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



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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; 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 soils 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.

**Keywords**

Atterberg limits, WRB Reference Soil Groups, genetic horizon, vulnerability, Alps

## 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 (Pavlova et al., 2014; Park et al., 2013; Borga 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 modelled, 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 characterised 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).

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 et al., 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, 2014) present in Aosta Valley from a pedogenic perspective. In particular, we compared 1) soils at different stages of development; 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 (figure 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 figure 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 (figure 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 firs (*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 (figure 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 limits 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 (SISS, 1997), and soils were classified according to WRB – World Reference Base for Soil Resources (IUSS Working Group, 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) was analyzed with the $BaCl_2$-triethanolamine method (Rhoades, 1982). The particle-size distribution (PSD) of the soil was determined by the pipette method with Na-hexametaphosphate before and after soil organic matter (SOM) oxidation with $H_2O_2$ (Gee and Bauder, 1986). Na-dithionite-citrate bicarbonate–extractable Fe ($Fe_{DCB}$), and $NH_4$-oxalate–extractable Fe ($Fe_{ox}$) were measured after Mehra and Jackson (1960). The Atterberg Limits (Liquid Limit, LL, and Plastic Limit, PL) were determined on the air dried soil for each horizon according to the standard methods reported in SISS (1997) after ASTM D 4318 (ASTM, 2010), i.e. the cone penetrometer and the thread roll method. The cone penetrometer (or fall-cone) is a standardized stainless steel cone with a weight of 80 g, and an angle of 30°, that drops freely from a fixed height into a soil and water mixture placed in a brass cup. The cone is released for 5 sec and then the penetration into the soil probe is measured. Several point measurements (normally 5-6) are done with decreasing gravimetric water content of the soil ((mass of water/mass of dry soil)*100). A regression line for penetration (mm) vs gravimetric soil moisture (%, after oven drying at 60°C) is obtained. Conventionally, LL is the gravimetric water content corresponding to 20 mm penetration, and is computed by interpolation.

The thread roll methods for PL determination is performed on soil sub-samples taken from the last fall-cone measurement. It consists of manually rolling a thread of 3.2 mm diameter on a flat, non-porous surface until it crumbles. The corresponding gravimetric water content is determined in the sample and corresponds to PL. If the thread cannot be formed, the soil is non-plastic.

The cone penetrometer method was chosen instead of the Casagrande device, often used in literature (Haigh, 2012), as it showed a better replicability and easier applicability in a pilot study conducted in Aosta Valley (Stanchi et al., 2009).

All soil analyses were made in duplicate and then averaged.

### *2.3. Statistics*

Differences among soil types and horizons were tested using one-way analysis of variance (ANOVA). Correlations were evaluated using the Pearson coefficient (two-tailed) after visual inspection of the data to verify that the dependence relationship was linear. All statistical analysis was carried out with SPSS software version 20.0.

## 3. Results

Aosta Valley displays a large variability in lithology and vegetation cover as visible from figure 1, and a considerable altitude range, from ca 300 m to over 4000 m a.s.l. (M. Bianco Massif). Considering the high variability of soil forming factors (parent material, vegetation, relief, climate etc.), many different soils types could be observed and were classified as Regosols (n=16), Podzols (n=9), Umbrisols (n=6), Phaeozems (n=7), Calcisols (n=3), Cambisols (n=15), Umbrisols (n=5), Leptosols (n=1) according to the WRB classification (IUSS Working group, 2014).

The main chemical and physical properties of the studied soils are reported in table 1. It should be noted that Leptosols are scarcely represented in our dataset. Actually, these soils often develop as soil pockets, typical of very steep slopes, and display shallow and discontinuous A horizons, therefore they were not widely included in this dataset.

Soil pH showed a wide variation range with extreme values represented by Calcisols horizons (pH around 8) and acidic surface horizons of Podzols, Cambisols and Umbrisols.

The TOC content in topsoil was lower in Podzols, Cambisols and Leptosols/Regosols while the maximum values were observed in Phaeozems. In Podzols, organo-mineral, TOC-rich A horizons were seldom observed and topsoils were usually represented by TOC-poor E ones. The C/N ratio showed the highest values in Podzols (20-30).. The CEC ranged from very low values for A horizons of Calcisols to more than double for A horizons of Umbrisols, and often showed a regular decrease along the soil profile. However in Podzols, the highest CEC values were often measured in subsurface Bh/Bs horizons. Soil textures were coarse, and the clay content was particularly low in Regosols and Leptosols. LL (table 2) ranged from 20 % to 104 %, while PL (when determinable) from 18 % to 74 %. PI (Plasticity Index, obtained as LL-PL) varied from 2 % to 26 %, with the majority classified as slightly plastic according to the ASTM D 4318 (2010) classification.

Figure 2 displays the Casagrande chart of the studied soils. As visible, most soil samples fall below the A-line indicating silty behavior, whereas the majority of C horizons fall above the A-line indicating more clay-like properties. The most frequent samples falling above the line are from Regosols, Calcisols and Cambisols (figure 2, left) when considering soil types. Considering horizon types, the majority of C horizons falls above the A-line (figure 2, right).

Figure 3 shows the average LL and PL (%) for soil types and horizons. Soil types showed significantly different LL values (ANOVA, $p=0.026$), and in particular, the highest values were observed for Phaeozems, Podzols and Umbrisols, while the lowest for Calcisols. Also PL significantly differed among soil types ($p=0.010$), with the lowest average for Calcisols and the highest for Phaeozems. Considering the horizon types, significant differences were observed again in LL and PL ($p<0.010$, both cases). In details (figure 3), LL and PL were higher in A and Bs or Bh horizons, and lowest in Bk and C horizon types. E horizons had intermediate values, normally lower than the underlying spodic ones.

The two variables (LL and PL) differed significantly (paired t test, $p<0.01$) and were positively correlated to each other (figure 4, $r=0.924$, $p<0.01$). When considering the different soil groups, all correlations still held (always $p<0.01$). However, while the r coefficients where >0.9 for most soil types, Podzols and Umbrisols showed poorer correlation coefficients ($r= 0.822$ and 0.730, respectively, $p<0.01$). Splitting the dataset into soil horizons the correlation observed for LL and PL still held and did not show notable differences in terms of goodness and significance.

LL (whole dataset) was positively correlated with TOC ($r= 0.742$, $p<0.01$) and CEC ($r=0.672$, $p<0.01$). TOC and CEC were, however, strongly intercorrelated. Considering the soil groups and the relationship between TOC and LL (figure 5), Podzols showed the highest $R^2$ (0.72) followed by Phaeozems, Calcisols ($R^2= 0.69$ both) and Regosols ($R^2= 0.65$ ). Considering the genetic horizons (figure 5), a strong positive relationship was observed only for spodic Bh, Bs and Bhs horizons ($R^2= 0.88$), while the others only showed poorer correlations ($R^2<0.50$).

A positive relationship was observed also between PL (whole dataset) and TOC and CEC ($r= 0.715$, $p<0.01$ and $r= 0.598$, $p<0.01$, respectively). No correlation of LL and PL was instead observed with the clay content for the whole dataset.

A positive significant correlation was observed between LL and $Fe_{ox}$ in Bs or Bh horizons from Podzols (r=0.91, p=0.02) and C horizons (r=0.63, p=0.09), and between LL and $Fe_{DCB}$ in the same horizon types (r=0.83, p=0.011; r=0.63, p=0.009, respectively). Considering all the soil groups, a positive correlation, though poorer, was still present between LL and $Fe_{ox}$ (r=0.53, p=0.009) and LL and $Fe_{DCB}$ (r=0.46, p=0.029).
No general correlation (whole dataset) between C/N values and Atterberg limits was observed. However, considering the different soil groups and horizons, Cambisols showed a positive correlation of C/N with LL (r= 0.334, p=0.038), while Podzols showed a negative correlation (r=-0.503, p=0.012). Among the genetic horizons, the C/N ratio in Bw showed a positive correlation with LL (r=0.405, p=0.021).

## 4. Discussion

A large variety of pedogenic processes are active in diverse mountain regions such as the Aosta Valley, revealing different responses to variations in parent material type, geomorphic processes, phytoclimatic belts and macro/microclimate. In our study area weakly developed Regosols or Cambisols were common (31 profiles out of 62), i.e. soils characterized by recent pedogenesis or incipient development stage with limited profile depths and horizonation due to intense erosion/deposition processes or other disturbances such as cryoturbation. Common features of these soils were abundance of skeleton and limited structure formation, as reported for similar soils by Stanchi et al. (2012b, 2013b) while chemical properties showed a wide range of variation as a response to the strong environmental spatial variability. Disturbance processes induced by natural (e.g. snowmelt, runoff, erosion and deposition processes) and anthropic processes (e.g. grazing) were often reported during the field survey and could have contributed to the limited development of soils. Agricultural soils, depending on the parent material and topographic position (e.g. terraced slopes), were generally classified as Cambisols and Regosols (Stanchi et al., 2012b). Cambisols, in topographically favorable positions characterized by limited erosion processes, could also develop under montane hardwood or spruce forests and under alpine grasslands, on all parent material lithologies. Calcisols were generally typical of Pleistocene glacial till of mixed lithologies and of calcschists in xeric microclimates, as the inner areas of the Region, where pedogenic carbonates could accumulate determining the formation of Bk, Bkm and Ck horizons (see figure 2). While Bk, Ck and similar horizons had the lowest Atterberg limits of the considered soils, i.e. were more potentially prone to losses of strength as a result of significant water input (e.g. intense precipitation), the more developed, strongly cemented Bkm showed a lower vulnerability to the loss of consistency thanks to strong cementing. The spatial distribution of these differently developed horizons characterized by different degrees of secondary carbonate accumulation was difficult to assess: both were commonly found under xerophilous steppe or forest-steppe plant communities, agricultural soils or xerophilous oak (*Quercus pubescens* Mill.) and Scots pine (*Pinus sylvestris* L.) forests on different slope aspects and steepness. Sometimes, the presence of a strongly cemented Bkm horizon under a vulnerable Bk might create an additional hazard, leading to a sharp decrease in soil permeability along the profile due to cementing. In these cases, the strong discontinuity in strength and hydraulic properties along the soil profile might trigger topsoil detachment as a consequence of intense rainfall.

Phaeozems and Umbrisols typically developed below pastures and alpine prairies. Both these soil types had the highest Atterberg limits in the topsoils, despite the different aggregation types characterizing biologically active Phaeozem and the strongly acidic Umbrisols. This was probably caused by the strong organo-mineral association which typically characterizes grassland soils, caused by a favorable C/N ratio in the organic matter produced by herbs and consequent high biological activity (worms in Mollic horizons, fungi and arthropods in Umbric ones).

Podzols were common under subalpine coniferous stands (figure 1) dominated by larch, bog pine and stone pine with ericaceous understory, and under subalpine anthropogenic grasslands, particularly on low slope angles on northward aspects. The well-defined altitudinal range where the podzolization process was active ranged from 1300-2300 m a.s.l. in humid areas to 2000-2500 m a.s.l. in the xeric inner-alpine central sector of the region. Also the parent material lithology had obvious effects on the intensity and altitudinal range of the podzolization process. Acidic sialic rocks, such as granites, gneiss and micaschists, mafic gabbros and amphibolites helped the development of particularly well developed Podzols, often characterized by strongly cemented ortstein Bsm horizons, while basic serpentinites usually supported only weakly developed Podzols in the most favorable micro-environment (e.g., D'Amico and Previtali 2008). On calcschists, weakly developed, loose Podzols were only observed in the most humid sectors of the region.

The ranges of LL and PL values observed (table 2) showed a high variability, but were overall comparable with values reported for smaller basins located within the same Alpine Region (Stanchi et al., 2009), where average LL ranged from 37 % (subsoil, i.e. AC and C horizons) to 49 % (topsoil, i.e. A horizons) and PL from 27 % (subsoil) to 38 % (topsoil), with an overall limited plasticity as expected for poorly developed, coarse-grained mountain soils (e.g. Stanchi et al., 2013). Moreover, the Casagrande chart (figure 2) evidenced that C horizons (i.e. fine-textured, SOM-poor subsurface horizons) had a prevalent clay-like behavior. A strong correlation between Atterberg limits is often reported for a variety of environments, and often PL has been predicted from LL values (e.g. Hemmat et al., 2010; Summa et al., 2010; Stanchi et al., 2009). Here, the same strong correlation has been observed. This indicates that, in the considered mountain area, the soils displaying lower PL values, i.e. those which are more likely to become brittle after drying , are also those where the LL can be reached more quickly. Soils displaying higher PL values are also characterized by relatively high LL values, and therefore can be considered of better physical quality (e.g. Stanchi et al., 2013a).

The strong positive correlation found between the Atterberg limits (both LL and PL) and organic C content is commonly observed in a variety of environments (e.g. Silva et al., 2007), and also our previous findings confirmed this trend (e.g Curtaz et al., 2014), indicating a significant role of organic matter in soil aggregation and consistency, i.e. in preserving soil physical quality. Moreover, the position of most samples falling below the A-line in figure 2 confirms the importance of the organic component in the studied samples. In Aosta valley pedogenic processes were strongly associated with organic carbon accumulation and redistribution with soil depth, and organic carbon was therefore the main factor influencing the liquid and plastic limits measured in the studied soils (see also Stanchi et al 2009, 2013a). In our study area, it explained higher LL values (figure 5) in topsoils (umbric and mollic horizons), naturally enriched of organic matter due to litter and root accumulation and soil organic matter (SOM) turnover, and spodic horizons, i.e. deep SOM-enriched soil horizons. Considering LL and PL at the soil group level, Phaeozems, Umbrisols and Podzols, i.e. soils with local SOM enrichment, still showed higher Atterberg limits than the other soil groups as an effect of the LL and PL values distribution in soil horizons.

The correlation between organic C and LL (figure 5), particularly evident in spodic horizons, confirmed that LL and PL values were mainly influenced by the organic matter content rather than the clay content (not correlated with LL, PL), considering the very low clay amount observed in the study area. We can assume that the CEC in the study area was related to organic matter rather than clays, and the correlation of Atterberg limits with CEC was highly dependent on the organic matter content rather than the clay content, quite low in all the considered soils. Therefore, while in mountain soil profiles with scarce to moderate soil development such as Regosols, Cambisols, Calcisols, a decrease in LL and PL is commonly observed with depth (e.g Stanchi et al., 2009, 2013 for Aosta Valley), with a sharp reduction of LL and PL in subsoils, an inverse trend can be observed for Podzols (figure 3), where subsurface spodic Bh and Bs horizons show LL and PL values that were higher than topsoil E ones, comparable with A horizons. Therefore, E horizons might represent a weakness surface with respect to the more resistant and more plastic spodic horizons. Considering the different relationship between LL and TOC in A horizons and SOM-enriched subsurface horizons (i.e. spodic), a role of the SOM quality besides amount might be hypothesized, too. However, the C/N ratio was not, or poorly correlated with either Atterberg limits. The C/N ratio is often considered an indicator of organic matter quality, with low values characteristic of easily decomposable organic substances.

In Podzols and, more weakly, in all C horizons, a significant correlation between Atterberg limits and Fe oxides (both poorly crystalline and crystalline) was observed, comparable to the more generalized function of the organic matter. Fe oxides, therefore, act as inorganic binding agents in structure formation (Sposito, 1989), participate in reducing horizon vulnerability. This confirmed that, depending on the predominating pedogenic processes, soil consistency could be controlled by the abundance of soil organic matter and/or inorganic binding agents. Despite the general absence of strong correlation between LL, PL and C/N ratio, a role of the organic matter quality could be hypothesized too, for specific soil types (e.g. Podzols, with lower C/N values, corresponding to higher LL values). The results of this study show that alpine soils display different behavior with increasing water content, suggesting varying vulnerability in response to intense precipitations. Therefore land management might consider the soil type, too, when dealing with soil hazards. Moreover, as the amount and quality of soil organic matter largely control the soil physical properties considered in this study, some effects of soil management and land use practices (e.g manuring, pasture etc..) exist and should be investigated in future research.

## 5. Conclusions

Despite its relatively small area, the Aosta Valley (NW Italian Alps) is characterized by a wide range of soil types, due the high variability of soil forming factors that affect the predominating pedogenic processes. We considered 62 soils, representative of 7 WRB reference soil groups, characterized by different profile evolution, and investigated the liquid and plastic limits in the different soil types and genetic horizons.

In general, soil consistency was largely determined by the organic matter content (both in topsoils and SOM-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, i.e. showed higher LL and PL values, than the deeper ones, generally characterized by a reduction of soil consistency. This was not confirmed in Podzols, where the SOM enrichment of spodic horizons determined a discontinuity in physical properties between the E horizons (more vulnerable) and the underlying, spodic ones. The same trend can be observed for Calcisols with a deep cemented Bkm.

The research provided a new overview on LL and PL in the main soil types present in Aosta Valley, supporting previous findings on topsoil vulnerability to degradation processes (erosion, consistency losses, losses of strength). This might be very helpful as an integration of regional soils database. The use of LL and PL as indicators of soil physical quality was approached with a pedogenic perspective, and might be helpful for a better definition of hazard mapping on a regional scale. The approach can be transferred to other mid-latitude mountain regions.

## References


Alewell, C., Meusburger, K., Brodbeck, M., and Bänninger, D., 2008. Methods to describe and predict soil erosion in mountain regions, Landsc. Urban Plann. 88, 46–53.

ASTM D 4318-10e1, Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils, ASTM International, West Conshohocken, PA, 2010, www.astm.org (last access 25/10/14)

Borga, M., Stoffel, M., Marchi, L., Marra, F., Jakob, M.,2014. Hydrogeomorphic response to extreme rainfall in headwater systems: flash floods and debris flows. J. Hydrol., in press.

Curtaz, F., Stanchi, S., D'Amico, M., Filippa, G., Zanini, E., Freppaz., M., 2014. Soil evolution after land-reshaping in mountains areas (Aosta Valley, NW Italy). Agric. Ecosys. Env. 199, 238-248.

D'Amico, M.,Previtali, F., 2008. Podzolization on ophiolitic materials in the western Alps (Natural Park of Mont Avic, AostaValley, Italy). Geoderma146, 129-137.

De Vente, J., Poesen, J., 2005. Predicting soil erosion and sediment yield at the basin scale: Scale issues and semi-quantitative models. Earth Sci. Rev. 71, 95-125.

Esposito, L., Esposito, A.W:, Pasculli, A., Sciarra, N., 2013. Particular features of the physical and mechanical characteristics of certain Phlegraean pyroclastic soils. Catena 104, 186-194.
Gee, G.W.,Bauder, J.W., 1986. Particle-size analysis, in: Methods of Soil Analysis: Part I, edited by: Klute, A., ASA, Madison, WI, USA, 2nd Edn., pp 383–409.
Haigh, S.K., 2012. Mechanics of the Casagrande liquid limit test. Can. Geotech. J. 49, 1015-1023.
Haigh, S.K., Vardanega, P.J., & Bolton, M.D., 2013. The plastic limit of clays. Geotechnique 63, 435-440.
Hemmat, A., Aghilinategh, N., Rezainejad, Y., 2010. Long-term impacts of municipal solid waste compost, sewage sludge and farmyard manure application on organic carbon, bulk density and consistency limits of a calcareous soil in central Iran. Soil Till. Res. 108, 43–50.
IUSS Working Group WRB, 2014. World Reference Base for Soil Resources 2014.
International soil classification system for naming soils and creating legends for soil maps. FAO, Rome.
Keller T., Dexter A., R., 2012. Plastic limits of agricultural soils as functions of soil texture and organic matter content. Soil Res. 50, 7-17.
Konz, N., Prasuhn, V., Alewell, C., 2012. On the measurement of Alpine soil erosion. Catena 91, 63–71.
Mehra, O. P., and Jackson, M. L.,. 1960. Iron oxide removal from soils and clays by a dithionite-citrate system buffered with sodium bicarbonate. Clay. Clay Miner. Proc. 7th National Conference on Clays and Clay Minerals, Washington, DC, 1958, pp. 317–327.
Mercalli, L., Castellano, C., Cat Berro, D., Di Napoli, G., 2003. Atlante Climatico della Valle
d'Aosta. (Climate Atlas for the Aosta Valley Region) (Società Meteorologica Subalpina), Torino
Park., D.W., Nikhil, N.V., Lee, S.R:, 2013. Landslide and debris flow susceptibility zonation using TRIGRS for the 2011 Seoul landslide event. NHESS 13, 2833-2849.
Pavlova, I.Jomelli, V., Brunstein, D., Grancher, D., Martin,E., Déqué, M., 2014. Debris flow activity related to recent climate conditions in the French Alps: a regional investigation. Geomorphology, in press.
Rhoades, J. D., 1982. Cation exchange capacity, in: Methods of soil analysis, Part 2, edited by: Page, A. L., Miller, R. H., and Keeney, D. R., Agron. Monogr. 9, Am. Soc. Agron., Madison, WI, USA, pp. 149–157.
Seybold, C. A., Elrashidi, M. A., and Engel, R. J., 2008. Linear regression models to estimate soil liquid limit and plasticity index from basic soil properties. Soil Sci., 173, 25–34.
S.I.S.S 1997. Metodi di analisi fisica del suolo. Ed. Franco Angeli Milano.
Sposito, G. 1989. The chemistry of soils. Oxford Univ. Press, New York.
Stanchi, S., Oberto, E., Freppaz, M., Zanini, E., 2009. Linear regression models for liquid and plastic limit estimation in Alpine soils. Agrochimica 5, 322–338.
Stanchi S., Freppaz M., Zanini E. , 2012a.The influence of Alpine soil properties on shallow movement hazards, investigated through factor analysis. NHESS 12, 1845- 1854.
Stanchi, S., Freppaz, M., Agnelli, A., Reinsch, T., Zanini, E., 2012b. Properties, best management practices and conservation of terraced soils in Southern Europe (from Mediterranean areas to the Alps): a review. Quat. Int. 265, 90–100.

Stanchi, S., Freppaz, M., Godone, D., Zanini, E., 2013a. Assessing the susceptibility of alpine soils to erosion using soil physical and site indicators. Soil Use Man. 29, 586-596.

Stanchi, S., Godone, D., Belmonte, S., Freppaz, M., Galliani, C., Zanini, E., 2013b. Land suitability map for mountain viticulture: a case study in Aosta Valley (NW Italy). J. Maps3, 367-372.

Stanchi S., Freppaz M., Ceaglio E., Maggioni M., Meusburger, K., Alewell. C., Zanini E., 2014. Soil erosion in an avalanche release site (Valle d'Aosta: Italy): towards a winter factor for RUSLE in the Alps. NHESS 14, 1761–1771.

Summa, V., Tateo, F., Giannossi, M. L., & Bonelli, C. G., 2010. Influence of clay mineralogy on the stability of a landslide in Plio-Pleistocene clay sediments near Grassano (Southern Italy). Catena 80, 75–85.

Vacchiano G., Stanchi S., Ascoli D., Marinari G., Zanini E., Motta R. 2014. Soil-mediated effects of fire on Scots pine (Pinussylvestris L.) regeneration in a dry, inner-alpine valley. Sci. Tot. Env. 472, 778-788.

Vardanega, P.J., Haigh, S.K., 2014. The undrained strength-liquidity index relationship. Can. Geotech. J. 51, 1073-1086.

Yalcin, A., 2007. The effects of clay on landslides: A case study. Appl. Clay Sci. 38, 77–85.

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Table 1: average values and st. dev. (in brackets) of relevant chemical and physical soil properties for soil and horizon types. A unique Leptosol case has been grouped with Regosols.

| Horizon type | pH | $CaCO_3$ (g $kg^{-1}$) | Org C (g $kg^{-1}$) | C/N | CEC ($cmol_c$ $kg^{-1}$) | Coarse sand (%) | Fine sand (%) | Coarse silt (%) | Fine silt (%) | Clay (%) | Feox (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Calcisols** | | | | | | | | | | | |
| A (n=3) | 8.1 (0.4) | 10.67 (5.86) | 30.01 (18.8) | 12.8 (4.9) | 5.72 (0.83) | 32.9 (5.9) | 28.9 (10.5) | 5.9 (5.4) | 12.1 (10.6) | 20.0 (18.6) | 0.11 |
| BC or BCk (n=2) | 8.6 (0.0) | 18.58 (1.06) | 4.5 (0.76) | 6.4 (0.56) | 3.98 (0.92) | 42.0 (1.3) | 11.4 (0.91) | 10.3 (1.1) | 21.9 (0.77) | 14.5 (4.1) | Nd |
| Ck or C (n=2) | 8.6 (0.1) | 20.70 (0.28) | 5.76 (0.29) | nd | nd | 19.0 (21.1) | 28.6 (14.0) | 14.0 (3.0) | 27.1 (4.3) | 11.4 (0.3) | 0.06 (0.01) |
| **Cambisols** | | | | | | | | | | | |
| A/AE (n=15) | 5.3 (0.7) | 0.0 | 22.4 (11.5) | 14.5 (3.4) | 13.9 (5.3) | 33.1 (9.5) | 27.7 (6.1) | 14.6 (5.5) | 14.5 (3.2) | 10.1 (3.5) | 0.42 (0.44) |
| BA (n=1) Bw (n=15) or BC (n=3) | 5.7 (0.8) | 0.0 | 10.4 (6.8) | 13.6 (3.7) | 8.1 (2.4) | 40.0 (12.1) | 28.2 (6.7) | 13.0 (6.9) | 11.6 (3.9) | 7.1 (3.8) | 0.39 (0.42) |
| CB (n=1) or C (n=5) | 6.7 (1.6) | 2.2 (3.5) | 5.2 (4.4) | 14.3 (5.9) | 4.9 (3.3) | 47.2 (10.9) | 23.9 (5.2) | 10.3 (1.9) | 12.0 (4.4) | 6.5 (5.5) | 0.30 (0.34) |
| **Leptosols/Regosols** | | | | | | | | | | | |
| A (n=16), or AC (n=1) | 6.1 (0.9) | 0.5 (1.9) | 23.8 (10.1) | 15.4 (3.2) | 11.1 (5.3) | 37.8 (9.4) | 28.2 (7.6) | 13.0 (3.7) | 13.5 (6.3) | 7.5 (3.0) | 0.26 (0.12) |
| Bw(n=2) or BC (n=1) | 5.7 (0.7) | 0.0 (0.0) | 9.1 (3.2) | 15.9 (4.9) | 8.2 (0.1) | 42.0 (11.0) | 27.0 (3.9) | 12.4 (0.3) | 12.0 (7.1) | 6.6 (3.8) | 0.15 (0.0) |
| CA (n=1)or CB (n=3) or C (n=15) | 6.6 (1.1) | 2.1 (5.8) | 7.2 (8.1) | nd | 5.3 (2.3) | 47.9 (10.4) | 23.2 (8.4) | 11.1 (3.2) | 11.9 (5.5) | 6.0 (2.9) | 0.26 (0.24) |
| Phaeozems | | | | | | | | | | | |
| A (n=7) or AC (n=1) | 6.6 (0.9) | 1.22 (2.90) | 36.4 (21.0) | 15.4 (4.8) | 14.1 (6.6) | 37.0 (18.5) | 26.3 (11.8) | 11.3 (2.4) | 15.6 (5.5) | 9.7 (4.0) | 0.23 |
| Bw (n=3) | 6.7(1.4) | 3.13 (5.42) | 6.3 (3.2) | 9.4 (6.1) | 8.5 (2.4) | 34.5 (18.8) | 27.3 (8.6) | 11.3 (5.3) | 16.4 (7.9) | 10.7 (4.8) | Nd |
| C (n=4) | 6.7 (1.2) | 12.1 (12.8) | 1.0 (0.9) | 12.5 (5.2) | 7.2 (3.9) | 45.5 (7.1) | 20.1 (3.0) | 11.9 (4.7) | 15.6 (3.0) | 7.0 (3.5) | 0.24 |
| Podzols | | | | | | | | | | | |
| A (n=1) or AE (n=2) | 4.4 (0.3) | 0.0 | 36.4 (16.0) | 14.5 (2.7) | nd | 19.7 (2.7) | 36.0 (2.9) | 13.2 (2.4) | 17.2 (2.6) | 14.0 (4.0) | 0.46 (0.04) |
| E (n=7) or | 4.5 (0.3) | 0.0 | 16.1 (6.4) | 23.8 (5.5) | 12.89 (2.9) | 30.6 (13.4) | 27.3 (3.7) | 16.2 (3.9) | 18.0 (5.3) | 7.9 (2.8) | 0.24 (0.18) |
| Bs or Bh or Bsh (n=9) or BE (n=1) or BC (n=2) or Bw (n=1) | 4.9 (0.4) | 0.0 | 18.8 (7.6) | 22.2 (2.7) | 12.08 (5.9) | 36.3 (7.9) | 32.4 (8.1) | 12.4 (5.7) | 14.3 (6.5) | 4.7 (1.8) | 1.15 (0.60) |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CB (n=1) or C (n=1) | 5.7 (0.1) | 0.0 | 5.5 (0.03) | 23.9 (6.0) | nd | 45.6 (1.9) | 11.4 (15.0) | 27.9 (17.0) | 11.2 (2.0) | 3.8 (1.8) | 0.27 (0.25) |
| | | | | | Umbrisols | | | | | | |
| A (n=8) | 5.4 (0.4) | - | 35.3 (11.4) | 17.2 (5.4) | 17.6 (4.7) | 26.7 (11.7) | 31.3 (9.8) | 15.2 (6.6) | 16.2 (5.1) | 10.6 (3.9) | 0.34 (0.3) |
| Bw (n=4) | 5.6 (0.5) | - | 11.2 (8.8) | 15.8 (6.7) | 12.3 (4.5) | 34.6 (15.2) | 23.6 (6.6) | 11.1 (7.0) | 20.6 (5.7) | 10.1 (2.1) | 0.27 (0.3) |
| C (n=1) | 5.9 (-) | - | 6.1 (-) | 6.7 (-) | nd | 50.0 (-) | 20.6 (-) | 10.8 (-) | 13.3 (-) | 5.4 (-) | 0.28(-) |

Table 2: descriptive of LL and PL (expressed in %). PL sometimes could not be determined. PI was calculated as LL-PL.

| Descriptives | LL | PL | PI |
|---|---|---|---|
| N | 139 | 88 | 88 |
| Min | 20 | 18 | 2 |
| Max | 104 | 74 | 26 |
| Mean | 48 | 36 | 10 |
| St. dev. | 15 | 10 | 4 |

Figure captions

Figure 1: study area vegetation and lithology, and soil profiles locations

Figure 2: Casagrande chart displaying PI vs. LL. The A-line is plotted on the graph.

Figure 3: LL (liquid limit, %) and PL (plastic limit, %) values for soil types (left side) and genetic horizons (right side)

Figure 4: relationship between LL and PL (both in %) for different soil and horizon types

Figure 5: relationship between LL (%) and organic C content (%) for different soils and horizon types.

Calcisol $R^2$ 0.687; Cambisol $R^2$ 0.475; Phaeozem $R^2$ 0.692; Podzol $R^2$ 0.725; Regosol $R^2$ 0.657; Umbrisol $R^2$ 0.556.

A, $R^2$ 0.491; E, AE, A/E $R^2$ 0.333; Bk nd; Bw $R^2$ 0.372; Bh, Bs $R^2$ 0.877; C $R^2$ 0.204.