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Liquid and plastic limits of mountain soils as a function of the soil and horizon type

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ABSTRACT

Soil degradation by processes such as soil erosion, shallow landslides, debris-flows etc. is a significant problem in mountain areas, and is a crucial issue for natural hazard assessment in mountain areas. Several soil properties, among which are the liquid and plastic limits, i.e. moisture contents for which a soil passes from the plastic to liquid state (liquid limit, LL) and from the semisolid to plastic state (PL, plastic limit), have been proposed as indicators for soil vulnerability to degradation processes, both of natural and anthropogenic origin.

In this research we investigated the liquid and plastic limits of the main soil groups of World Reference Base for Soil Resources (WRB) classification present in Aosta Valley (N–W Italian Alps) from a pedogenic perspective. In particular, we compared 1) soils at different stages of development; and 2) different genetic horizons. Our main aim was to provide and interpret data on soils' consistency and mechanical behavior that may be used as indexes for the assessment of soil vulnerability.

Despite its relatively small area, the Aosta Valley is characterized by a wide range of soil types.

Sixty-two soils with different profile evolution stages, representative of 7 WRB soil groups, were investigated and LL and PL in genetic horizons were studied at the soil type and genetic horizons level.

In general, soil consistency was largely determined by the organic matter content (both in topsoils and organic matter-enriched subsurface horizons), but in spodic horizons and some C horizons a role of poorly crystalline and pedogenic iron oxides was observed too.

Considering the vulnerability to consistency loss, that can result in erosion processes and overall soil degradation, surface horizons were generally less vulnerable, as could be expected on the basis of previous research, i.e. showed higher LL and PL values, than the deeper ones, generally characterized by a reduction of soil consistency. Therefore, topsoil could receive higher water inputs while still preserving their consistency and strength. This was not confirmed in Podzols, where the organic matter enrichment of spodic horizons determined a discontinuity in physical properties between the E horizons (more vulnerable) and the underlying, spodic ones. The same trend was observed for Calcisols with a deep cemented Bkm horizon.

The research provided a novel overview on LL and PL in the common soil types present in the Alpine region, integrating the already existing research on topsoil vulnerability to degradation processes (erosion, consistency losses, losses of strength), and the regional soil database. The use of LL and PL as indicators of soil physical quality was approached with a pedogenic perspective, which might be helpful for a better definition of hazard assessment at the regional scale.

1. Introduction

Soil erosion, shallow landslides, debris-flows etc. are important problems in mountain areas as remarked by Alewell et al.(2008), and may result in considerable soil degradation (Borga et al., 2014; Park et al., 2013; Pavlova et al., 2014). The surfaces affected by shallow movements triggered by different mechanisms (soil aggregate breakdown, erosion, loss of consistency) can be very large and the masses and volumes involved are potentially destructive for infrastructures, urban areas, human activities and lives, making the risk level unbearable in densely settled areas (e.g. Alewell et al., 2008; Esposito et al., 2013). Therefore, soil degradation in mountain regions is a crucial issue for natural hazard assessment and civil protection preparedness.

The assessment of soil loss by erosion can be modeled, but none of the available models are fully satisfactory (De Vente and Poesen, 2005; Konz et al., 2012; Stanchi et al., 2014). Moreover, besides sheet and rill erosion, other shallow processes involving soils, such as shallow landslides and debris-flows, can affect mountain areas. These processes are characterized by space and time scales that conventional observation systems for rainfall, streamflow and sediment discharge cannot monitor with effectiveness, as remarked by Borga et al. (2014).

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Several soil properties have been proposed as indicators for soil vulnerability to degradation processes, both of natural and anthropogenic origin. The Atterberg limits provide information on the consistency of soils and can be related to soil strength and the mechanical behavior (Yalcin, 2007). They are typically used in the field of engineering and geotechnics (e.g. Haigh, 2012; Haigh et al., 2013; Vardanega and Haigh, 2014) but their use has been extended to agronomy and tillage. For example, Seybold et al. (2008) and more recently Keller and Dexter (2012) remarked the importance of the Atterberg limits (in particular, LL, liquid limit; PL, plastic limit) to understand the mechanical behavior of agricultural soils with respect to tillage and compaction hazard. However, some applications for soil conservation and management have been proposed too. For example, Yalcin (2007) underlined that soils with limited cohesion, when subjected to water saturation, are susceptible to erosion during heavy rainfall. Stanchi et al. (2012a),Curtaz et al. (2014) and Vacchiano et al. (2014) proposed LL and PL as indicators to assess the vulnerability of mountain soils to erosion (also including in this term all shallow movements affecting the topsoil layer). Soil consistency may in fact influence soil susceptibility to hydrogeological hazard and therefore it may be a relevant indicator of soil physical quality, which is strongly dependent on soil water content. Soil can pass from the plastic to liquid state as the water content increases. Between the solid and liquid state, an interval of plastic behavior is observed. LL and PL, according to this approach, can be seen as proxies of soil physical quality, i.e. the capability to preserve soil's structure, consistency, and strength.

Atterberg limits are in general influenced by many soil properties, but primarily by organic matter and clay content (Hemmat et al., 2010).

The Aosta Valley Region (NW Italian Alps) has been severely affected by erosion and shallow soil instability phenomena in recent years. In October 2000 intense rainfall affected the Region, and many soil slips, debris flows, and shallow landslides were reported (Stanchi et al., 2013a). The considerable water discharge increased solid transport, and rapidly saturated the soil. Up to 450 mm of rain concentrated in 2–3 days were registered, that represents a very high threshold when compared with annual average precipitation. After this extreme event, the hydrogeological service of the Aosta Valley Region encouraged a series of studies on natural hazards, and in particular the assessment of soil vulnerability to erosion and shallow soil losses.

In this research we investigated the liquid and plastic limits of the main soil groups (IUSS Working Group WRB, 2014) present in Aosta Valley from a pedogenic perspective. In particular, we compared 1) soils at different stages of development; and 2) different genetic horizons. Our main aim was to provide and interpret data on soils consistency and mechanical behavior that may be used as indexes for the assessment of soil vulnerability.

2. Materials and methods

2.1. Study area

The Aosta Valley is located in the NW Italian Alps and covers a surface of 3262 km^2 of which more than 80% is located above 1500 m a.s.l., with steep slopes and cryogenic features (Fig. 1).

Most of the rock types found on the entire Alpine range are also found in the region, where lithologies belonging to the African and European continental and oceanic plates coexist over a very small surface. In particular, the south-eastern part and the highest massifs located in proximity of the administrative borders are made of sialic metamorphic rocks, such as gneiss and micaschists. The eastern-central part is occupied by large ophiolitic outcrops, with ultramafic serpentinite, mafic metamorphic gabbros and prasinites, and calcschists the most common rock types. Calcschists and black shales occupy large sectors in the western part, while granite and other intrusive igneous sialic rocks emerge in the north-western sector. Glacial till or slope debris of mixed lithology cover large surfaces. The mean annual air temperature at 2000 m a.s.l. ranges from 0 to 3 °C. The climate is strongly affected by the orography, and has a wide range of humidity with a typically inner alpine continental central area and a more humid, sub-Atlantic outer area (Mercalli et al., 2003). Topography in this region exerts a major influence on several meteorological variables, for example on the precipitation amount and distribution: while on the south-eastern boundary of the region the external mountain side receives as much as 2000 mm y^{-1}, about 70% of the region receives less than 1000 mm y^{-1} precipitation with minima of less than 500 mm y^{-1} in the innermost part (Mercalli et al., 2003). During winter, according to the elevation, most of the precipitation occurs in the form of snow, with a snow cover duration at 2000 m a.s.l. equal to 6 months. The study area (Aosta Valley) and the soil profiles' location are represented in Fig. 1.

The climate variability caused by altitude, slope aspect and geographic position as well as the extreme lithological diversity create a range of habitats for many different plant communities (Fig. 1). The present day treeline lies at around 2200–2400 m a.s.l.; above it, alpine grassland and meadows dominate the landscape up to ca. 2500–2800 m, and above only pioneer plant communities are observed on screes, boulder fields, rocks and glaciers. Below treeline, the subalpine forests are mainly composed of larch (*Larix decidua* Mill.), Swiss stone pine (*Pinus cembra* L.) and Bog pine (*Pinus uncinata* Mill.), with *Rhododendron ferrugineum* L. and *Vaccinium* ssp. as common understory species. The lower limit of the subalpine forest ranges from 1300–1500 m in the wettest south-eastern sector to 1800–2000 m in the drier central part of the valley. Spruce (*Picea abies* L.) and fir (*Abies alba* Mill.) are locally common at the upper montane belt, while the lower montane belt is colonized by Scots pine (*Pinus sylvestris* L.) and chestnut (*Castanea sativa* Mill.). At the lowest elevations, *Quercus pubescens* Willd. becomes very common, particularly in the central part, while beech (*Fagus sylvatica* L.) is locally common where rainfall is highest. Large areas on the sunny southward slopes are covered by xerophilous steppes and scrublands.

2.2. Soil sampling and analyses

Sixty-two soil profiles (for a total of 139 genetic soil horizons) were sampled on homogenous surfaces, considering vegetation types, parent material lithology, and slope steepness; given the wide area and the rather wide sampling scale, we did not consider visibly disturbed areas, such as ski slopes, landslides, reshaped agricultural lands, stream beds or avalanche chutes. Soil profiles (Fig. 1) were chosen after the determination of the representative soil type developed on each land unit, and the observation of minipits. In the field, we visually assessed the most important site properties, such as slope steepness (°), plant cover (%), tree cover (%), vegetation species and species cover (%), surface stoniness and rockiness (%), parent material type and lithology, and the main geomorphic processes. We determined and described the genetic horizons according to IUSS Working Group WRB (2014); a sample of each genetic horizon was collected, oven dried and sieved at the <2 mm fraction for chemical and PSD (particle-size distribution) analyses, at the <0.452 mm fraction for the Atterberg limit determination. In the studied soils the <0.452 mm fraction can be estimated in a range from 70 to 80% of the total fine earth fraction.

Soil horizons were characterized chemically and physically according to standard methods reported in the Italian Soil Science Society (SISS) Manual (S.I.S.S, 1997), and soils were classified according to WRB — World Reference Base for Soil Resources (IUSS Working Group WRB, 2014). Soil pH was determined potentiometrically and total C (TC) and total N (TN) contents were determined by dry combustion with an elemental analyzer (NA2100 Carlo Erba Elemental Analyzer). Total Carbonate content was measured by volumetric analysis of the carbon dioxide liberated by a 6 M HCl solution. The total organic C (TOC) content was calculated as the difference between C measured by dry combustion and carbonate-C. Cation exchange capacity (CEC)