Soil Use
and Management

Soil Use and Management, December 2013, **29**, 586–596 doi: 10.1111/sum.12063

Assessing the susceptibility of alpine soils to erosion using soil physical and site indicators

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Abstract

Soil erosion in mountainous regions is a key issue in land use planning, and this is particularly true in the Alps where intense anthropogenic influences at low elevations and abandonment in higher regions often coexist to affect soils. Natural hazard and risk assessment are essential given the density of settlements and associated facilities. Soil loss due to water erosion is very common and is becoming more frequent as a consequence of climate change which affects precipitation regimes, frequency of extreme meteorological events, snow melt and vegetation. In this study, we describe the production of a map showing susceptibility to soil erosion in the Aosta Valley (northwest Italian Alps). Most research on slope instability has focused on rock failures, but we investigated upper soil horizons by analysing chemical and physical properties, which could contribute to slope instability. The steps involved in creating the map are explained, and these involved GIS overlay, sampling, soil description, selection of relevant chemical and physical indicators of soil susceptibility to erosion, and overall erosion susceptibility assessment. The resultant indicator values correspond well with field observations to thus validate the methodology and demonstrate its usefulness in land use planning and management in Alpine areas.

Keywords: GIS, soil conservation, soil use and management, soil erosion prevention, soil structure, soil physical properties

Introduction

Mountain soils suffer from intrinsic vulnerability to natural stresses such as extreme rainfall (Giannecchini *et al*., 2007; Meusburger & Alewell, 2008) and changes in precipitation. Such phenomena are becoming more frequent as a consequence of climate change as stated in the IPCC report (2007) and can enhance soil and slope instability leading to considerable soil loss (Alewell *et al*., 2008) and movement by shallow landslides. Despite the shallow soil depth (<1 m), the areas affected by these movements can be extensive and the consequences can be loss of life and damage to buildings and services (Aleotti & Chowdhury, 1999; Alewell *et al*., 2008). Soil aggregates vary in their susceptibility to water erosion and saturation according to the amount and type of organic and inorganic bonding agents. Several laboratory indexes are available for quantifying soil structural resistance (Amezketa, 1999).

Land management practices can contribute to reducing soil susceptibility to erosion. For example, the input of organic matter aids conservation of soil structure and plasticity (Freppaz *et al*., 2002; Stanchi *et al*., 2008, 2009). Manuring promotes soil aggregation through enhanced bonding, leading to more stable aggregates and minimizing the effects of surface run-off (Lal, 2004). Vegetation can influence soil aggregate stability (Freppaz *et al*., 2002), thus reducing sheet and rill erosion. Large roots have a major physical effect (Roering *et al*., 2003), retaining soil on steep slopes, but finer roots and microflora (fungi) also promote soil and slope stability through improvements in soil structure and aggregate formation (Barni *et al*., 2007). Soils under undisturbed, continuous vegetation cover have favourable characteristics in terms of physical qualities. Terracing, a very common land management practice in Alpine regions, is widely used to improve soil chemical and physical qualities (Sandor *et al*., 1990), in addition to

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Received December 2012; accepted after revision May 2013

stabilizing slopes and mitigating soil erosion and degradation (Stanchi *et al.*, 2012b).

In recent years, the Aosta Valley (northwest Italian Alps) has been severely affected by erosion and shallow soil instability. In October 2000, intense rainfall affected the region, and many soil slips, debris flows and shallow landslides occurred throughout the area. The melting of snow up to an elevation of 3500 m exacerbated the effects of that extreme meteorological event, giving rise to considerable run-off and rapid soil saturation. Rain gauges recorded up to 450 mm in 2–3 days, a very large amount given the annual average precipitation of 500–950 mm. The effects of the October 2000 flood were more severe than the ones in 1846, 1956, 1977 and 1993. After 2000, the hydrogeological service of the Valle d'Aosta Region encouraged studies on natural hazards and, in particular, on the assessment of soil susceptibility to erosion. The general objective was to create a potential susceptibility map for early warning and civilian protection. In this study, we investigated five study areas in the Aosta Valley (Figure 1), characterized by a high frequency of events in the recent past with the aims of (i) assessing soil potential susceptibility to erosion using a set of physical and site indicators and (ii) comparing potential susceptibility derived from a regional inventory of shallow soil instabilities as occurred in recent years to assess the effectiveness of the indicators.

Material and methods

Study area

Five study areas covered ca 790 km^2 (Table 1). Three (Nus, N; Valpelline VP; Valtournenche VT) were entire catchments, while two (C, Cogne; SR, Saint-Rhemy) were classified after the 2000 flood as very susceptible to high frequency and shallow landslide events. All the areas included transitions from broadleaved forests to coniferous ones and then to scrubland and pastures above the timberline. Agricultural areas, often terraced, were on the lower part of slopes. In the Saint-Rhemy (SR) and Valtournenche (VT) areas, there were slopes used for skiing. Most of the soil parent materials were of mixed alluvial, colluvial or glacial origins. Slopes were often steep, sometimes >50%, and the topography was complex with high spatial variability.

Land unit types

Three soil survey campaigns were conducted in the spring–summers of 2005, 2006 and 2007. Sampling was based on land unit types (LUTs) with a GIS overlay procedure using the main soil forming factors in Jenny's classic equation (1941) where soil formation is a function of climate (cl) (precipitation, temperature, moisture), organisms (o) (microfauna and mesofauna, macrofauna including humans), relief (r) (slope, aspect, curvature), parent material (p) (geology, lithology) and time (t). We considered four soil formation factors (excluding time) and overlaid them using GIS. The classes are given in Table 2. Climate was classified using available meteorological data or by applying a lapse rate of 0.65 °C/100 m (Blandford *et al.*, 2008) where meteorological records were not present. For the soil temperature regime, an elevation of 1800 m marked the transition from a frigid to a cryic regime. Land cover classes were determined from the CORINE land cover database (vector format –.shp), and we considered seven vegetation types corresponding to the main land use and cover categories which influence soil formation in the study areas (type and amount of litter deposition, degree of anthropogenic influence and management). Information on parent material was derived from geological maps with six

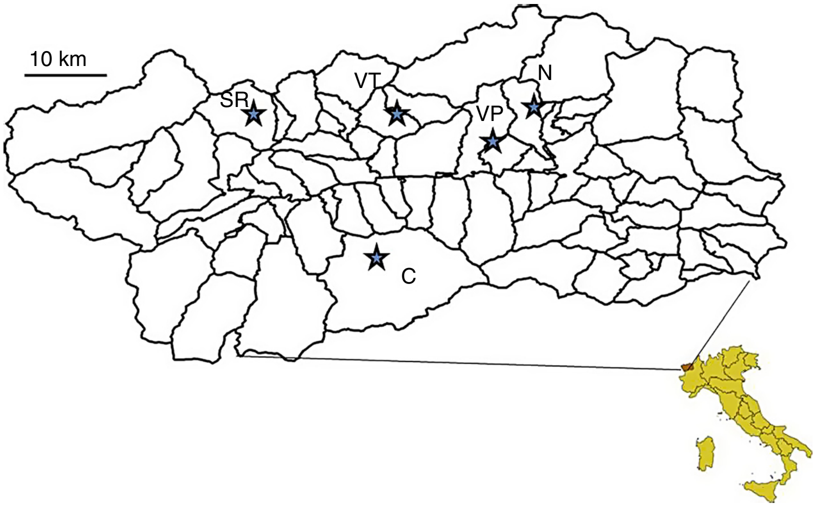

Figure 1 Location of the study sites (with detail given for the Aosta Valley). Stars indicate the centre of each study site. Black lines indicate Municipalities.

Table 1 General characteristics of the study sites

Name	Abbreviation	Number of soil samples (profiles or transect points)	Altitude range (m asl)	Main vegetation cover classes	Geology including surface deposits	Main natural hazard types
Nus	N	18	500–3500	*Larixdecidua, Pinuscembra*, mixed pioneer broadleaves forests, alpine grassland, agricultural areas	Alluvial deposits, moraine and debris, prevalence of mixed lithologies	Landslides, solid transport; wildfires; soil slips, debris flows, diffuse surface erosion
Valpelline	VP	45	800–4150	*Larix decidua, Piceaexcelsa, Pinuscembra*, mixed broadleaves forest, alpine grassland, agricultural areas	Dioritic formations and moraines, talus slopes	Landslides, soil slips; diffuse surface erosion
Valtournenche	VT	54	460–3900	*Larix decidua, Piceaexcelsa, Pinuscembra*, mixed broadleaves forest, alpine grassland, agricultural areas, ski slopes	Schists, gneiss, alluvial and colluvial deposits, glacial deposits of mixed lithologies	Landslides, soil slips, diffuse surface erosion
Saint-Rhemy-en-Bosses	SR	18	1660–1900	*Larix decidua, Piceaexcelsa*, alpine grassland, pastures, ski slopes	Quartzites, dolomite, schists, alluvial and colluvial deposits of mixed lithologies	Debris flows soil slips; diffuse surface erosion
Cogne	C	15	1550–2678	Agriculture (terraces), *Larix decidua*, alpine grassland and pastures	Calcareous schists, colluvial deposit of mixed lithologies	Landslides, soil slips; diffuse surface erosion

categories, most of which were mixed deposits of alluvial/glacial origin. The number of vegetation and geology classes was a compromise between the detail of available maps and the geology/vegetation combinations for the following steps. For the relief variable, we considered four slope classes based on erosion intensity and three aspect classes (north, south and others). South- and north-facing slopes are known to affect soil formation (Eger & Hewitt, 2008; Sidari *et al.*, 2008); we considered east and west orientations as independent.

All the spatial data were rasterized, and each of the four soil forming factors (climate, geology, vegetation and relief) was then reclassified using a code as in Table 2. As an example, code 1111 was used to indicate coniferous forest on alluvial deposits, gently sloping, south facing, at low altitude. The codes were used to derive an overall score. The workflow as shown in Figure 2 was expressed as a routine process in Visual Basic (ESRI). The resultant LUTs were verified in the field using standard soil survey procedures (details in Annex S1). Profiles were sampled by genetic horizons, while transect points were sampled at 0–20 cm depth (topsoil, mainly A horizons) and at 20–70 cm (subsoil, mainly AC horizons). Soil genetic horizons were characterized chemically and physically using standard methods (S.I.S.S., 2010), and soils were classified according to Soil Taxonomy (Soil Survey Staff, 2010) and WRB – World Reference Base for Soil Resources (IUSS Working Group, 2006).

Indicators of soil susceptibility to erosion and their mapping

Many methods have been developed (Table 3) for estimating the susceptibility of soil to erosion, but each focuses on a specific loss mechanism or indicator. In this study, we used a set of soil properties related to the most relevant soil loss mechanisms appropriate to the study area. A potential susceptibility value based on the indicators in Table 2 was

Table 2 Map layer properties and reclassification codes

Map layer	Format	Classification	Reclassification codes
Climate (elevation)	Raster (from DEM, digital elevation model)	<1800 m asl	100
		>1800 m asl	200
Land cover (Corine land cover)	Shapefile	Coniferous	1000
		Broadleaves	2000
		Grassland	3000
		Agriculture	4000
		Mixed forest (coniferous and broadleaves)	5000
		Shrubland and pioneer vegetation	6000
Parent material (geological and lithological maps)	Shapefile	Alluvial deposit	10 000
		Serpentinites and schists	20 000
		Mixed gravitative deposit	30 000
		Gneiss and mica schists	40 000
		Moraine	50 000
		Gneiss, marbles and calceschists	60 000
Slope	Raster	Gently sloping	1
		Strongly sloping	2
		Moderately steep	3
		Steep/very steep	4
Aspect	Raster	South	10
		East or West	20
		North	30

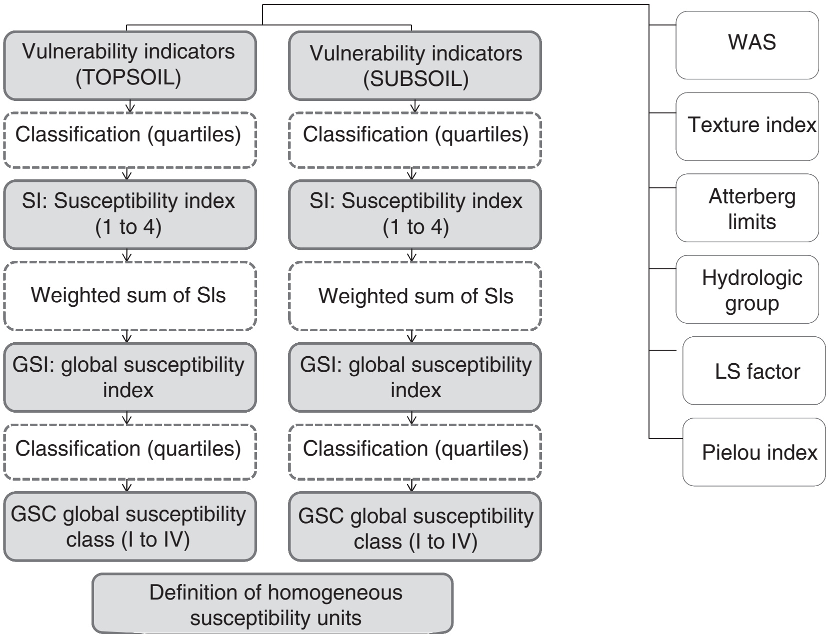

Figure 2 Conceptual steps involved in producing the soil susceptibility maps.

assessed for each LUT (Figure 2) using one or more representative soil profiles.

Wet aggregate stability. The WAS index is an indicator of soil vulnerability to water erosion by slaking (quick submersion and consequent water saturation) and abrasion (wet sieving to simulate the effect of surface run-off). This method provides a laboratory-derived indicator for the assessment of soil vulnerability. We used the kinetic approach proposed by Yoder (1936) and modified by Zanini *et al.* (1998). The WAS model is based on the aggregate breakdown ratio which is a unique function for the net amount of aggregates in soil, and disaggregation follows an

Table 3 Soil susceptibility indicators in this study

Indicator	References	Significance	Soil loss processes
WAS (wet aggregate sieving)	Zanini *et al*., (1998)	Wet sieving, simulating soil aggregates losses by surface water erosion/abrasion; estimation of soil structure	Resistance to water erosion (run-off)
Soil-aggregated clay	Stanchi *et al*., (2008)	Importance of clay in soil aggregation	Resistance to water erosion (run-off, splash)
Atterberg limits (liquid limit, LL; plastic limit, PL)	Casagrande, (1932) Casagrande, (1958); S.I.S.S., (2010)	Soil consistence, resistance to liquefaction, plasticity	Resistance to water erosion and intense precipitation
Hydrologic group	U.S. Soil Conservation Service, (1972)	Soil drainage	Resistance to water erosion (run-off)
LS factor	Desmet & Govers, (1996)	Effects of slope topography on soil erosion	Water erosion
Pielou Index (vegetation index)	Pielou (1966)	Vegetation abundance, evolution and biodiversity	Resistance to soil losses for erosion

exponential curve described by the function:

$$Y = a + b(1 - e^{-t/c}) \quad (1)$$

where Y is aggregate loss (%); t, time of wet sieving (min); a, initial aggregate loss (%) for water saturation (simulating splash erosion effect), for $t = 0$; b, maximum aggregate loss for abrasion (%); c, time parameter (min) related to the maximum aggregate loss (for $t = 3c$ the disaggregation curve approaches the asymptote).

Soil samples (10 g, 1–2 mm fraction) were submerged on a rotating 0.2 mm sieve for fixed time intervals of 5, 10, 15, 20, 40 and 60 min. Aggregate loss (%) as a function of sieving time was measured and then fitted to the exponential model described in equation (1). The curve parameters (a, b and c) were estimated, and goodness of fit was calculated. We used the scaling parameter λr described by Zanini *et al*. (1998) to compare disaggregation curves. For each curve, a scaling parameter (≥0) was computed. When λr is <1, aggregates show a less stable behaviour than the mean scale curve (i.e. a curve representing the ‘typical’ soil behaviour in the area), while $\lambda r > 1$ indicates a relatively stable soil (always with respect to the reference data set). The advantages of these indicators are as follows: (i) the aggregate breakdown curve gives not only a quantitative but also a qualitative assessment of soil loss, as soils with a similar total loss (a + b) may show different behaviours (e.g. fast loss at short sieving times vs. gradual loss), and (ii) the scaling factor allows comparison of different loss curves using a unique numerical value instead of parameters a, b and c.

Atterberg limits. Soil physical qualities are very dependent on soil water content. In this study, we used the liquid (LL,%) and plastic limits (PL,%) as indicators of soil loss susceptibility (Marinissen, 1994; Blanco-Canqui *et al*., 2006; Stanchi *et al*., 2009). Atterberg limits are influenced by many soil properties, but primarily by organic matter and clay content (Hemmat *et al*., 2010). These are often applied in tillage research (Keller & Dexter, 2012), but they are also relevant to the assessment of landslide hazards (Yalcin, 2007; Di Maio *et al*., 2010).

Aggregated clay. Soil texture depends on the sand, silt and clay contents and can be determined with or without organic matter removal. When soil organic matter is removed by oxidation with hydrogen peroxide, the abundance of sand, silt and clay primary particles is determined. When binding agents are not removed, the determination includes aggregates in the sand, silt and clay size range, that is, clay and/or silt particles aggregated into silt-sized or sand-sized secondary units, respectively. Therefore, the clay content after organic matter removal is greater than from the previous method. For well-structured soils characterized by pronounced aggregation, a clear difference between the two particle-size distributions is to be expected. The ratio between clay content with/without organic matter removal (always ≥1) is a good indicator of aggregation, and higher ratios indicate more pronounced aggregation. Such an indicator has been proposed as a measure of soil physical quality for Alpine soils as it shows a positive relationship with soil consistence and resistance to liquefaction (Stanchi *et al*., 2009, 2012a).

Soil hydrologic group. A soil hydrologic group (U.S. Soil Conservation Service, 1972) includes similar soils on the basis of infiltration/run-off characteristics. Soil hydrologic groups are indicated with capital letters (A, B, C, D), and several classification methods are available, but in general, the 'A' group includes soils with fast drainage and limited run-off, while for the 'D' group, the run-off component is dominant. The hydrologic group is influenced strongly by soils and other surface properties which influence the ratio of run-off to infiltration. A and B groups are common in mountainous environments. They generally have coarse textures, low to moderately low run-off when thoroughly wet and free drainage.

LS factor (RUSLE length-slope factor). The USLE (Universal Soil Loss Equation, Wischmeier & Smith, 1978) and RUSLE (Revised Universal Soil Loss Equation, Desmet & Govers, 1996) for soil erosion estimation include a topographic factor (LS, length-slope factor) among the parameters for predicting soil loss. We used the GIS-based procedure proposed by Desmet & Govers (1996) and subsequently modified by Mitasova *et al.* (1996) to calculate LS, a parameter influencing soil vulnerability due to site characteristics. The LS factor takes into account the upslope contribution to run-off, the concavity and convexity of the topography and slope angle. In a GIS, LS can be computed from a digital elevation model using the ArcGIS HydroTools (ESRI Inc.). LS (dimensionless) was calculated according to the following equation, which is often applied for mountainous regions (e.g. Prasannakumar *et al.*, 2012):

$$LS(r) = [F(r)/a_0]^m [sinS(r)/S_0]^n \tag{2}$$

where F is the flow accumulation grid (length and amount of run-off multiplied by cell size), S is the slope, m and n parameters depending on run-off type, and a_0 and S_0 are, respectively, 22.1 m and 0.09 (length and slope of the USLE experimental plot, respectively).

Pielou index (vegetation index). Litter and vegetation cover affect the stability of slopes. In our erosion susceptibility assessment, we included the Pielou vegetation indicator (Pielou, 1966). This is a vegetation indicator varying from 0 to 1 depending on plant community composition, biodiversity and degree of community development (Crotteau *et al.*, 2013).

Classification of soil susceptibility: definition of classes. Figure 2 describes in detail the steps involved in assessing the potential susceptibility to erosion in Alpine environments using both soil physical indicators (soil physical properties) and site characteristics (topography, vegetation). All the soil indicators (aggregate losses, LL and PL, Pielou Indicator and LS factor) were subdivided into quartiles (25th, 50th, 75th and 100th percentiles) for T and S data sets. The resulting susceptibility indicators (SI) were then classified from 1 to 4 with increasing hazard. Then, the indicator scores were added using a weighting factor of 2 for LS which is known to be the most influential among the RUSLE factors in mountainous areas, 0.5 for vegetation (assuming that the vegetation index is less sensitive with respect to the others) and one for the others to provide a GSI (Global Susceptibility Indicator) for topsoil and one for subsoil for each LUT. Then, classification into quartiles was applied to the GSIs as performed before for SIs for the two soil depths (T, S). We used this information to define homogeneous susceptibility units (HSUs), that is, areas with similar soil indicators and therefore similar potential behaviour. These indicate the potential susceptibility to soil erosion according to Alewell *et al.* (2008) for each study area and can be represented with graduated colours on the LUT map. The hazard records from 2000 to the present as provided by Regione Autonoma Valle d'Aosta – Assessorato Territorio, Ambiente e Opere Pubbliche, were analysed to assess the correspondence between values of the potential susceptibility index and actual phenomena.

Results and discussion

The complete database of susceptibility parameters is given in Annex A. All the study areas have been affected by shallow landslides (mainly soil slips and debris flow) from 2000 to the present despite heterogeneity in landform, management and vegetation cover.

Soil analyses and classification

Soils were generally poorly developed and coarse textured (mainly Entisols or Inceptisols, according to the USDA classification, Regosols and Cambisols according to the WRB), and diagnostic horizons had limited development when detected. Soil texture was coarse, with a sand content >60% and very little clay (generally <5%). Some differences were apparent between T and S samples; T samples (data not shown) had significantly greater organic matter and more pronounced aggregation than the deeper horizons, a trend also reported in other studies in this region (e.g. Stanchi *et al.*, 2012a). The organic C content was small even for T samples (average 37.0 g per kg), which is consistent with some Alpine soils and frequent land abandonment, but was probably sufficient to promote soil structural formation.

Wet aggregate stability

Subsoil samples had greater aggregate loss compared with the corresponding topsoil ($P < 0.01$). This is an effect of soil organic matter, greater for topsoils than for subsoils due to manuring or pasture (Cerdá, 1998), but possibly also as a result of natural inputs such as from herbaceous roots (Preti & Gladrossich, 2009; Burylo *et al*., 2011; Pohl *et al*., 2011).

Atterberg limits

Topsoils had generally better consistence ($P < 0.01$), that is, greater liquid and plastic limits, indicating that topsoils can receive greater water inputs without undergoing liquefaction and/or significant changes in plasticity. In general, greater LL and PL values were associated with grassland and pasture soils, characterized by more organic matter and better aggregation. The range of determined values is consistent with those reported by Stanchi *et al*. (2009) for a smaller data set in the same region.

Soil-aggregated clay

Topsoils had greater amounts of aggregated clay than subsoils ($P < 0.01$). For mountain soils, this can be explained by the greater organic matter and cation exchange capacity in surface soils (Stanchi *et al*., 2009), which improve soil physical quality. Such variability in soil quality with depth, along with the differences in aggregate stability and Atterberg limits, may be an indicator of susceptibility for the shallow slopes in the study areas and could indicate a hazard risk in densely inhabited areas.

Soil hydrologic group

Soils in the study area belonged mainly to the A and B groups, characterized by rapid drainage as a result of their coarse textures.

LS factor (RUSLE length-slope factor)

The LS factor reflected the complexity of the topography with marked spatial variability and high average values, generally >20 and often >50, comparable with those reported for other Alpine areas (Meusburger *et al*., 2010).

Pielou index (vegetation index)

The values for this index, often <0.5, indicated ecosystems where natural evolution is limited by strong anthropogenic influence as in ski runs and overgrazed areas. Such ranges in values are consistent with data reported for disturbed forest ecosystems (Onaindia *et al*., 2004).

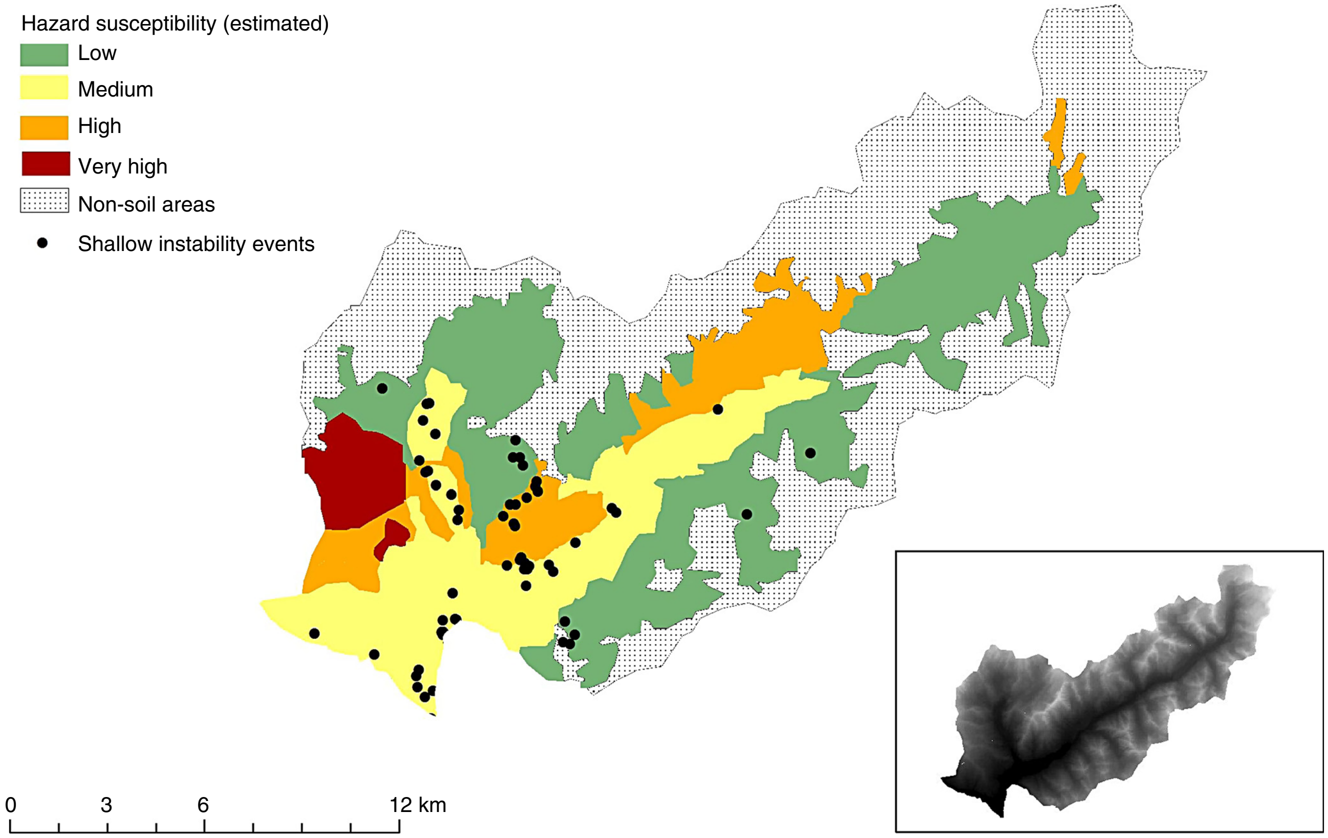

Figure 3 Example of a susceptibility map for the VP study area.

Susceptibility map

An example of a susceptibility map is shown in Figure 3 for the VP study area. Most of the area is of moderate to high susceptibility, and this is true also for the other study areas. Greater susceptibility was typical for abandoned agricultural areas, pioneer forests and unmanaged forest. All these areas showed evidence of soil degradation in terms of aggregate stability and consistence (LL, PL). Sharp differences in soil physical properties occurred deeper in the profiles to indicate potential soil instability.

Analysis of past events

The hazard records from 2000 to the present were analysed and then compared with the susceptibility indexes in Annex A. We computed the density of shallow movements (number of events per km^2) for each land unit type (last field in Annex A table). As a general trend, we found that the hazardous events were concentrated at low and medium altitudes, often on strongly sloping or moderately steep areas (mainly class 2 and 3 of the present study, Table 2) which also coincided with dense habitation. This was particularly

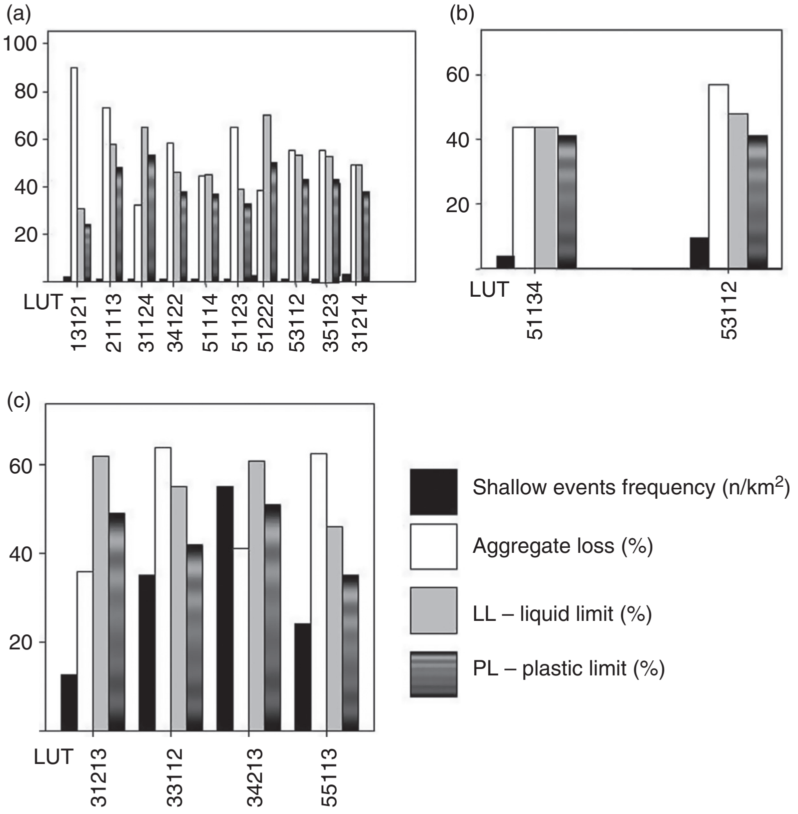

Figure 4 Distributions of events with frequency $\geq$1 and selected soil properties (aggregate loss -%, liquid limit -%, plastic limit -%) on different LUTs (a: frequency from 1 to 5 events per km^2; b: frequency from 5 to 10 events per km^2; c frequency >10 events per km^2). LUTs codes: 13121 (Active or partially active alluvial fan (fan- or cone-shaped deposits of sediment built up by streams), impacted by periodic flooding; mixed lithology; herbaceous cover); 21113 (Gently to strongly sloping; calcareous schists and serpentine substrate; coniferous forest); 31124 (Steep/very steep; alluvial fan (fan- or cone-shaped deposits of sediment built up by streams) and unconsolidated sediments; inactive slope instabilities; mixed lithology; coniferous forest); 34122 (Strongly sloping; low elevation; colluvial deposit; mixed lithology; herbaceous cover; North facing); 51114 (Steep/very steep; moraine; mixed lithology; herbaceous cover; South facing); 51123 (Moderately steep; unconsolidated sediments and rock outcrops; mixed lithology; coniferous forest); 51222 (Strongly sloping; moraine; mixed lithology; coniferous forest); 53112 (Strongly sloping; low elevation; moraine; mixed lithology; meadow); 35123 (Moderately steep; unconsolidated sediments; mixed lithology, mixed coniferous/broadleaf forest); 31214 (Steep/very steep; alluvial fan (fan- or cone-shaped deposits of sediment built up by streams); mixed lithology; coniferous forest); 51134 (Steep/very steep; unconsolidated sediments and rock outcrops; mixed lithology; coniferous forest; North facing); 53112 (Gently to strongly sloping; unconsolidated sediments and moraine; presence of deep gravitational deformations; mixed lithology; herbaceous cover); 31213 (Moderately steep; colluvial material and unconsolidated sediments; low to medium elevations; mixed lithology; prevalent coniferous forest); 33112 (Strongly sloping; medium elevation; mixed lithology; colluvial deposit; prevalent herbaceous cover; South facing); 34213 (Moderately steep; high elevation; mixed lithology; colluvial deposit; prevalent herbaceous cover; South facing); 55113 (Moderately steep; moraine; mixed lithology; coniferous forest).

true on the lower portion of the Nus slopes characterized by dense settlement, and for the lower portions of the Valpelline lateral valleys. Both the Nus (N) and Saint-Rhemy (SR) areas were severely affected by deep landslides (not included in the present study). In particular, Saint-Rhemy (SR) was characterized by marked human impacts on soils, mainly on ski slopes which were redesigned after 2000. The severe impact of piste management on soils is well documented. For example, Freppaz *et al*. (2012) report that there is often the exposure of parent material or deep soil horizons. The main effects are a considerable reduction in soil thickness together with the formation of a turbated topsoil, characterized by an almost complete lack of structure, as well as possible compaction and enhanced erosion. The actual event densities were then compared with the estimated GSIs. In general, the observed phenomena were concentrated in LUTs where (i) the calculated susceptibility index was rather high (i.e. GSI >30 at both soil depths) or (ii) the differences between topsoil and subsoil in terms of physical properties were particularly pronounced, potentially triggering shallow instabilities (e.g. LUT 53112, Nus). In general, the areas where the calculated GSIs were less showed no events or event densities close to zero. However, not all the LUTs of high potential susceptibility were affected by events during the study period.

In general, frequencies of 20 events per km^2 as often observed in SR and C areas can be considered as very high (Turner *et al*., 2010). The overlay between this information and the susceptibility map shows a good correspondence between potential soil susceptibility and historical records. In Figure 4, we limited the analysis to frequencies exceeding 1 event per km^2 with three frequency ranges: 1–5 events per km^2, 5–10 events per km^2 and >10 events per km^2. In general, a larger number of land unit types was included in range 1 (10 units), while the number decreased significantly with ranges 2 and 3 (2 and 4 units, respectively). The 1–5 range (Figure 4a) included grasslands on moraine with moderate steepness, lower than 1800 m and coniferous pioneer forest on moraine at the same altitude on steep or very steep slopes. Range 5–10 (Figure 4b) included two land unit types that were present in the study areas. Greater frequencies were observed for grasslands on moraine at low and medium elevation and with moderate steepness. These areas were characterized by high aggregate loss for topsoils, while the plastic and liquid limits were comparable with typical values for alpine soils (Stanchi *et al*., 2012a). In the C, ST and N study sites, these areas were characterized by a high density of settlements and roads and were partly covered by abandoned terraces which often had degradation features. The other land unit types were characterized by moraine as parent material and pioneer coniferous vegetation on steep slopes. The land unit types with greater frequencies (Figure 4c) were concentrated in the VP and VT areas and were in agricultural use at low elevation on mixed colluvial deposits or inactive mass movements, with moderate steepness. All demonstrated the effects of agriculture, skiing and terracing. In general, events were more frequent on moderately steep slopes and seem to be strongly related to unconsolidated parent materials and agricultural land use. This suggests that the effect of land management plays a key role in soil shallow movements.

A highly significant correlation ($r = 0.92$, $P < 0.01$) was found between the GSI (Global susceptibility index) as computed in this study and the observed frequency of events (Figure 5). The event frequencies demonstrate a marked exponential trend with respect to GSI values. Increased GSI values correspond to greater event frequencies per unit surface area.

Conclusion

In this article, we demonstrate a method for assessing soil susceptibility to erosion in Alpine areas (Valle d'Aosta, northwest Italy) using chemical and physical data from two soil depths. The physical indicators take into account soil aggregation, erodibility, structure and consistence. In general, topsoil samples had better aggregation and stability in terms of structure and plastic and liquid limits. The presence of abrupt changes in soil physical properties with depth can be a trigger for shallow landsides from intense rainfall when topsoil can slip over underlying horizons. All the indicators were classified according to potential susceptibility to soil erosion, and a map of soil vulnerability was produced for each study area to show the distribution of potential hazards. The map corresponded well with the historical record of soil instabilities as occurred in recent extreme events.

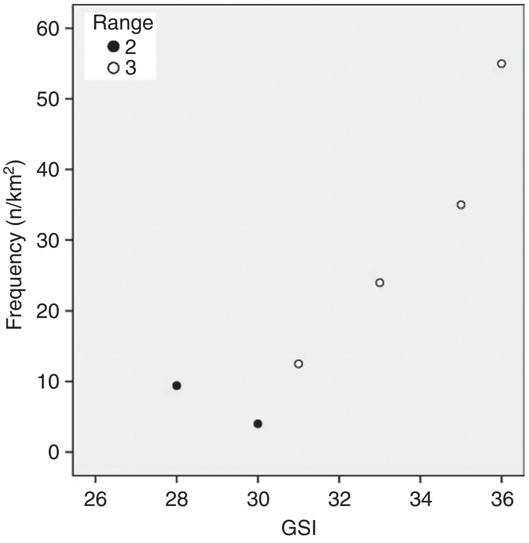

Figure 5 Plot of event frequency (only for thresholds 2 and 3) and the Global Susceptibility Index (GSI).

The susceptibility map is not a risk assessment map and does not provide a prediction of soil loss events, but it can be a useful tool for land planners through indicating which areas require special land management to reduce and mitigate potential damage from soil erosion. Moreover, the conceptual steps leading to the final susceptibility estimate, as presented in this article or with local adjustments, can be applied in other mountainous areas characterized by analogous environmental conditions and similar hazard types.

Acknowledgements

This research was funded by Regione AutonomaValle d'Aosta – Assessorato Territorio, Ambiente e Opere Pubbliche, Dipartimento Territorio Ambiente e Risorse Idriche. Special thanks to Dr Sara Ratto, Dr. Marco Cauduro and Dr Evelyne Navillod. Thanks to Dr Angelo Caimi for the vegetation data and Dr Elisa Oberto for the field and lab work. Thanks to Dr Thomas Reinsch and Dr Paul Reich (USDA-NRCS – Soil Science Division) who helped in the final revision of the manuscript.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Annex S1. List of the Land Unit Types for the subareas of the study. For each subarea, relevant parameters for susceptibility evaluation, described in the manuscript, are reported in detail.