS, could

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confirm that in RA and TA the deeper horizons became exposed to the surface after the erosion of the upper horizons, while in SB the soils were more likely disturbed during the construction of the snow bridge. The organic carbon content is higher in RS (4.1 %) and SB (4.9 %) and lower in RA (3.3 %) and TA (3.8 %), showing that in SB, where also the soil density is the lowest, the vegetation cover seems to have better stabilized the soil. (Table 2).

The mean ^{137}Cs activity in RA was 37.3 Bq kg^{-1}, while values of 74.0 Bq kg^{-1} and 61.4 Bq kg^{-1} were found in TA1 and TA2 transects, respectively. In SB the mean ^{137}Cs activity was equal to 62.8 Bq kg^{-1}, with an increasing trend down the slope. Converting the ^{137}Cs inventories to soil erosion rates, using the profile distribution model, the values confirmed that in these areas erosion phenomena occurred, except for the point 5 in SB. The SB site shows a decreasing trend in soil erosion rates from the highest to the lowest sampling point, with 30.0 Mg ha^{-1} yr^{-1} and −0.3 Mg ha^{-1} yr^{-1}, respectively (the negative value of −0.3 Mg ha^{-1} yr^{-1} means deposition) (Fig. 8). This phenomenon could be due to the protection effect of the avalanche defense structures. It seems that snow bridges have also an influence on soil erosion processes, allowing the colonization by shrubs and larch seedlings. In the other transects the erosion values are more variable and without any trends along the slope. Considering the mean erosion rates in the different areas no significant differences ($p < 0.05$) were found (Fig. 9) even if a lower value was observed in the TA (8.8 Mg ha^{-1} yr^{-1} vs. 13.4 Mg ha^{-1} yr^{-1}in RA and 12.6 Mg ha^{-1} yr^{-1} in SB)

These values are in the range (6–37 Mg ha^{-1} yr^{-1}) determined, also with the caesium-137 method, by Konz et al. (2009) for steep alpine slopes in the Central Swiss Alps, which are also partly heavily affected by avalanche activity. Taking into account the mean bulk density of the different soil layers, the erosion rates ranged between 1.0 and 1.9 mm yr^{-1} in TA and SB, equivalent to a total soil erosion, during the 24-year period (1986–2010) of 23.3 mm and 45.7 mm, respectively. These results are comparable to the erosion values estimated by data from the deposits of the two full-depth avalanche events (2008/2009, 2009/2010) considered in this study (Table 1): in fact

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the average basin mass removal of the two events was 12.0 Mg ha^{-1} with an estimated soil removal equal to 1.0 mm (0.3–1.7 mm event^{-1}).

4 Conclusions

Alpine regions are particularly susceptible to soil erosion because of their extreme climatic and topographic conditions. Avalanche paths are often places where soil is redistributed by snow movements. In fact the soil erosion and deposition rates estimated by considering the deposits of the two surveyed full-depth avalanches are considerable. In particular the snow related soil erosion rates estimated from the sediment yield at avalanche deposit area is comparable to the yearly erosion rates assessed with the Cs-137 method. The snow related soil accumulation estimated with data from the deposit area is even more intense than the yearly deposition rates assessed with Cs-137. This might be due to the disturbance of the lower deposition area (LDA) by human activity and/or to the discrepancy between the long-term (since 1986) signal of the Cs-137 method compared to rates of 2009 and 2010. Even though the comparability is limited by the different time scale of the applied methods, both methods yielded similar magnitudes of soil redistribution rates indicating that soil erosion due to snow movements is the main driving force of soil redistribution in the area. Moreover during the last few years the frequency of full-depth avalanches has increased if compared to previous decades. But also where avalanches don't release (ASB), the erosion and deposition of soil particles from the upper part of the basin is considerable and likely related also to snow gliding.

Therefore winter processes have to be taken into account when assessing soil erosion as they significantly contribute to soil redistribution in mountainous areas.

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References

Ackroyd, P.: Erosion by snow avalanche and implications for geomorphic stability, Torlesse Range, New Zealand, Arctic Alpine Res., 19, 65–70, 1987.

Agnesod, G., Operti, C., Zappa C., and Capodaglio, P.: Distribuzione comparata di Cs137 in diverse matrici ambientali sul territorio della Valle d'Aosta. ARPA (Agenzia Regionale per la Protezione dell'Ambiente), "Atti del III Convegno nazionale Controllo ambientale degli agenti fisici: dal monitoraggio alle azioni di risanamento e bonifica", Biella, 7-8-9 giugno, 2006.

Bell, L., Gardner, J., and DeScally, F.: An estimate of snow avalanche debris transport, Kaghan Valley, Himalaya, Pakistan, Arctic Alpine Res., 22(3), 317–321, 1990.

Bonnett, P. J. P.: A review of the erosional behavior of radionuclides in selected drainage basins, J. Environ. Radioactiv., 11, 251–266, 1990.

Boubakari, M. and Morgan, R. P. C.: Contour grass strips for soil erosion control on steep lands: a laboratory evaluation, Soil Use Manage., 15, 21–26, 1999.

Bozhinskiy, A. N. and Losev, K. S.: The fundamentals of avalanche science, Mitteilungen des Eidgenössisches Institute für Schnee- und Lawinenforschung, Translation of "Osnovy Lavinovedeniya", Leningrad, Gidrometeoizdat, 1987, editd by: Bartelt, C., 55, 227 p., 1998,

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Confortola, G., Maggioni, M., Freppaz, M., and Bocchiola, D.: Modelling soil removal from snow avalanches: a case study in the Italian Alps. Cold Regions, accepted, 2011.
Descroix, L. and Mathys, N.: Processes, spatio-temporal factors and measurements of current erosion in the French Southern Alps: A review, Earth. Surf. Proc. Land., 28, 993–1011, 2003.
Facchinelli, A., Magnini, M., Gallini, L., and Bonifacio, E.: ^{137}Cs contamination from Chernobyl of soils in Piemonte (North-West Italy): spatial distribution and deposition model, Water Air Soil Poll., 134, 341–352, 2002.
Felix, R. and Johannes, B.: Bodenerosionsuntersuchungen auf Testparzellen im Kalkhochgebirge, Mittlgn. Österreich. Geogr. Ges., 137, 76–92, 1995.
Freppaz, M., Lunardi, S., Maggioni, M., Valfrè, F., Bizzocchi, T., and Zanini, E.: Soil erosion caused by snow avalanches: preliminary results of two case studies in the Aosta Valley (NW-Italy), Poster Session, ISSW 2006, Telluride, Colorado, October 1–6 2006, 880–886, 2006.
Freppaz, M., Godone, D., Filippa, G., Maggioni, M., Lunardi, S., Williams, M. W., and Zanini, E.: Soil erosion caused by snow avalanches: a case study in the Aosta Valley (NW Italy), Arctic, Arctic Alpine Res., 42 (4), 412–421, 2010.
Gabriels, D., Ghekiere, G., Schiettecatte, W., and Rottiers, I.: Assessment of USLE cover-management C-factors for 40 crop rotation systems on arable farms in the Kemmelbeek watershed, Belgium. Soil Till. Res., 74, 47–53, 2003.
Gardner, J. S.: Observations on erosion by wet snow avalanches, Mount Rae area, Alberta, Canada, Arctic, Arctic Alpine Res., 15(2), 271–274, 1983.
Heckmann, T., Wichmann, V., and Becht, M.: Quantifying sediment transport by avalanches in the Bavarian Alps – First results, Zeitschriftfür Geomorphologie N. F., Suppl. 127, 137–152, 2002.
Higgitt, D. L., Froehlich, W., and Walling, D. E.: Applications and limitations of Chernobyl radiocaesium measurements in a Carpathian erosion investigation, Poland, Land Degradation & Rehabilitation, 3, 15–26, 1992.
Isselin-Nondedeu, F. and Bedecarrats, A.: Influence of alpine plants growing on steep slopes on sediment trapping and transport by runoff, Catena, 71, 330–339, 2007.
Jomelli, V. and Bertran, P.: Wet snow avalanche deposits in the French Alps: structure and sedimentology, Geograf. Ann., 83, 15–28, 2001.
Kohl, B., Brauner, H., and Markart, G.: Soil erosion due to avalanches: measurements on

HESSD
8, 8533–8563, 2011

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an avalanche cone, International Symposium on Snowmelt and Related Problems, 28–30 March 2001, Oslo, Norway, 38, 2001.

Konz, N., Schaub, M., Prasuhn, V., Baenninger, D., and Alewell, C.: Caesium-137 based erosion-rate determination of a steep mountainous region, J. Plant Nutri. Soil Sc., 172, 615–622, 2009.

Konz, N., Baenninger, D., Konz, M., Nearing, M., and Alewell, C.: Process identification of soil erosion in steep mountain regions, Hydrol. Earth Syst. Sci., 14, 675–686, doi:10.5194/hess-14-675-2010, 2010.

Konz, N., Prasuhn, V., and Alewell, C.: On the measurement of Alpine Soil Erosion on Plot scale, Catena, in press, 2010.

Leser, H., Meier-Zielinski, S., Prasuhn, V., and Seiberth, C.: Soil erosion in catchment areas of Northwestern Switzerland. Methodological conclusions from a 25-year research programme, Z. Geomorphol., 46, 35–60, 2002.

Luckman, B. H.: The geomorphic activity of snow avalanches, Geograf. Ann., 59, 31–48, 1977.

Mabit, L. and Fulajtar, E.: The use of ^{137}Cs to assess soil erosion and sedimentation processes: advantages and limitations, Book of the Extended Synopses of the International Conference on Environmental Radioactivity: From Measurements and Assessments to Regulation, IAEA Publication, 338–339. IAEA-cn-145, 2007.

Mabit, L., Benmansour, M., and Walling, D. E.: Comparative advantages and limitations of fallout radionuclides (^{137}Cs, ^{210}Pb and ^{7}Be) to assess soil erosion and sedimentation, J. Environ. Radioactiv., 99 (12), 1799–1807, 2008.

Meusburger, K., Konz, N., Schaub, M., and Alewell, C.: Soil erosion modelled with USLE and PESERA using QuickBird derived vegetation parameters in an alpine catchment, Int. J. Appl. Earth Obs., 12, 208–215, 2010.

Nearing, M. A., Govers, G., and Norton, L. D.: Variability in soil erosion data from replicated plots, Soil Sci. Soc. Am. J., 63, 1829–1835, 1999.

Owens, P. N. and Walling, D.: Spatial Variability of Caesium-137 Inventories at reference Sites: an Example from Two Contrasting sites in England and Zimbabwe, Appl. Radiat. Isot., 47, 7, 699–707, 1996.

Prasuhn, V., Liniger, H., Hurni, H., and Friedli, S.: Map of soil erosion risk in Switzerland, Agrarforschung, 14, 120–127, 2007.

Renaud, P., Pourcelot, L., Métivier, J.-M., and Morello, M.: Mapping of ^{137}Cs deposition over eastern France 16 years after the Chernobyl accident, Science Total Environ., 309, 257–264,

2007.
Ritchie, J. C. and McHenry, J. R.: Application of radioactive fallout caesium-137 for measuring soil-erosion and sediment accumulation rates and patterns – a review, J. Environ. Qual., 19, 215–233, 1990.
SMS: Atlante climatico della Valle d'Aosta. Società Meteorologica Subalpina, Torino, 239–241, 2003.
Sutherland, R. A.: Examination of Caesium-137 areal activities in control (uneroded) locations, Soil Technol., 4, 33–50, 1991.
Sutherland, R. A.: Caesium-137 soil sampling and inventory variability in reference locations: a literature survey, Hydrol. Process. J., 10, 43–53, 1996.
Walling, D. E. and He, Q.: Improved models for estimating soil erosion rates from caesium-137 measurements, J. Environ. Qual., 28, 611–622, 1999.
Walling, D. E. and Quine, T. A.: Calibration of caesium-137 measurements to provide quantitative erosion rate data, Land Degradation and Rehabilitation, 2, 161–175, 1990.
Wischmeier, W. H. and Smith, D. D.: Predicting Rainfall Erosion Losses: A Guide to Conservation Planning, Agriculture Handbook No. 537. USDA/Science and Education Administration, US. Govt. Printing Office, Washington, DC., 58, 1978.
Zhang, X. B., Higgitt, D. L., and Walling, D. E.: A preliminary assessment of the potential for using caesium-137 to estimate rates of soil erosion in the Loess Plateau of China, Hydrol. Sci. J., 35, 267–276, 1990.
Zapata, F.: Handbook for the Assessment of Soil Erosion and Sedimentation using Environmental Radionuclides, Kluwer Ac. Publ., Dordrecht, The Netherlands, 219, 2002.

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Table 1. Main characteristics of the two snow avalanches (season 2008/2009 and 2009/2010) with estimates of the sediment transported into the Lower Deposition Area (LDA) and of the relative soil erosion and accumulation rates.

AVALANCHE EVENTS	Winter 2008/2009	Winter 2009/2010
Release + track area (m^2)	60440	60440
Deposition area (LDA) (m^2)	6889	7810
Deposition volume (m^3)	10471	11822
Sediment concentration ($kg\,m^{-3}$)	122.41 (±47.00)	818.20 (±454.67)
Total sediment load (kg)	19449	125512
Soil deposition ($Mg\,ha^{-1}$)	28.2	160.7
Soil accretion (mm)	2.4	13.4
Erosion rate ($Mg\,ha^{-1}$)	3.2	20.8
Soil erosion (mm)	0.3	1.7

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Table 2. Main physico-chemical characteristics of the investigated soils (average values).

Site	Total Depth (cm)	Samples	Skeleton (>2 mm) %	Sand %	Silt %	Clay %	Bulk Density $kg\,m^{-3}$	pH	TOC %	C/N
RS	30–40	(0–18 cm)	5	50.0	40.2	9.8	908	5.4	4.1	10
		(18 cm +)	27	59.9	33.5	6.7	1198	5.3	0.7	7
RA	50–60	(0–9 cm)	41	35.4	38.2	9.7	1073	4.3	3.3	7
		(9 cm +)	47	37.9	34.6	10.8	1073	4.0	1.3	5
TA	50–60	(0–9 cm)	31	32.2	33.2	9.5	908	5.4	3.8	8
		(9 cm +)	42	33.5	30.2	11.4	1137	5.4	1.2	5
SB	40–50	(0–9 cm)	33	39.0	46.9	14.1	659	5.2	4.9	10
		(9 cm +)	38	38.1	42.1	19.8	1085	5.0	2.3	8
UDA	40–50	(0–30 cm)	43	45.5	40.8	13.7	1206	6.0	2.9	9
LDA	40–50	(0–50 cm)	60	56.1	37.3	6.6	1348	8.0	1.6	8
AS	30–40	(0–18 cm)	12	38.4	47.9	13.7	875	5.0	5.6	9
		(18 cm +)	27	49.0	37.8	13.3	1132	4.8	2.1	6

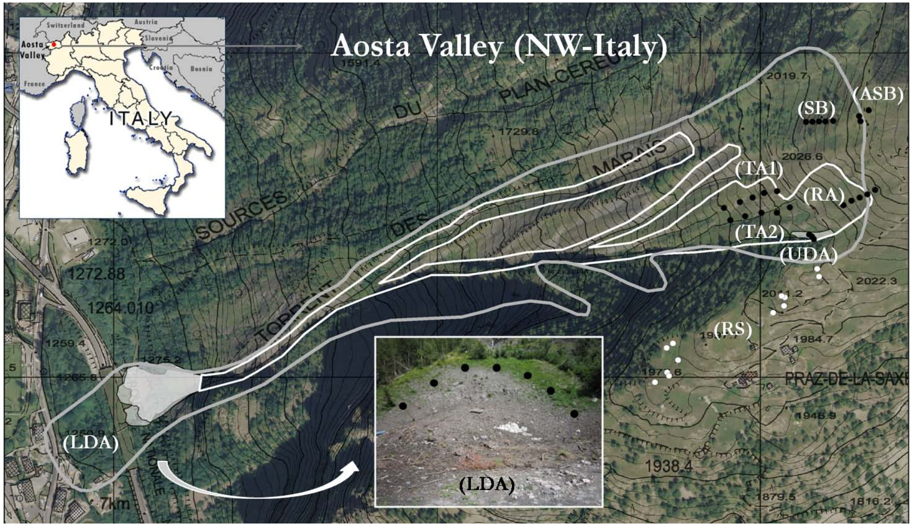

Fig. 1. Avalanche site called "Torrent de Marais – Mont De La Saxe" – Gray line: perimeter of the maximum event recorded in the Avalanches Cadastre of the Valle d'Aosta Region; white line: release and track perimeters of the events recorded in the seasons 2009 and 2010; gray areas (light and dark): avalanche deposits of the same events (Source: RAVDA-Snow and Avalanche Office); white circles: sample points for Reference Site (RS); black circles: sample points for soil redistribution rates for Release Area (RA), Track Area (TA), Snow Bridge area (SB), Above Snow Bridge area (ASB), Upper Deposition Area (UDA), Lower Deposition Area (LDA).

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Fig. 2. Snow deposit in the Lower Deposition Area (LDA): 2008–2009 avalanche event. On the right a particular of the sampling method for the deposit surface (top) and for the sub-superficial snow (bottom); on the left the pit dug into the deposit.

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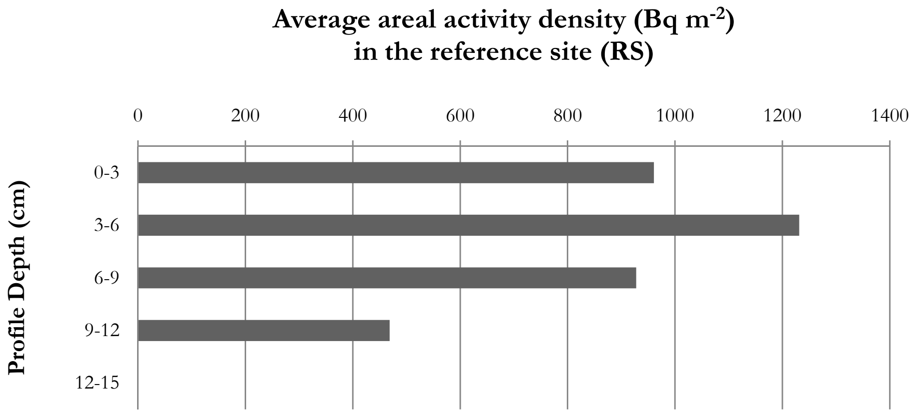

Fig. 3. Mean depth distribution of ^{137}Cs (Bq m^{-2}) in the soil of reference site (0–15 cm).

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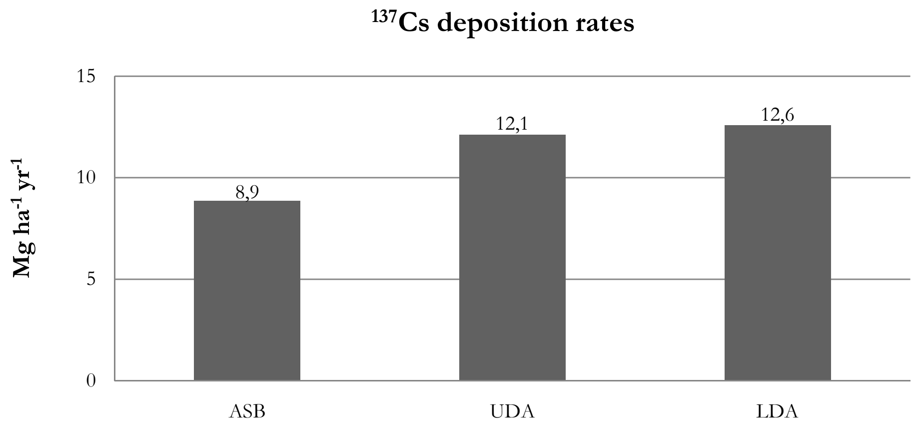

Fig. 4. Soil deposition rates in the area Above the Snow Bridges (ASB), in the Upper Deposition Area (UDA) and in the Lower Deposition Area (LDA).

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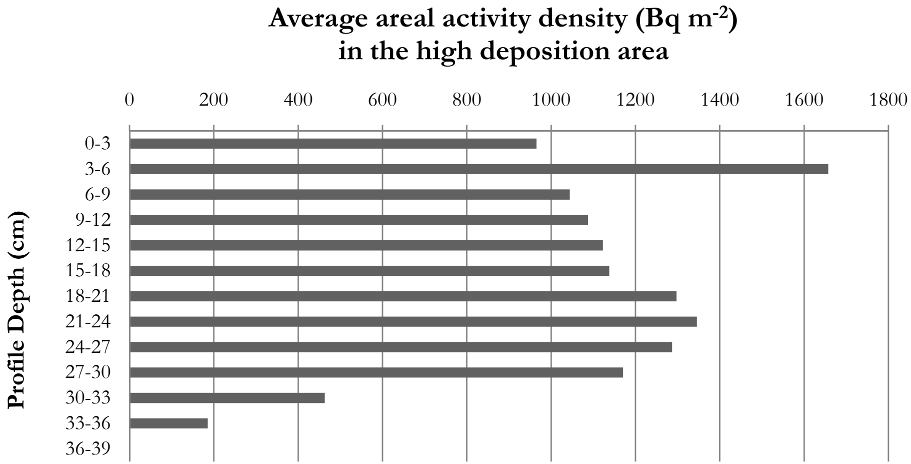

Fig. 5. Mean depth distribution of ^{137}Cs (Bq m^{-2}) in the soil of the upper deposition area (UDA).

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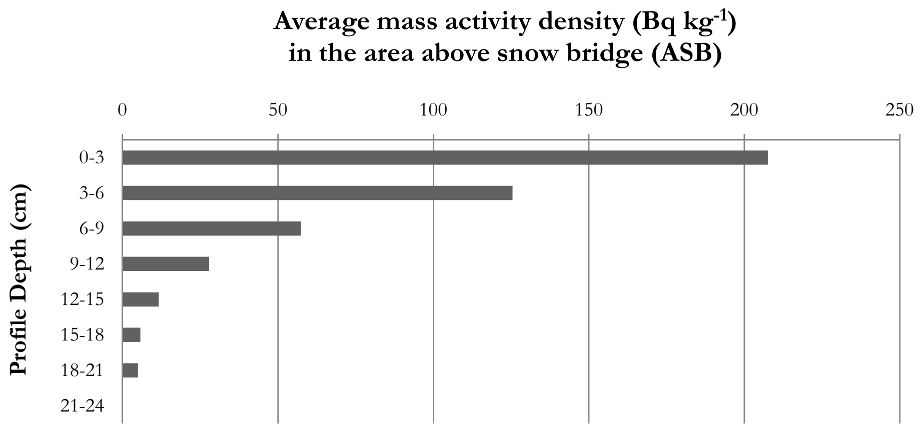

Fig. 6. Mean depth distribution of ^{137}Cs (Bq kg^{-1}) in the soil of the area Above Snow Bridge (ASB) (0–24 cm).

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Fig. 7. Particle sedimentation in the Above Snow Bridges (ASB) area after the snow melting.

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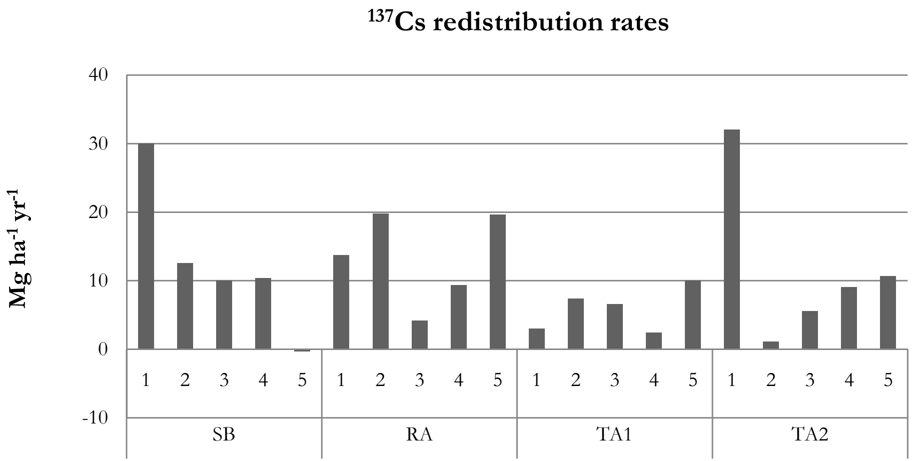

Fig. 8. Soil redistribution rates in the three site: Snow Bridge area (SB); Release Area (RA); Track Area (TA). Positive values indicate erosion, while negative ones indicate accumulation. In each transect n. 1 is the point at highest elevation and n. 5 is the point at lowest elevation.

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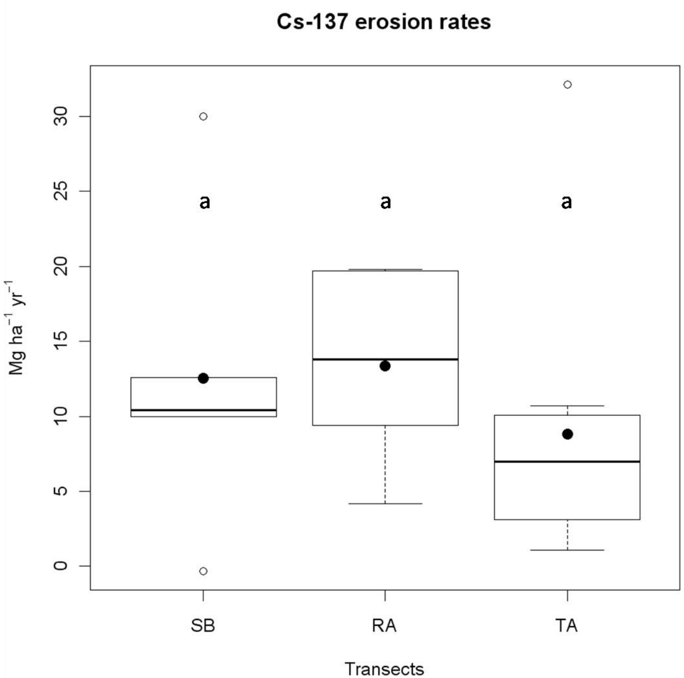

Fig. 9. Soil erosion rates found in the site: Snow Bridge area (SB); Release Area (RA); Track Area (TA), that includes the mean value of all the points belonging from T1 and T2. The full dark points indicate mean values.

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