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Soil Erosion Caused by Snow Avalanches: a Case Study in the Aosta Valley (NW Italy)

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Abstract

Snow avalanches can exert considerable erosive forces on soils. If a snow avalanche flows directly over bare ground, basal shear forces may scrape away and entrain soil. Soil material entrained by the avalanche is transported to the deposition zone, changing the chemical composition of the soils and potentially contributing to unique landforms. The quantity of soil material eroded and accumulated depends on avalanche characteristics and on morphological features, as well as soil properties and vegetation cover.

We monitored a channeled avalanche path in the Aosta Valley of NW Italy in order to assess the contribution of avalanche debris to the formation of soils in the runout zone. Sediment concentration estimates and measurements of the avalanche deposit volumes were used to estimate the total sediment load. The collected sediments were separated into fine sediments (<2 mm) and large (>2 mm) organic and mineral fractions. Results, obtained from the winter seasons of 2006, 2007, and 2008, showed that the amount of sediment deposited on the preexistent soil at the foot of the avalanche path was mainly the fine sediments fraction. The total carbon and nitrogen content in the fine sediment fraction ranged respectively from 6.6 to 9.0% and 0.37 to 0.42%. The total sediment load transported out of the 3.5 km^2 basin was estimated to be 7585 kg in 2006, 27,115 kg in 2007, and 2323 kg in 2008. This mass transport resulted in basin averaged denudation rates ranging from 0.67 g m^{-2} $event^{-1}$ in 2008 to 7.77 g m^{-2} $event^{-1}$ in 2007. Annual accumulation in the runout zone was 240 Mg ha^{-1} in 2006, 38 Mg ha^{-1} in 2007 and 10 Mg ha^{-1} in 2008. The inorganic N concentration of the snow in the runout zone was significantly greater than in the starting zone and was correlated with the organic fraction accumulated by the avalanche.

By redistributing snow, avalanches not only redistribute water but also nutrients that can be available for plants in the growing season. Moreover, avalanche paths are places where soil accumulates in some areas and erodes in others, contributing to potentially unique pedo-environmental conditions.

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Introduction

Deposits of debris from snow avalanches are common in high-mountain environments. They result almost exclusively from dirty snow avalanches that erode, transport and deposit soil, organic material, and rock debris. Most avalanches start relatively free of debris and then pick up varying amounts of sediments *en route*, ultimately becoming debris avalanches or slides. These were sometimes termed ''dirty avalanches'' (Rapp, 1960) or ''mixed avalanches'' (Washburn, 1979). Dense avalanches have high shear strength, and their ''rigid plugs'' can support clasts as large as boulders (Blikra and Sæmundson, 1998).

Wet avalanches are prominent during spring melt in mountain environments. This period is intuitively suitable for avalanche erosion for two reasons (Gardner, 1983): (1) isothermal snow which is the product of melt-freeze metamorphism often produces full-depth avalanches in which direct contact between the moving snow and ground surface occurs; (2) spring snowpacks are sporadic in their distribution so that downslope areas traversed by avalanches may be snow-free and thawed.

Where avalanches involve the whole depth of snow or run onto snow-free areas they may incorporate large amounts of debris (Luckman, 1978). The rock and soil material transported by avalanches derives from the erosion of the underlying bedrock or soil in the starting zone or along the transition zone (Gardner, 1983; Jomelli and Bertran, 2001). Although the vegetation cover usually protects the underlying surface from erosion (Luckman, 1978), soils can be eroded in different ways, depending on the avalanche type. If full-depth avalanches predominate, and the flows interact directly with bare ground, then in the track zone soils are stripped off, appear fragmented or are highly degraded (Freppaz et al., 2003, 2006). Complex soil profile morphologies may occur along an avalanche path with both buried or truncated horizons (King and Brewster, 1978). If surface avalanches predominate, then soils in the transition zone are better preserved and the avalanche channels can be completely grass-covered (Bozhinskiy and Losev, 1998).

Avalanche activity creates a unique habitat where plant diversity is higher than in adjacent undisturbed sites because of the

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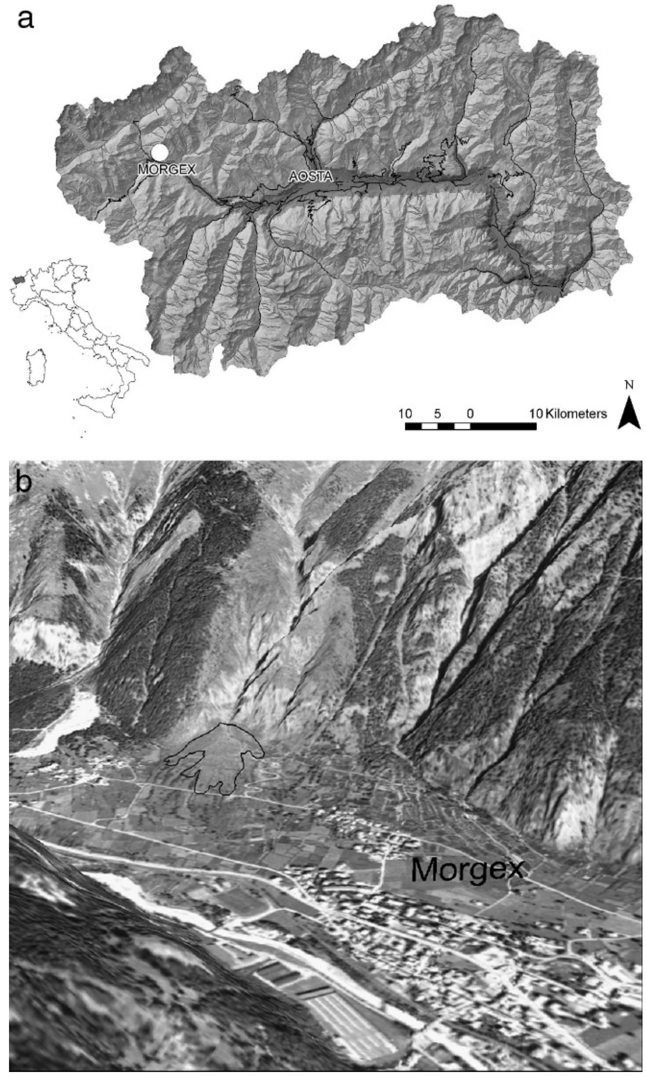

FIGURE 1. Location of the study site Lavancher in the municipality of Morgex (AO), 45°45′28″N, 07°2′17″E (authorization for use of image, no. 1072).

mechanical stress, extended snow-cover season, and a supply of plant debris and fine substrata (Rixen et al., 2007). Avalanche activity can also cause the alpine flora to extend below the treeline (Korner, 2003). Moreover, snow in the runout zone represents a non-flowing water storage during the winter, which is released when the temperature increases during the summer growing season (Luckman, 1977, 1988).

Previously published studies on this topic investigated the mass of sediment transported by avalanche events in the runout zone and relied on various observation periods (e.g. Ackroyd, 1987; Bell et al., 1990; Kohl et al., 2001; Heckmann et al., 2005). Most of the previous studies have dealt only with the transport of debris. Fewer studies have characterized the fine sediment fraction (<2 mm) and the nutrient quality of such material in relation to the soil development in the runout area (e.g. carbon and nitrogen content). Deposition of fines and organic matter from avalanche debris may contribute to the development of unique pedo-environmental conditions. Avalanche deposits are usually separated by soil horizons and some of them have an organic-rich matrix. Blikra and Sæmundson (1998) tried to estimate the avalanche frequency by the analysis of sedimentary successions.

TABLE 1

Avalanche path geomorphometry.

Parameter	Units	Value
Aspect	—	SE
Vertical fall	m	2000
Mean slope angle	deg	30
Starting zone angle	deg	42
Track zone angle	deg	38
Runout zone angle	deg	15
Basin area	m^2	3,500,000

The objective of this paper is to quantify and describe the composition of the fine sediment fraction and of the snow in the runout zone along a single avalanche path. To our knowledge, this is the first report to quantify the organic matter content and inorganic nutrients in avalanche debris and to relate these findings to soil development.

Materials and Methods

The monitoring of a channeled avalanche path was carried out in the Aosta Valley (NW Italy) during winter 2005–2006, 2006–2007, and 2007–2008 (hereafter referred to as 2006, 2007, and 2008). The Lavancher study site is located in the northwestern part of the Aosta Valley about 15 km SE from Mt. Blanc Massif (4810 m a.s.l.) and 20 km WNW from Aosta, close to the municipality of Morgex (Fig. 1).

The area is characterized by a precipitation maximum during autumn, with an average cumulative annual snowfall of about 700 cm (SMS, 2003).

The avalanche path is a partly channelized site, with a total vertical drop of about 2000 m and a track length of about 4500 m; the average inclination of the whole path is about 30° (Table 1). The starting zone is represented by a large (about 2.5 km^2) and rather homogeneous open bowl, mostly composed of alpine tundra with a low surface roughness (Barbolini et al., 2000). The vegetation cover is constituted by *Carex curvula*, *Elyna myosuroides*, *Festuca halleri*, *Geum montanum*, *Poa alpina*, *Salix herbacea*, and *Trifolium alpinum*.

Soil properties along the avalanche path have been determined through a pedological investigation. The soils were described (FAO, 2006), sampled, and classified according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2006). Moreover in 2008, in the runout zone, soil coring was carried out on a 50 × 50 m grid square (n = 36). All the soil samples were analyzed for pH, total C, and N using a CHN analyzer. The soil samples from the soil profiles were also analyzed for carbonates, texture, CEC, and exchangeable cations (SISS, 1985).

The snow deposits of individual avalanche events were mapped in the field as soon as further avalanche activity was judged to be minimal. We focused on three large slab wet avalanche events: 5 March 2006, 2 March 2007, and 6 May 2008 (Figs. 2, 3). For the purpose of volumetric and sediment estimation, each avalanche deposit was surveyed one to several times: winter 2006 (30 March, 12 April, 24 April, 29 April, 13 May, 8 June); winter 2007 (6 March, 17 April); winter 2008 (6 May).

We determined the volume of the avalanche deposit during winter 2006 using the protocols developed by Bell et al. (1990), previously discussed and evaluated by Schaerer (1988). During winter seasons 2007 and 2008 the avalanche deposits were

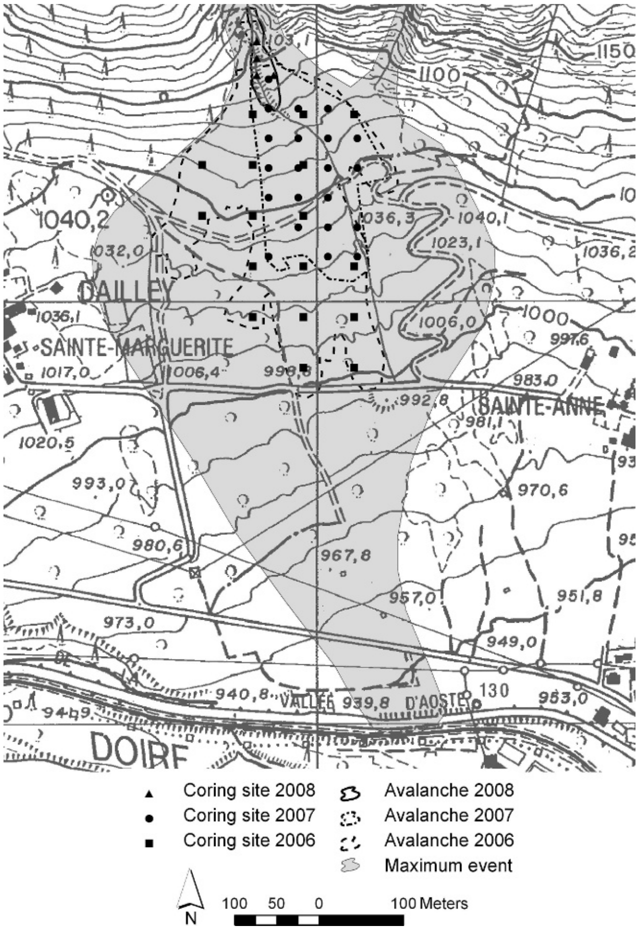

FIGURE 2. Avalanche deposits in the study site: 5 March 2006; 2 March 2007; 6 May 2008. The snow avalanche sampling grid is shown on the different avalanche deposits. Also, the extent of the maximum event recorded in the Avalanche Cadastre is shown.

FIGURE 3. Release area (a) and sediment deposits in the runout zone (b) of the avalanche event on 6 May 2008.

surveyed with kinematic GPS measurements. A base station, equipped with a radio modem device, was positioned outside the accumulation zone. The area was surveyed when the site was snow free to develop a base map ($n = 322$ points). After an avalanche, a GPS survey of the avalanche deposit was conducted with a second receiver mounted on a pole, equipped with radio modem receiving real-time differential corrections from the base station. The volume of the avalanche deposit was then calculated as the difference of the avalanche surface minus bare ground.

Three measurements were conducted in winters 2007 and 2008: a day after the avalanche event, one month later, and several months later, the last one in order to measure bare soil. The distance between the reference station and the rover antenna was never more than 500 m, with no signal loss between the two instruments. The horizontal accuracy of the coordinates was ±1.1 cm, while the vertical one was ±1.8 cm thanks to the RTK approach. The number of points collected during the first survey during winter 2007 (90) may be inadequate to describe a complex object such as an avalanche deposit, but the snowpack conditions at the starting zone did not allow a prolonged stay in the accumulation zone due to the risk of new avalanches.

The GPS data were processed using Leica Geo Office^{TM} and exported in ASCII format. Files containing the x, y, z coordinates of each point were then imported in Surfer 8^{TM} and interpolated to surfaces using the "Triangulation with Linear Interpolation" algorithm (Guibas and Stolfi, 1985; Lawson, 1977; Lee and Schachter, 1980). We used this approach in order to preserve the surveyed geometries and to reduce smoothing introduced by other kinds of estimators. Avalanche volume was then calculated from the volume included between the "bare soil" surface and the "deposit" surface obtained after the avalanche event.

The physical, chemical, and sediment properties of the avalanche snow in the runout zone were sampled using a gridded design. During winter 2006 the sampling points were distributed on a 60 × 60 m grid square (30 March [$n = 17$], 12 April [$n = 16$], 24 April [$n = 11$], 29 April [$n = 11$], 13 May [$n = 8$], 8 June [$n = 5$]). Sampling in 2007 and 2008 was conducted at higher spatial resolution, using respectively a 35 × 35m and a 20 × 20m grid square (6 March 2007 [$n = 21$], 17 April 2007 [$n = 12$]; 6 May 2008 [$n = 4$]) (Fig. 2).

The sampling sites were mapped by GPS in order to have their position georeferenced. We measured snow density at each sampling site at 10-cm depth using a 0.5-L stainless steel cutter (Cagnati, 2003). Snow was collected from the first 10 cm of the avalanche deposit at each point using a steel coring device that was 5 cm in diameter with a volume of 200 mL.

The snow samples were melted and then filtered through a pre-weighted 0.45 μm filter (regenerated cellulose filter, JCR). The filters were then dried (40°C, 24 hours) and weighed to obtain the mass of sediment. In 2007 and 2008 the filtered water was then analyzed for pH and major solute content. Ammonium concentration was measured by the dichloroisocyanurate method (Crooke and Simpson, 1971). Anions (NO_3^-, SO_4^{2-}, Cl^-, and

PO_4^{3-}) were analyzed using a Dionex DX-500 device equipped with an ASRS-ULTRA Self Regenerating chemical suppressor. Anions were separated on an Ion Pack AS9 column. The detection limit was less than 0.5 μeq L^{-1} and accuracy was less than 0.1 μeq L^{-1}.

The measured surface sediment concentrations were then used in conjunction with the measured avalanche deposit to estimate the total amount of sediment in the avalanche deposit. The exact distribution of sediment within the deposit cannot be determined using this method, which can give only a minimum estimate of the total mass transported. The total amount of sediment was calculated as V·C, where V is the avalanche sample volume in the runout zone (surface at the last sampling campaign × snow coring depth = 0.10 m), and C the average sediment concentration measured during the last sampling campaign, which was after the majority of the snow had melted.

The basin average mass removal rate for each year was calculated by dividing the total sediment load (kg) transported that year by the total basin area (Table 1). This mass removal rate was converted into a bedrock denudation rate (mm event^{-1}) by dividing the mass removal rate by the intact bedrock density of 2500 kg m^{-3}. Similarly, the yearly average mass accumulation rate was calculated by dividing the total sediment load (kg) transported in one year by the total deposit area. This mass accumulation rate was converted into a rate of soil accretion by dividing the mass accumulation rate by the unconsolidated debris density of 1200 kg m^{-3}.

The collected sediments were sieved with a 2 mm mesh in order to separate the rocks and the large organic debris from the fine sediment fraction (<2 mm). The pH and the total carbon and nitrogen in the fine sediment fraction were measured as in soil samples.

Average values are reported as mean ± 2SE. Correlations between selected parameters were carried out using Spearman or Pearson correlation, depending on homogeneity of variances (Levene test). Intra-year variability was tested with one-way ANOVA, sampling averages as variables, sampling dates as treatment. All statistical analyses were carried out with the software SPSS 12.0 Windows (SPSS, 2003).

Fine sediments and rock concentrations have been interpolated, in order to evaluate spatial trends, with the employment of geostatistical techniques (Matheron, 1970). Data have been processed by ArcGis Geostatistical Analyst (Johnston et al., 2001).

Results

SNOW AVALANCHE VOLUME AND DENSITY

The volume of the avalanche deposit on 5th March 2006 was estimated at 70,000 m^3, with a surface area of 61,400 m^2. The average snow density increased from 580 kg m^{-3} at the first sampling date (n = 17) to 630 kg m^{-3} at the last one (n = 5). The amount of water stored in the runout zone was therefore estimated to be 40,600 m^3.

The volume of the avalanche deposit in 2007 was similar to that of 2006 at 62,800 m^3, with a surface area of 29,426 m^2 (Figs. 6a and 6b). The average snow density during the first snow sampling (n = 21) was equal to 515 kg m^{-3} and to 480 kg m^{-3} during the second one (n = 12), due to the fresh snow accumulated on the avalanche debris. The amount of water released in the runout zone was equal to 32,335 m^3.

The volume of the avalanche deposit from 6th May 2008 was much smaller than the other two years at 2445 m^3, with a surface area of 2381 m^2 (see picture in Figure 3b). The average snow density of the deposit was equal to 670 kg/m^3 (n = 4). The amount of water released in the runout zone was equal to 1638 m^3.

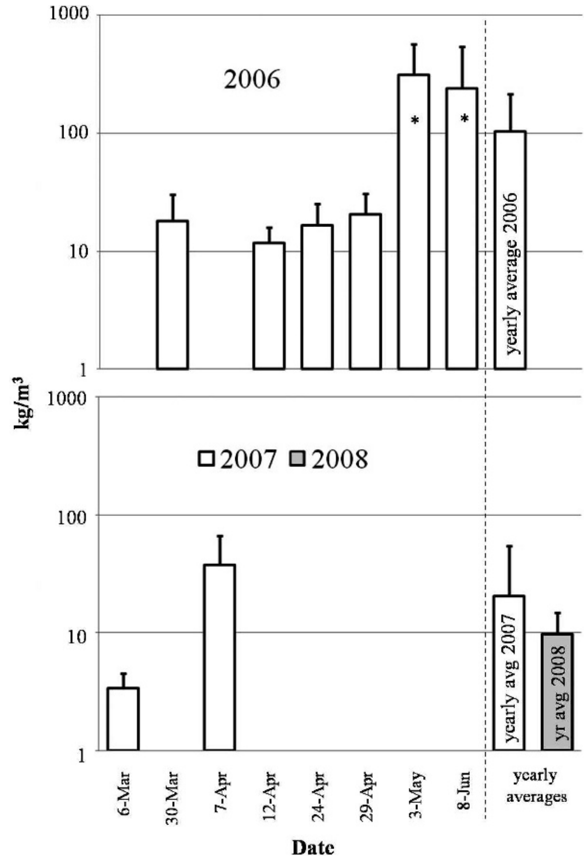

FIGURE 4. Near-surface average sediment concentration (kg m^{-3}) at different sampling dates in 2006, 2007, and 2008. Error bars are 2SE. Asterisks denote significant differences (sampling dates as treatment, $p < 0.05$) within the same year.

LOAD AND CHEMICAL-PHYSICAL CHARACTERISTICS OF THE SEDIMENTS

The sediment concentration in the top 10 cm was variable, though generally increasing with time due to the melting of snow that left the sediments behind. In 2006, the maximum near-surface concentration was recorded in the last sampling (240.8 kg m^{-3} ± 150.3) (Fig. 4). The total sediment load was estimated to be 7585 kg. This resulted in a mass accumulation of 240.8 Mg ha^{-1} in the runout zone, and a basin average mass removal equal to a 2.16 g m^{-2} event^{-1} (which corresponds to a layer of about 0.0009 mm). The mean sediment accumulation on the soil in the runout zone was equal to 20.1 mm. The percentages of the different fractions that constituted the sediments are reported in Figure 5. The fine sediment fraction (<2 mm) constituted the majority of the sediment (63%), with an average total carbon concentration of 9.0 ± 0.91%, a total nitrogen concentration of 0.42 ± 0.02%, and a pH around 7.5.

In 2007, the near surface concentration was 3.4 (± 0.6) kg m^{-3} in March and 37.5 (± 14.5) kg m^{-3} in April (Fig. 4). The sediment load due to this event was estimated to be 27,115 kg. This resulted in a mass accumulation of 37.5 Mg ha^{-1}, and a basin average mass removal equal to a 7.77 g m^{-2} event^{-1} (0.0031 mm). The mean sediment accumulation on the soil in the deposition zone was equal to 3.1 mm.

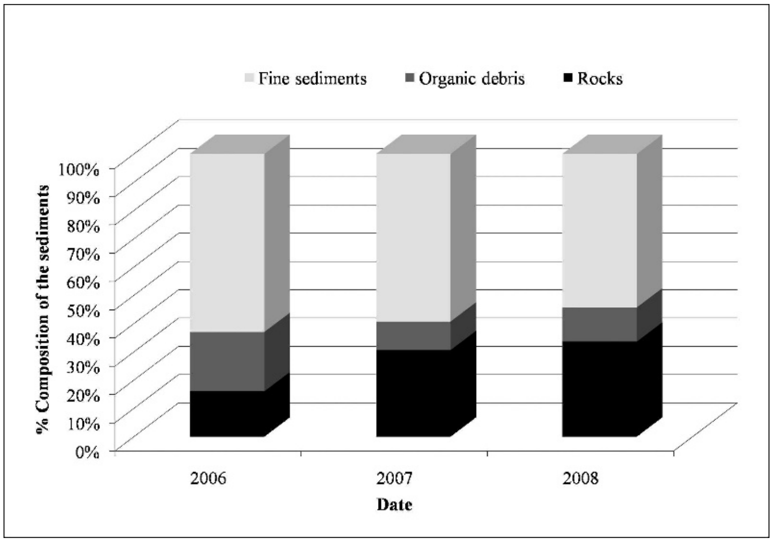

FIGURE 5. Average composition of the near-surface snow sediments (%) in the avalanche deposits for the three considered seasons: rocks (>2 mm) (black), organic debris (>2 mm) (gray), fine sediments (<2 mm) (white).

The percentages of the different fractions that constituted the sediments are reported in Figure 5. The fine sediment fraction again constituted the majority of the sediment (59.3%), with an average total carbon concentration of 6.6 ± 0.8% and a total nitrogen concentration of 0.37 ± 0.08%. The carbon content in the fine sediment fraction was significantly correlated with the amount of total nitrogen ($r = 0.890$, $p < 0.01$).

In 2008, the near surface concentration was equal to 9.8 (± 5.1) kg m^{-3}. The sediment load due to this event was estimated equal to 2323 kg. This resulted in a mass accumulation of 9.8 Mg ha^{-1}, and a basin average mass removal equal to a 0.67 g m^{-2} $event^{-1}$ (0.0003 mm). The mean sediment accumulation on the soil was equal to 0.8 mm. The percentages of the different fractions that constituted the sediments are reported in Figure 5. The fine sediment fraction again constituted the majority of the sediment (54.3%), with an average total carbon concentration equal to 6.4 ± 1.1%, a total nitrogen concentration of 0.42 ± 0.11%, and a pH around 7.6. The total carbon in the fine sediment fraction was again significantly correlated with organic nitrogen ($r = 0.890$, $p < 0.01$).

A noticeable feature of all the deposits was the development of rounded snow clods, as reported also by Ackroyd (1987) in New Zealand.

SNOW CHEMICAL CHARACTERISTICS

In 2007 the average N-NH_4^+ and N-NO_3^- concentrations in the snow were respectively 0.56 (± 0.81) mg L^{-1} and 0.34 (± 0.21) mg L^{-1}. There was a significant correlation between the organic debris content and concentrations of NH_4^+ ($r = 0.942$, $p < 0.01$; Fig. 7), Cl^- ($r = 0.714$, $p < 0.01$), NO_3^- ($r = 0.688$, $p < 0.01$), and PO_4^{3-} ($r = 0.796$, $p < 0.01$). Moreover, a significant correlation was found between the concentrations of NH_4^+ and NO_3^- ($r = 0.686$, $p < 0.01$), Cl^- ($r = 0.471$, $p < 0.01$), and PO_4^{3-} ($r = 0.444$, $p < 0.01$) (Table 2).

In 2008 the average N-NH_4^+ and N-NO_3^- concentrations in the liquid parts were respectively equal to 0.51 (± 0.61) mg L^{-1} and 0.29 (± 0.18) mg L^{-1}. In the avalanche snow a significant correlation was found between the organic debris (>2 mm) and the NH_4^+ ($r = 0.940$, $p < 0.01$; Fig. 7), SO_4^{2-} ($r = 0.900$, $p < 0.01$), NO_3^- ($r = 0.890$, $p < 0.01$), and PO_4^{3-} ($r = 0.960$, $p < 0.01$) concentrations. Moreover, a significant correlation was found between the NH_4^+ and the NO_3^- ($r = 0.994$, $p < 0.01$) and PO_4^{3-} ($r = 0.991$, $p < 0.01$) concentrations.

SOIL PROPERTIES

Soils in the release zone have been classified as Cambisols and Regosols. The soils on the track zone, frequently truncated, were classified as Regosols and Leptosols, while most of the track itself is constituted by rocks, with limestone inclusions. The soils in the runout zone have been classified as Regosols.

In the release zone the soil depth ranged between 30 and 40 cm. The texture was sandy loam. All the soils had a well developed A horizon, with depth ranging between 4 and 15 cm and a granular structure. The total carbon in the A horizons ranged between 2.3 and 9.0%, with a sharp decrease with soil depth. The pH in the A horizons ranged between 4.6 and 5.2. The total carbon was significantly correlated with the cation exchange capacity ($r = 0.885$, $p < 0.01$) and the pH ($r = -0.462$, $p < 0.05$). The rock content ranged between 10 and 20%.

In the track zone the soils were frequently truncated with the removal of the A horizons and the exposure of C and AC horizons. The pH of these horizons ranged between 4.9 and 7.4.

In the runout zone the soil depth ranged between 40 and 50 cm. All the soils had a well developed A horizon, with a depth ranging from 7 to 18 cm and a granular structure. The texture was sandy loam. The total C concentration in the A horizons ranged between 3.1 and 7.8%, with concentrations quite high also at greater soil depth (2.1–3.5% at the bottom of the soil profile). The pH in the upper horizons ranged between 7.4 and 8.0, comparable to the values recorded in the sediments transported by the avalanche. The total C was significantly correlated with the pH ($r = -0.772$, $p < 0.01$) and the cation exchange capacity ($r = 0.809$, $p < 0.01$). In the deposition zone the $CaCO_3$ content in the soils ranged between 4.5 and 30.1%, with consequently a significant correlation with soil pH ($r = 0.763$, $p < 0.01$). The rock content ranged between 40 and 50%.

In the runout zone, the concentration of rocks in the topsoil (0–10 cm depth) was higher than in the surrounding soils, while an opposite trend was found for the fine sediments (Figs. 8a and 8b).

Discussion

Snow avalanches are seen to act as geomorphic agents in several ways. "Clean" avalanches have indirect effects through the nourishing of glaciers or modification of snowmelt runoff patterns the sediments in the avalanche runout zone were transported there by any other means than the avalanches. In all the events, on leaving the snow-covered starting zones, the avalanches crossed snow-free, thawed surfaces, making direct contact with the ground.

Considerable variability in sediment concentration was found at all sampling dates. In particular, a significant increase in the near surface sediment concentration during spring time was observed during season 2006 and 2007, and attributed to the progressive surface melting that accumulated the transported debris at the surface, as reported by Bell et al. (1990). Moreover, the increase of the near surface sediment concentration from the avalanche deposit as the snowmelt proceeds may reveal that the sediments are not accumulated only on the surface of the deposit, but also at greater depth (Issler et al., 2008). This might indicate that some quantity of sediment is transported at the interface between avalanche flow and soil surface (Jomelli and Bertran, 2001). Bell et al. (1990), instead, reported a lower debris concentration in the subsurface snow samples (30 cm depth). This surface concentration of debris is explained by the same authors as: (1) later avalanches with higher debris concentrations, and (2) debris concentration through surface ablation of the snow deposits, as observed in our work.

The transported sediment distribution generally shows little segregation and no clear pattern at the avalanche surface. Jomelli and Bertran (2001) did not observe any longitudinal sorting according to the size or the debris morphology. Issler et al. (2008), instead, for a dry avalanche, found that the distal part of the deposits, which clearly corresponds to the head of the avalanche, did not contain soil particles. The erosion front reached the soil well after the head had passed the location. The shear stresses were apparently sufficient to erode the soil only for a short interval, diminishing towards the tail.

In our work the concentrations of debris measured in the snow samples were used in conjunction with the measured surface areas and volume of the avalanche deposits (0.10 m depth) to produce estimates of the total debris loads of the deposits. Given the very large volumes of snow involved and the potentially large variation in debris concentrations in the deposits, the sampling scheme can be expected to yield only very rough approximations of avalanche debris loads. The estimated values of mass accumulation in the runout zone (240.8 Mg ha^{-1}, 37.4 Mg ha^{-1}, and 9.76 Mg ha^{-1}, respectively, during winter 2006, 2007, and 2008), are in the high range reported by Bozhinskiy and Losev (1998), who indicated an annual removal of mineral material by avalanches per hectare of the runout and transition zones between less than 1 Mg and more than 100 Mg, according to the geographical conditions and geological structure of the terrain. The sampling scheme employed in this work is more sensitive to small clasts and fine material, therefore large clasts (>5 cm diameter) have gone unmeasured although they may have contributed significantly to the total sediment load. Jomelli and Bertran (2001), in the Ecrins Massif with granite lithology, found that gravel-sized debris (2 mm–2 cm) accounted for 47 to 61% of the total sediment weight. In their work an approximately linear relationship was found between the maximum size of the transported debris and the volume of the snow involved in the avalanche. The large organic debris constituted about 10–20% of the sediments, and was represented mainly by roots and grass cover. Turf and grass may be contained in the snow clods, which are formed during the avalanche motion (Bozhinskiy and Losev, 1998). The basin average mass removal (denudation rate) ranged between 0.0003 and 0.0031 mm $event^{-1}$, though the erosive processes are mainly concentrated in the track zone, where the transport rate largely exceeds the weathering rate, limiting the soil

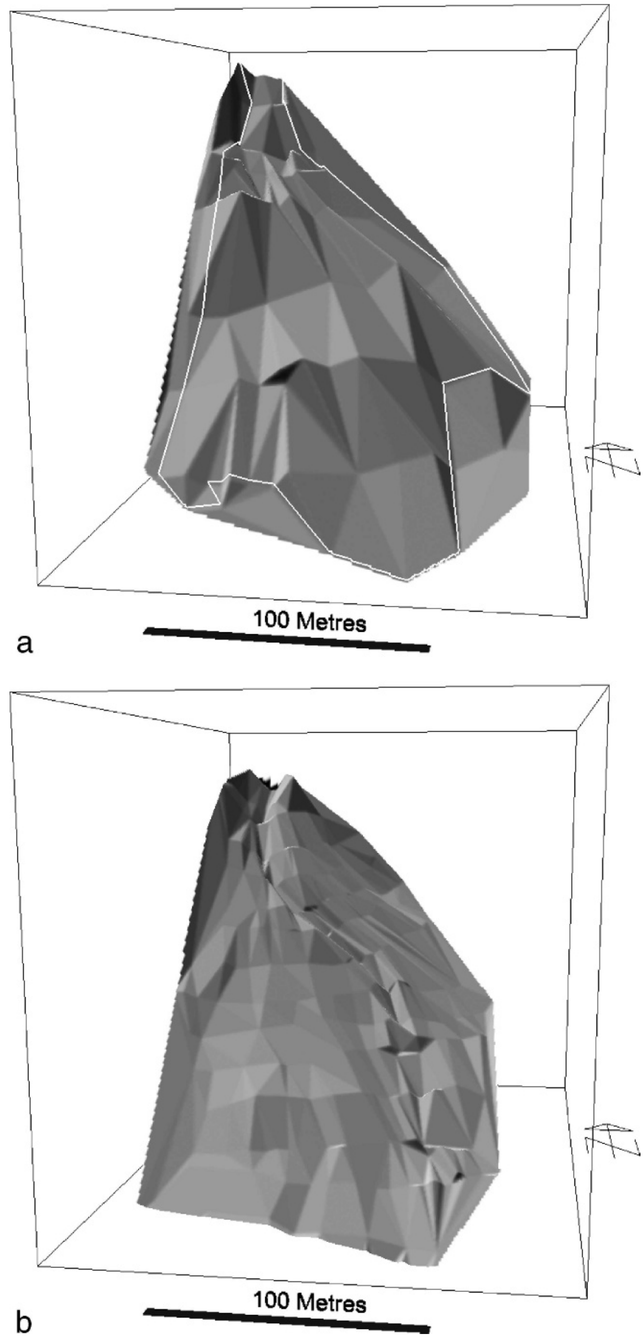

FIGURE 6. Digital elevation model, interpolated from GPS surveys, showing: (a) the avalanche deposit a few days after the event (6 March 2007), and (b) the bare soil measured after the snowmelt (27 July 2007).

(Luckman, 1978). Where avalanches involve the whole depth of snow or run onto snow free areas they can incorporate a large amount of debris and redeposit them further downslope, including abrasion of bedrock surfaces and formation of impact depressions ("plunge pools") at a slope foot (Gardner, 1983). The amount of sediments transported by avalanches was considerable. Luckman (1978) and Ackroyd (1986) have shown that, given optimum environmental factors (e.g. type of avalanche, debris available), even moderately sized avalanches can transport an exceptional quantity of debris. Our results support these earlier observations. The amount of sediment transported by the avalanches was considerable as was the snow volume. There was no evidence that

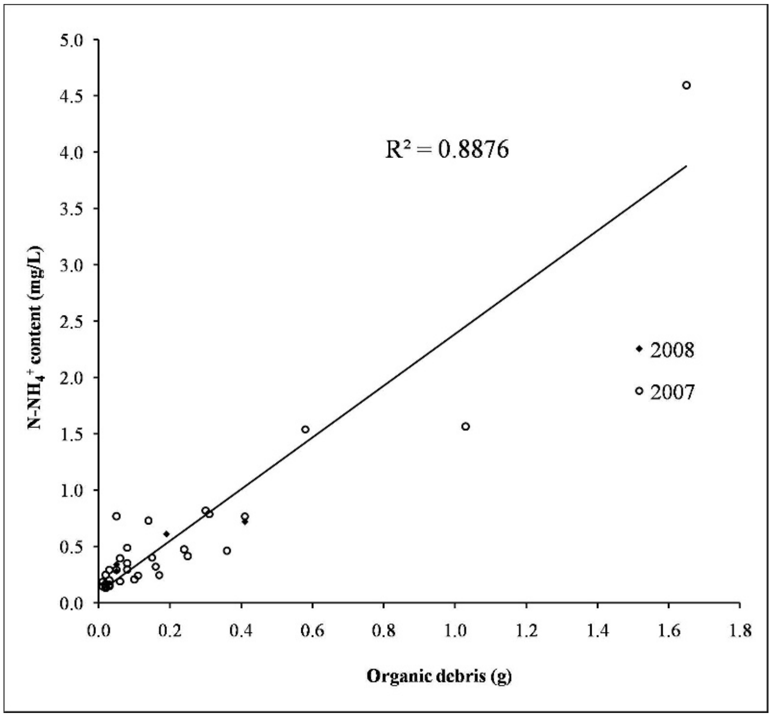

FIGURE 7. Relationship between ammonium concentration in snow and organic debris in the respective near-surface sediment ($p < 0.01$). Data for the snow avalanches in 2007 and 2008.

development. Our values are comparable to those calculated using the data reported by Bell et al. (1990) and Rapp (1960). The limited soil development in the track zone is in strong contrast to the thick and well developed soils in the release zone.

The chemistry of this avalanche snow was completely different from natural snow. Ion concentrations were 10–15 times higher than what is reported for natural alpine snowpacks (Nickus et al., 1997) (Fig. 4, Table 3). The distribution of chemicals in natural snowpacks usually reflects to a certain extent the chemical composition of air masses originating the precipitation, resulting in typical correlations between species such as chloride and sodium (Nickus et al., 1997; Filippa et al., in press). In the avalanche snow, we did not observe any such correlations. In spite of that, we observed a strong correlation between several compounds and the organic debris transported by the avalanche (Table 2, Fig. 7), suggesting that the latter may release a large amount of ionic species to the snow, which becomes enriched in NH_4^+, Cl^-, NO_3^- and PO_4^{3-}. The amount of ammonium released during the snow melting, obtained by multiplying the estimated water released and the ammonium concentration, was equal to 6.15 kg ha^{-1} in 2007 and 3.4 kg ha^{-1} in 2008. N inputs of this order of magnitude have been shown to cause episodic N saturation in several alpine ecosystems (Williams and Tonnessen, 2000), suggesting that this input may locally exceed the N retention capacity of soil. Although N saturation in the European Alps has never been suggested as an environmental issue at the landscape scale, avalanche runout zones may represent critical areas where N inputs from melting of avalanche snow may determine nutrient imbalances. Additionally, the runout zone of dirty avalanches with annual frequency such as the one studied here may be considered as natural experimental sites where long-term effects of augmented N deposition and release to the soil can be studied. At the regional scale, the impact of this local N deposition will depend on the extent of the runout zones and on frequency of avalanche events. So far, few studies have addressed the impact of nutrient redistribution by avalanches on soil.

TABLE 2

Correlation matrix (Pearson r) of selected chemical analyses in avalanche snow, data set 2007, $n = 33$.

	Rocks$^{(1)}$	Organic debris$^{(1)}$	C $^{(1)}$	N $^{(1)}$	N_{inorg}	N-NH_4^+	N-NO_3^-	Cl^-	PO_4^{3-}	SO_4^{2-}
Rocks$^{(1)}$	1									
Organic debris$^{(1)}$	0.553$^{(**)}$	1								
C $^{(1)}$	−0.100	0.214	1							
N $^{(1)}$	−0.103	0.447$^{(*)}$	0.890$^{(**)}$	1						
N_{inorg}	0.354	0.927$^{(**)}$	0.282	0.511$^{(**)}$	1					
N-NH_4^+	0.340	0.942$^{(**)}$	0.302	0.538$^{(**)}$	0.991$^{(**)}$	1				
N-NO_3^-	0.339	0.688$^{(**)}$	0.150	0.307	0.846$^{(**)}$	0.766$^{(**)}$	1			
Cl^-	0.226	0.714$^{(**)}$	0.215	0.428$^{(*)}$	0.816$^{(**)}$	0.797$^{(**)}$	0.737$^{(**)}$	1		
PO_4^{3-}	0.063	0.796$^{(**)}$	0.419$^{(*)}$	0.635$^{(**)}$	0.875$^{(**)}$	0.908$^{(**)}$	0.577$^{(**)}$	0.735$^{(**)}$	1	
SO_4^{2-}	0.074	0.446$^{(*)}$	0.139	0.218	0.606$^{(**)}$	0.574$^{(**)}$	0.614$^{(**)}$	0.443$^{(**)}$	0.503$^{(**)}$	1

$^{(1)}$ Measured in the sediment.

(*) Correlation is significant at the 0.05 level (2-tailed).

(**) Correlation is significant at the 0.01 level (2-tailed).

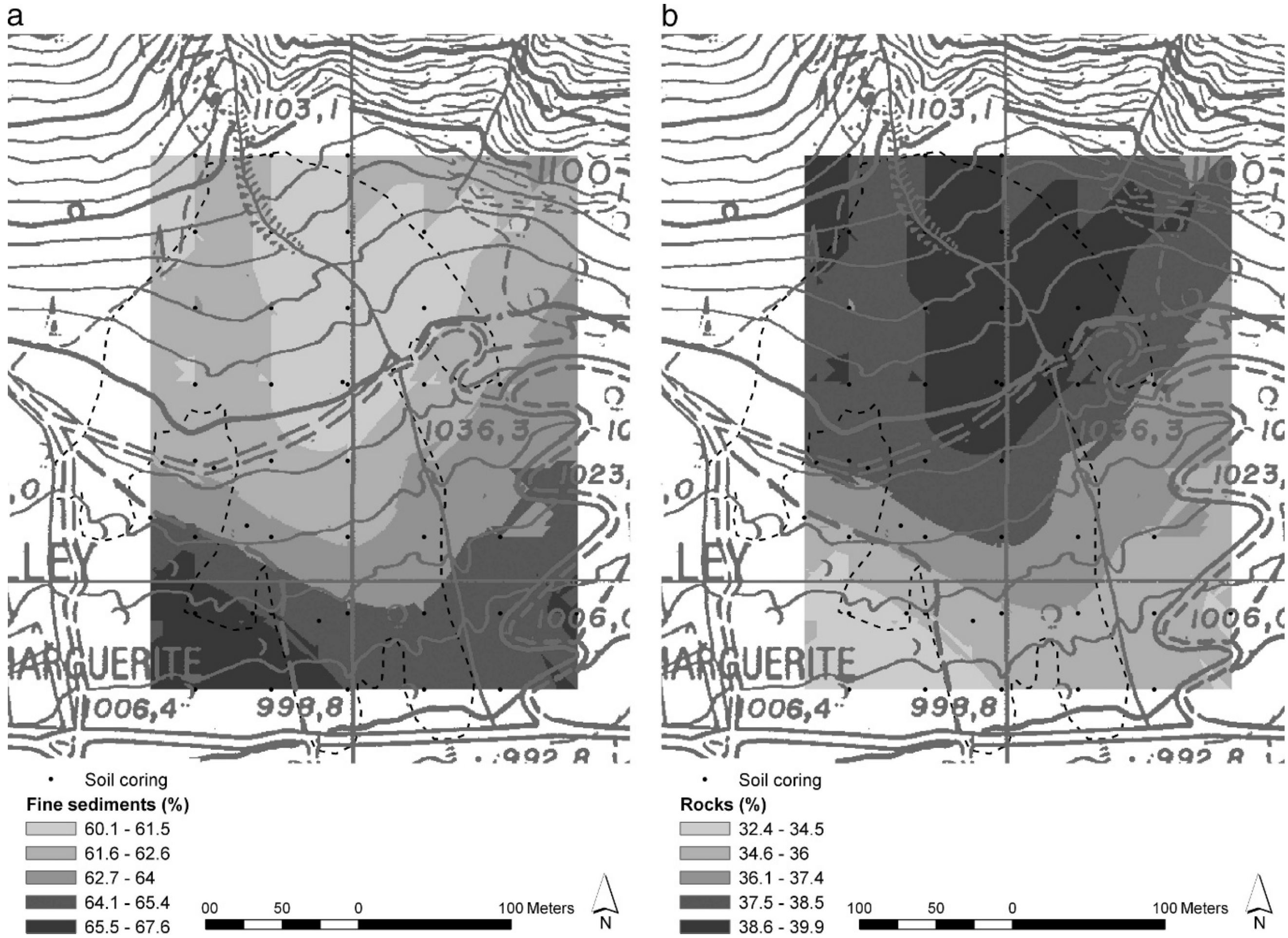

FIGURE 8. Spatial distribution of fine sediment (a) and rock content (b) in the topsoil of the runout zone (values in %).

The measured quantities of fine sediments (54–63%) were higher than that reported by Heckmann et al. (2002), who found a percentage of about 30% in an area constituted mainly by loamy soils. The high content of fine sediments in the material found in these avalanche deposits confirms that the catchment area is located on slopes characterized by a certain degree of soil development and that not only the surface of the avalanche path was eroded, but also the deeper horizons, especially in the track zone. Whole clods of soil were torn out along the avalanche path and deposited at the bottom of the valley. Such eroded areas, as well as the deposits, without vegetation, may become exposed to soil erosion by water also during snowmelt and during summer storms (Kohl et al., 2001; Heckmann et al., 2002), with the removal of part of the fine sediments deposited in the runout zone (Figs. 8a and 8b).

The fine sediments fraction was 7–9% of total carbon and 0.37–0.42% of total nitrogen. Therefore, it may significantly contribute to soil development in the avalanche runout zone, as

TABLE 3

Selected chemical properties of avalanche snow (pH, $N\text{-}NH_4^+$, $N\text{-}NO_3^-$, PO_4^{3-}) and sediment (pH, C, N). Data for comparison are reported respectively from natural snow and soil characteristics in the release and runout zones.

	Snow				Sediment		
Source	pH	$N\text{-}NH_4^+$ (mg/L)	$N\text{-}NO_3^-$ (mg/L)	PO_4^{3-} (mg/L)	pH	C (%)	N (%)
Avalanche 2006	n.m.	n.m.	n.m.	n.m.	7.5	9.0	0.42
Avalanche 2007	7.8	0.56	0.34	0.15	n.m.	6.6	0.37
Avalanche 2008	7.9	0.51	0.29	0.17	7.6	6.4	0.42
Natural snowpack*	5.9	0.06	0.08	<0.03			
Soil**					4.9	4.8	0.51
Soil***					7.7	5.5	0.44

* Data from the Regione Autonoma Valle d'Aosta (Filippa et al., in press).
** Soil A horizon in the release zone.
*** Soil A horizon in the runout zone.
n.m.: Not measured.

reported also for some case studies in Pakistan by de Scally and Gardner (1987). Bell et al. (1990) reported how fine organic and inorganic material is recognized to contribute to soil development in the avalanche runout zones which are used preferentially throughout the area of potato cultivation after snowmelt. The snow avalanches considered in this work transported a high quantity of debris, and the source of this material appears to be in the lower part of the starting zone and in the track zone, as reported also by Ackroyd (1987) and Issler et al. (2008). Complex soil morphologies may occur here with both buried or truncated horizons (King and Brewster, 1978). The sediments transported by the snow avalanche are partly pedogenized, with the incorporation of organic carbon and $CaCO_3$ also at greater depth in the soil profile. Further erosion in the deposits was also observed, with the removal of the finer material and the accumulation of rocks fragments (Figs. 8a and b). This may be due to the high frequency of the avalanche events, almost yearly, and to further erosion processes, due to summer rain events. The extent, volume, and area of maximum avalanche runout vary considerably from year to year. This variability results in the overlap of the erosional and depositional zone when multiple years are considered.

The snow density measured in the runout zones was in accordance with what reported by Ackroyd (1986), who, for deposits from wet snow avalanches, reported a value of 700 kg m^{-3}. Therefore, the water input during the snowmelt was considerable and, together with the sediment load, contributes to the determination of specific pedo-environmental conditions in the runout zone.

Conclusions

Results obtained from this study showed that the sediment transported by dirty snow avalanches was significant. The amount of material deposited in the runout zone was estimated equal to several Mg ha^{-1} of sediments, with no dependence on the size of the avalanche. In all the considered avalanche events, the fine sediment fraction represented the main fraction of the sediments collected, revealing the erosion of soil material mixed with organic debris. The chemical composition of the snow in the runout zone was significantly different from the natural snow, revealing a potential release of ionic species mainly by the organic debris transported by the avalanche. By redistributing snow, avalanches not only redistribute water but also nutrients that can be available for plants in the growing season. Moreover avalanche tracks are places where soil accumulates in some areas and erodes in others, contributing to potentially unique pedo-environmental conditions. Therefore, the analysis of the soil characteristics in the runout zone may be of interest in projects related with avalanches as environmental modifying factors.

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