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Soil evolution after land-reshaping in mountains areas (Aosta Valley, NW Italy)

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Abstract

Mountain agriculture needs to face several limitations related to climate and topography. Land levelling, reshaping, and terracing are widely adopted in Europe, in order to ease mechanization and make agriculture more rentable. However, while the economic and productive benefits of these operations are well known, the effects on soil chemical and physical properties are not always assessed, and need constant monitoring over time. Intense soil rebuilding has been carried out in Aosta Valley (NW Italian Alps) to improve the accessibility and mechanization, including irrigation, of mountain grasslands.

In this research we present studied on 3 soil chronosequences established in grasslands subject to soil rebuilding practices. The aim was to investigate the effects of land-reshaping operations on soil chemical and physical properties over time, by comparing changes in some selected soil properties such as organic C and soil laboratory indexes for quantifying soil structural resistance.

The soil profiles generally showed a simpler morphology after rebuilding. Soil structure and consistency, that are recognized as soil physical quality indicators, after a sharp negative effect of the disturbance (i.e. decrease in Liquid limit, increased soil aggregates loss) generally showed a trend towards the restoration of the characteristics of the original soils in the medium or long-term time span. Despite the limited sample size, the results represent a first attempt to assess the effects of a technique which is being more and more applied in a mountain region, such as the Aosta Valley Region, where manufactured soils are a significant part of agricultural land. The main findings of our research indicated that: 1) structure and consistency of soils (i.e. aggregate loss, LL, PL) can be used as indicators of soil quality in response of anthropogenic soil disturbance due to land-reshaping operations, as they reflect the evolution of soil properties after intense disturbance; 2) after disturbance, soil recovery was relatively quick, despite the strong deterioration of the physical quality in the immediate (~6-12 months) aftermath of the operations.

Keywords: soil rebuilding, manufactured soils, anthropogenic soils

1 Introduction

Mountain agriculture needs to face several intrinsic limitations resulting from difficult climatic and topographic conditions. Soil chemical and physical fertility, steep slopes and problematic land accessibility, besides climatic conditions, are the main obstacles to profitable agricultural production, and may have indirect effects on land conservation, when marginal areas are abandoned and become prone to natural hazards such as slope failures and enhanced erosion (Crosta et al., 2003; Stanchi et al., 2012).

Land levelling and terracing are important in European agriculture, but associated problems and impacts have not been widely studied (e.g. Martinez-Casasnovas and Sanchez-Bosch, 2000; Ramos et al., 2006a; Ramos et al., 2006b). For example, in vineyards in north east Spain, extensive land levelling to reduce slope gradient and increase field size to allow mechanization has occurred in the last years leading to a significant increase in soil loss (Jiménez-Delgado et al., 2004). Specific land-reshaping techniques have been proposed in Aosta Valley (NW Italian Alps) to improve the accessibility and mechanization, including irrigation, of mountain agricultural areas (grasslands), consequently increasing the crop economic rentability. These practices involve the abandoning of traditional soil conservation measures and the alteration of soil profiles, causing the destruction of the natural soil cover, potentially leading to a loss of fertility and to a strong erodibility at least in the early stages of the evolution of newly-manufactured soils. Thus, soil rebuilding (Buondonno et al., 2013) and land restoration practices (Tobias et al., 2008), which are commonly adopted for the reclamation of sites affected by anthropic disturbance (building sites, mining, etc), are necessary. The interventions include a wide set of techniques with the long-term goal of recovering the original soil properties prior to disturbance in terms of quality and fertility (Harris et al., 1996; Loveland and Webb, 2003; Schaffer et al., 2007). In the case of agricultural soils this means re-establishing and enhancing a high and sustainable soil quality for plant production (Bauer and Black, 1994; Kaufmann et al., 2009). The result is a newly manufactured soil, which can be defined as a HAHT (human-altered or human-transported soil) according by the definition proposed by ICOMANTH (2003) and then discussed by Capra et al. (2013).

While the economical benefits of soil restoration are clearly defined, especially considering the amelioration of agricultural mechanization, potential negative effects can be observed, too, in a wide range of soil properties and at different time scales. However, such effects are extremely variable and little investigated. In general, the agricultural and tillage practices adopted in soil rebuilding may induce considerable changes in soil properties (Martinez-Casasnovas and Sanchez-Bosch, 2000; Borselli et al., 2006; Cots-Folch et al. 2006) with direct consequences on the soil chemical and physical quality. In mountain agroecosystems, the cultivation of steep slopes generally includes deep excavation, refilling, land reshaping, and leveling (Kaufmann et al., 2009), often accompanied by the creation of man-built terraces, resulting in the reduction of the slope angle and the limitation of potential water stresses (Stanchi et al., 2012). The excessive stoniness typical of mountain soils can damage machinery and restrict root growth, and therefore surface stone removal has been largely adopted, too. However, also advantages deriving from surface stoniness have been reported, such as limiting splash erosion (Ramos and Martinez-Casasnovas, 2010), mitigating surface crusting (Poesen and Lavee, 1994), reducing sediment yield (Nyssen et al., 2001). In fact, coarse fragments resting on the surface have the same effects as other mulching materials in protecting the soils against the impact of rain-drops (Chow et al., 1992; Chow and Rees, 1994; Poesen et al., 1994). Despite these contrasting effects, stone removal and subsequent crushing has become a commonly adopted technique which have been recently carried out for land-reshaping in Aosta Valley (Bassignana et al., 2011). Levelling operations may alter the soil microtopography, affecting soil roughness, stoniness, slope, porosity and structural voids (Capolongo et al., 2008), again reducing the total soil depth with potential consequences on plants survival (Kosmas et al., 2000). Land reshaping often imply deep changes in soil chemical and physical properties related with soil fertility such as organic matter depletion, structure degradation, reduction of the infiltration capacity, enhanced erosion (Ramos and Martinez-Casasnovas, 2010; Lundekvam, 2007). Martinez-Casasnovas and Ramos (2009) observed that soils which were subjected to deep ploughing and levelling suffered intense erosion, soil depth reduction, loss of organic matter, reduction of the cation exchange capacity (CEC), overall degradation. Soil organic matter directly influences the aggregate stability and the vulnerability to erosion processes (Stanchi et al., 2012). Therefore, soil structural stability has been suggested as a fundamental indicator of the overall soil quality, particularly in vulnerable soils (e.g. Freppaz et al., 2002; Salome et al., 2010). A reduction of the soil structural stability has been in fact reported as a potential effect of disturbance in mountain soils, together with a reduction of soil consistency (Stanchi et al., 2008, 2009, 2012).

Manuring, together with compost addition and subsequent re-seeding, is a diffuse practice in anthropogenic soils (Pagliai et al., 2004; Buondonno et al., 2013) and it has been adopted also in the management and rebuilding of Alpine grasslands and agricultural soils, too (Larnet and Janzen, 1997; Liu et al., 2006; Bassignana et al., 2011). The use of seeds from introduced grass species has been commonly suggested to establish new vegetation cover in mountain areas (Hagen et al., 2014), in order to increase the speed of natural recovery after disturbances.

In Aosta Valley (Italian NW Alps) large areas (around 55 km^2over 550 km^2 agricultural surfaces, on a total regional area 3263 km^2) have been interested by intensive soil rebuilding, whose extension varies from less than 1 ha to hundreds of ha. In this work we present results from a study on 3 soil chronosequences established in grasslands subject to soil rebuilding practices. The aim was to investigate the effects of land-reshaping operations on soil chemical and physical properties over time, by comparing changes in some selected soil properties such as organic C and soil laboratory indexes for quantifying soil structural resistance. This was done at two levels: a) comparing the soil properties of reference profiles (prior to rebuilding, undisturbed) and rebuilt profiles; b) investigating the evolution of selected soil physical properties (structure and consistency) with the soil age in the study areas.

2 Material and methods

2.1 Study Areas

Our research was conducted in Aosta Valley (NW Italian Alps). We considered three experimental sites: two of them (Verrayes -VE, and Saint-Denis -SD), are located in the central part of the Valley while the third, Gaby (GA), is situated in a lateral valley in the eastern part of the Region (Fig. 1). In general the climate of the region is semi-continental of mountain temperate-cold with low rainfall (Mercalli et al., 2003). Average yearly rainfall is higher in GA than in VE and SD, which have a continental, inner-alpine climate (1000 mm $year^{-1}$ in GA versus less than 600 mm $year^{-1}$ in the other sites). Precipitation maxima are in May and October, with a rainfall minimum during winter. During summer months, precipitations are slightly higher than in winter: the average July precipitations is about 78 mm/month in GA and around 40 mm/month in VE and SD, respectively. Water stress is thus a common problem of VE and SD sites.

The site geology, relief, and land cover are summarized in table 1.

2.2 Experimental design and soil sampling strategy

The chronosequences include sub-areas of different ages at the time of sampling (year 2011), corresponding to different times when land improvement operations took place. For each study area a soil profile was dug, after checking its representativeness with observations by soil coring (approximately 5 minipits/ha). Moreover, a soil profile had been sampled before the operations, in order to check the original soil types and properties. Field description of soil profiles was done according to Soil Survey Staff (1993). Approximately 1 to 2 kg of soil material was collected from every genetic horizon in the soil representative profiles. In the VE area the soil rebuilding was carried out on 83 hectares, divided into 3 sectors where the operations were carried out in year 2000, 2006 and 2008 (soil ages: 11, 5 and 3 years at the time of sampling, respectively). In the SD area the soil rebuilding was carried out on 120 hectares, divided into 3 sectors in each of ones the operation were carried out in year 1997, 2002 and 2008 (soil ages: 14, 9 and 3 years, at the time of sampling, respectively). In the GA area the soil rebuilding was carried out on 4 hectares in 2010 (soil age at the time of sampling: max 1.5 years).

The actions carried out are summarized in table 1. In general, the main aim of the rebuilding operations was to allow the site mechanization, reducing slope and improving the accessibility, however they did not follow a unique protocol for the different sites, but were adapted to local needs and site conditions. The excavations sometimes reached a depth of 6 m (SD in particular, depending on topography), therefore the soils profiles were deeply rebuilt.

2.3 Chemical and physical analyses

Soil pH was determined potentiometrically in water (Soil Survey Staff, 2004), total C (TC) and total N content (TN) were determined by dry combustion with an elemental analyzer (NA2100 Carlo Erba Elemental Analyzer). Carbonate content was measured by volumetric analysis of the carbon dioxide liberated by a 6 M HCl solution (Soil Survey Staff, 2004). The total organic C (TOC) content was calculated as the difference between C measured by dry combustion and carbonate-C (Soil Survey Staff, 2004). Cation exchange capacity (CEC) was analyzed with the $BaCl_2$-triethanolamine method (Rhoades, 1982). Soil texture 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). The WAS (wet aggregate stability) was determined according to the kinetic approach proposed by Zanini et al. (1998). The measurement of the wet aggregate loss allows to know the total loss of aggregate due to explosion after water saturation (corresponding to splash erosion) and abrasion, and the kinetics of disaggregation. The aggregate losses (%) were fitted through a non linear iterative procedure to this exponential model:

$y(t)= a(1-e^{-t/c})+b$ (Equation 1)

where:

y = total aggregate loss (%)

a = maximum aggregate loss caused by abrasion (%)

b = the initial failure of aggregates (%) caused by explosion at water saturation

c = time parameter

The Liquid Limit (LL) was measured with the cone-penetrometer method (SISS, 1997), which gives comparable values as the Casagrande device (Stanchi et al., 2008). The Plastic Limit (PL) was measured using the thread rolling method (SISS, 1997).

All analyses were performed in double and then averaged.

Statistical analyses (Anova, Spearman correlation) were performed with SPSS version 20 (IBM Corp. Released, 2011.) or with R 3.0.1 software (R Development Core Team, 2000).

3 Results

The detailed physical and chemical properties of soil horizons are reported in appendix A (Table A1).

The profiles sketches are represented in Fig. 2. Total depth in undisturbed soil profiles varied from 60 and 80 cm ca., and the topsoils were represented by A horizons (upper 15-20 cm). The main pedogenic processes active in the three sites before the land reworking were different: organic matter accumulation, leading to the formation of deep A and AC horizons, was dominant in GA (Haplic Regosol (Humic, Dystric, Skeletic, Arenic), according to IUSS Working Group WRB, 2006); weathering, leading to the formation of Bw horizons in undisturbed SD soils (Haplic Cambisol (Eutric, Escalic)); $CaCO_3$ accumulation in subsurface Bk diagnostic calcic horizons, characterized by abundant pseudomycelia and small, soft concretions, was observed in VE (Hypocalcic Calcisol (Skeletic)). After soil rebuilding operations, soil depth was considerably reduced, particularly in the GA subarea. However, no absolute trends for A horizon thickness could be observed, because of microscale topography and variability in the performed activities. The newly-formed topsoils were mainly classified as Ap horizons, characterized by anthropogenic origin (presence of anthropic materials). Platy structure and massive consistence characterized many subsoil horizons (Table A1). Genetic Bk and Bw horizon disappeared in newly-built soils, at least in the early stages of development (Fig. 2). In a few cases, the original subsurface B horizons were preserved thanks to localized shallow reworkings (in particular, in site SD3). The restored soils were generally classified as Escalic Anthrosols.

In Fig. 3 the boxplots of some selected chemical and physical properties are presented, comparing topsoil (A and AB horizons) and subsoil (B, C and transition horizons) for control plots and restored soils. The pH values showed higher variability in control profiles, with similar variation ranges for the considered soil depths, due to the significant heterogeneity of climate and parent materials in the study areas (Fig, 3a, see Table A1 for details). Soil pH ranged from acid values in GA subarea, characterized by acid sialic rocks, and alkaline values in the VE subarea, with a substrate rich in calcschists. While the median values of control soils were subacid or close to neutrality (pH ranging from 6 to 7), the median values of the reclaimed soils were subalkaline to alkaline (range of pH 7-8), with some outliers; in particular, restored soils in GA had slightly acidic pH values. In general, rebuilt soils showed rather homogeneous pH values in the subsoil portion, while a higher variability was preserved in the topsoil samples, with a shift of the median towards higher values with respect to the control soil. The carbonates content (Table A1) was highly heterogeneous in the control profiles, but the variability decreased considerably after the soil rebuilding operations. As visible in appendix A, carbonates were absent in the control plot in the SD area, but became relevant after the input of allochtonous soil materials.

The soil texture, too, showed some relevant changes after the soil rebuilding. The skeleton content was slightly reduced after soil rebuilding practices (Fig. 3b, both topsoil and subsoil). Reclaimed soils were characterized by lower sand content (both depths, Fig, 3c), and higher contents of finer fractions (i.e. silt, clay, Fig. 3d, 3e).

The organic C content did not change considerably in terms of range and median values, when considering the same soil depth (Fig. 3f). However, single topsoil samples (e.g. SD- 2002) displayed high organic C content. The C/N ranges did not change significantly as a result of soil rebuilding operations. The CEC in the topsoil samples showed similar median values for control and rebuilt soils (range 10-15 $cmol^{(+)}kg^{-1}$), with around 25% samples with CEC exceeding 15 $cmol^{(+)}kg^{-1}$, while for subsoil samples the CEC value was generally higher after the improvement operations (Fig. 3g).

The GA site showed a much higher total aggregates loss for topsoil samples (Fig. 4a) in the 6 months old soil (ca 80% loss) with respect to the control profile (ca 10% loss). This aggregate loss value, which is extremely high, was very close to the one observed for the allochtonous material used for the land-reshaping operations and to the value of the soil after grinding (Fig. 5). However, after 18 months, a considerable reduction of the total aggregates loss was again observed, with final values comparable to the initial conditions (GAC). The aggregate breakdown curves (Fig. 5) confirmed the trend. In fact, the initial slope of the curves was higher for the recently disturbed soils, while the control and 18 months old soils showed smoother breakdown trends.

The total aggregate loss in VE (Fig. 4b) showed the highest total losses in the 3 years old soil (>90%), while lower losses, however always >70%, were observed for the 5 and 11 years old soils. The total losses were much higher than the ones observed in the control site (< 20%). Also in the SD site (Fig. 4c) the highest total losses were observed 3 years after disturbance (SD3) with values comparable to VE3, while the oldest soil (SD14) displayed a total loss comparable with the control (around 70%). The 9 years old soil (SD9) instead displayed the lowest total aggregate loss.

The LL in GA site (Fig. 6a) dropped around 15 points after 6 months from the land improvement, while very similar values were observed in control plot and in the 18 month soil (LL=62 and 65 respectively). The plastic limit (PL) could not be determined for the GA0.5 (Fig. 6b). In the SD site, the liquid limit initially dropped to around 22 in SD3, but then it increased abruptly (SD9) and finally approached the initial value (SD14, much closer to SDC). The plastic limit could be determined only for SDC and SD9, where an increase was observed in SD9 with respect to the control point (Fig. 6d). In the VE site (Fig. 6e), LL increased with soil age after disturbance, passing from 33 (GA3) to 58 (GA5), and finally 77 (GA11), the latter very close to the control plot value (GAC, LL=88). The plastic limit (when determined) followed a similar trend for the 3 and 5-years-old soils, while a slight reduction was instead observed after 11 years (Fig. 6f).

A positive correlation was observed between the LL and organic C content (Fig. 7a, r= 0.782, p=0.003), a negative one between LL and clay content (r=-0.555, p=0.031, Fig. 7b) and a positive, significant one between LL and the CEC (r= 0.762, p=0.004, Fig. 7c). A highly significant negative correlation between the organic C content and the total aggregate loss (a+b coefficients of Equation 1) for topsoil samples (r=-0.890, p<0.01, n=12) was found (Fig. 7d). LL and PL (when determined) were always well correlated (r=0.738, p<0.035).

4 Discussion

Contributing factors to soil erosion processes within a catchment, such as tillage, land reshaping (e.g., terracing) and ski slopes preparation can have significant impacts on soil profile characteristics in mountain areas, generally leading to an increase of soil erodibility (Poesen and Hooke, 1997; Freppaz et al., 2012). An assessment of soil profile morphology, considering possible truncation, has been one of the traditional approaches for quantifying changes in soil properties caused by erosion (e.g. Phillips et al., 1999). In our study sites the soil rebuilding operations generally resulted in a reduction of the number of soil horizons and total soil depth, i.e. in an overall simplification of the soil profile, which is often reported as a result of intense soil disturbance (e.g. McPherson and Timmer, 2002). One of the most evident effects is the formation of poorly developed "proto-horizons", as defined by Buondonno et al. (2013), i.e. anthropogenic soil surface horizons then subject to natural pedogenesis. The disturbance effect is evidenced by the presence of massive Ap horizons in the reconstructed soils, often characterized by a platy structural aggregation, caused by machine surface reworkings. The physical properties of the control profiles (in particular LL, PL, and aggregate loss) were in line with the ranges found in previous research focusing on Aosta Valley soils, including some natural grasslands (e.g. Stanchi et al., 2008; Stanchi et al., 2012).

The effects of the input of allochtonous material, with characteristics that may differ considerably from the control profile, as evident in Fig. 5 for aggregate breakdown kinetics for soil chemical and physical properties, is particularly evident in the SD site, where a sharp pH increase was directly related with the high $CaCO_3$ content of the allochtonous material used and to calcareous (calcschists) stone grinding, added to amend the carbonate-free control soil (Table A1). Stone grinding was probably responsible of the widespread pH increase observed in restored sites compared to control ones. In fact, only in the GA subarea the pH values remained below neutrality after the land-reshaping, thanks to the acidic nature of the parent lithologies. The general shift towards finer textural classes observed for rebuilt soils can be interpreted as a result of stone grinding, too, that caused also the slight skeleton reduction. The amount of organic carbon in rebuilt soils generally showed an increase with soil age as visible in Table A1 and it was, at least in the early stages of soil development, strictly related with manure inputs. In general, the C/N ratio does not suggest any significant change in organic matter quality and stage of alteration in restored soils. The C/N values calculated in the soils are in fact typical of manured grassland soils, with a good biological activity and a fast nutrient cycling (Körner, 2003). A particularly high C/N ratio was measured in the 2Cg2 horizon of soil VE5, and it was related to a buried histic horizon, developed in ancient times and naturally buried beneath weakly pedogenized materials (2CBg, 2Cg1). The CEC in topsoils is highly correlated with the organic C content ($r=0.889$, $p=0.018$ for control profiles; $r= 0.865$, $p<0.001$ for restored profiles) while no correlation is observed with the clay content (data not shown). The quite unexpected absence of relationship between clay and CEC and between clay and the liquid limit (Fig. 7b) might be another effect of the milling of the allochtonous material, i.e. the soil particles in the dimensional range of clay are not of pedogenic origin, but only a result of the mechanic operations carried out during the land-reshaping.

Our data suggest that in the immediate aftermath of land reshaping operations and soil rebuilding the soil structure and consistency may be deeply affected, as visible from the trends depicted in Figs. 4 and 6. Literature data support these findings. For example Lundekvam et al. (2003) found very adverse effects of land levelling on soil structure and erodibility. However, some signals of recovery could be seen after a limited amount of time. For example, the GA site showed a considerable reduction in soil physical quality in terms of structure (aggregate loss) and consistency (Atterberg Limits) immediately after the rebuilding, then followed by a recovery after a relatively short time (only 18 months since the end of the operations). The aggregate breakdown curves (Fig. 5) confirmed this trend, not only in terms of total amount of soil loss, but also from the qualitative point of view. In fact, the aggregates loss was almost immediate for the newly manufactured topsoils, behaving as loose sediments, while after 18 months the curve nearly reflected the original topsoil conditions (control, undisturbed), thanks to a high organic matter accumulation and incorporation in organo-mineral aggregates and a good biological activity. Similar findings have been reported in other sites for physical properties. For example, Kaufmann et al. (2009) observed that physical qualities (e.g. compaction degree) in an Eutric Cambisol become close to optimal values just after the end of the restoration, with a relatively quick regeneration time (3 years). In VE and SD the trend in aggregates loss shows a surprisingly low value in the 5 years old and 9 years old topsoil, i.e. soils with intermediate development stage were less vulnerable to aggregates loss than control plots. An explanation for this behavior was hypothesized for the SD site, where the organic C content of the rebuilt topsoil was more than double with respect to the control topsoil (Table A1). In this case, a comparable behavior was observed for the liquid limit of topsoil, too. We could not find a clear explanation for the VE5 topsoil, where the organic C content does not seem to justify the lower aggregate loss, for the intermediate soil age, that was in this case much less pronounced. We can however hypothesize some local variability in site/soil properties, meteorological conditions at the time of restoration, or more likely accidental differences in the restoration procedures (i.e. absence of a common operational protocol) which cannot be quantified. The trend of liquid limit in the VE site was instead well related with soil age. Different speed of recovering of the original structural stability could be caused also by different climatic conditions: the higher biological activity characterizing GA site is probably associated also with a higher rainfall compared to the more xeric, inner-alpine VE and SD sites.

The relationships between organic C content and soil physical properties indicates a strong contribution of the organic matter to soil structure and consistency, already reported for Aosta Valley environments by Stanchi et al. (2008, 2009). The importance of soil C production and of biological activity in ameliorating soil resistance is verified in all study areas, where manuring contributed to a rapid recovery of the soil organic matter content in the re-shaped lands. In fact, restricting the dataset to newly built soils, the correlation between aggregate stability with organic C is still present ($r=-0.884$, $p<0.001$) as well as the correlation between LL and organic C ($r=0.651$, $p<0.01$).

5 Conclusions

The effects of land-reshaping techniques, used to improve the land accessibility and workability of alpine grasslands, on soil properties were analyzed considering three sites in Aosta Valley (NW Italian Alps). Chemical and physical soil properties and soil profiles morphology were described for the different soil ages and compared with control sites (undisturbed soils). The newly manufactured soil profiles generally showed a reduced total depth, with a simplification of soil horizon types and number. Soil structure and consistency, that are recognized as soil physical quality indicators, after a sharp negative effect of the disturbance (i.e. decrease in Liquid limit, increased soil aggregates loss) generally showed a trend towards the restoration of the characteristics of the original soils in the medium or long-term time span A few exceptions were observed for soil aggregates loss in intermediate soil ages, possibly related with climate conditions or site variability.

Despite the limited sample size of our case study, the results represent a first attempt to assess the effects of a technique which is being more and more applied in a mountain region, such as the Aosta Valley Region, where manufactured soils are a significant part of agricultural land. The main findings of our research indicated that: 1) structure and consistency of soils (i.e. aggregate loss, LL, PL) can be used as indicators of soil quality in response of anthropogenic soil disturbance due to land-reshaping operations, as they reflect the evolution of soil properties after intense disturbance; 2) after disturbance, soil recovery was relatively quick, despite the strong worsening of the physical quality in the immediate (~6-12 months) aftermath of the operations.

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Table 1: site characteristics and experimental design

	Gaby (GA)	Verrayes (VE)	Saint Denis (SD)
UTM WGS 84 Coordinates (X; Y)	403166; 5062640	385350; 5070433	385350; 5070433
Altitude (m a.s.l.)	1028-1096	1365-1600	1200-1400
Aspect	SSW	SSW	SSW
Surface area	4 ha	83 ha	120 ha
Geomorphology	Alluvial fan	Glacial till / slope	Glacial till / slope
Substrate lithology	Gneiss, mica-schists	Mixed local ophiolitic materials (serpentinite, gabbros, calcschists)	Mixed local ophiolitic materials (serpentinite, gabbros, calcschists)
Land cover (in brackets, land use of control site, if different)	Grassland	Irrigated Grassland (abandoned terraced grassland)	Irrigated Grassland
Number of profiles, dates of reworking and soil age during	5 profiles: - 1 control (GAC) – 2 2011 (GA0.5a.	4 profiles: - 1 control (VEC) - 1 2000 (VE11)	4 profiles: - 1 control (SDC) - 1 1997 (SD14)

sampling	GA0.5b) - 2 2011 (GA1.5a, GA1.5b)	- 1 2006 (VE5) - 1 2008 (VE3)	- 1 2002 (SD9) - 1 2008 (SD3)
Slope reshaping	Masonry (terraces) reconstruction Surface modelling	Installation of irrigation system Surface modelling	Installation of the irrigation system Surface modelling
Soil removal	Topsoil removal Stone removal Excavation -	Sward removal and topsoil removal Deep soil excavation (more than 2 m) Stone removal Rocks landfilling	Sward removal and accumulation of the superficial horizons Deep excavation of the soil (up to 6 m) Rocks landfilling
Soil and vegetation restoration	Soil reconstruction (with previously removed topsoil). Stone milling Grinding and redistribution of milled	Soil reconstruction Manuring Hydro seeding	Soil reconstruction Stone milling Manuring Hydro seeding

	material Manuring (cattle manure-Compost); Hydro seeding		

Fig. 1. The study areas in the North-Western Italian Alps.

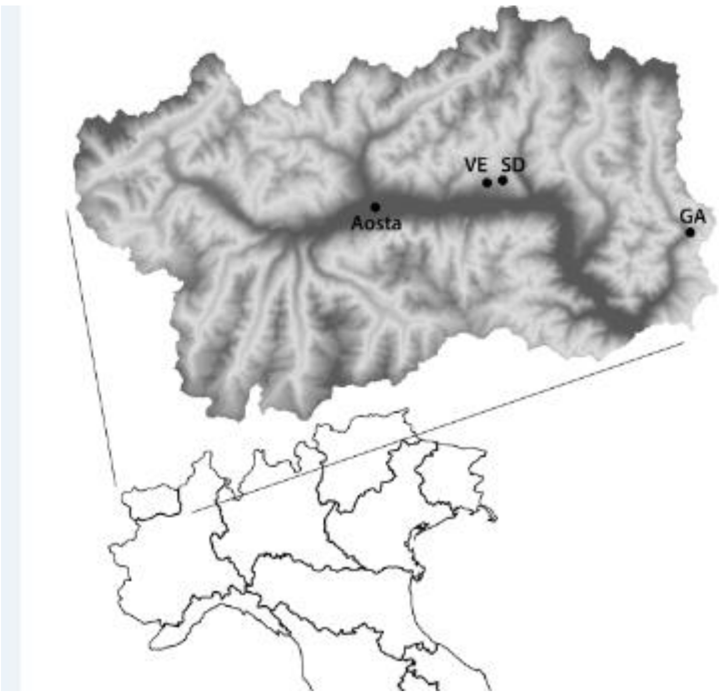


Fig. 2. Soil profiles along the studied chronosequences, developed with the soil profile package for R (Filippa, 2013). X evidences horizons with play structure and massive consistence.

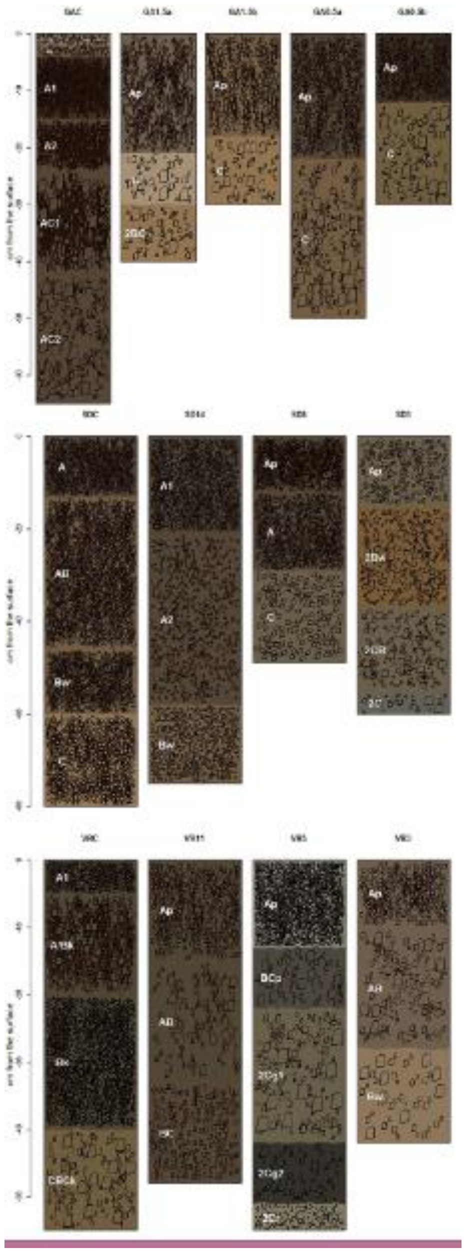


Fig. 3. Boxplots of relevant soil properties for topsoil and subsoil samples: pH values (a), skeleton w/w % (b), sand textural fraction % (c), silty fraction % (d), clay % (e), TOC g*kg^{-1} (f), C/N ratio (g), CEC cmol* kg^{-1} (h); marginally significant differences ($p<0.1$) between groups are shown with small letters above the boxes. Rtop and Rsub refer to restored soils top horizons and subsoil ones respectively, Ctop and Csub to control top and subsoil horizons.

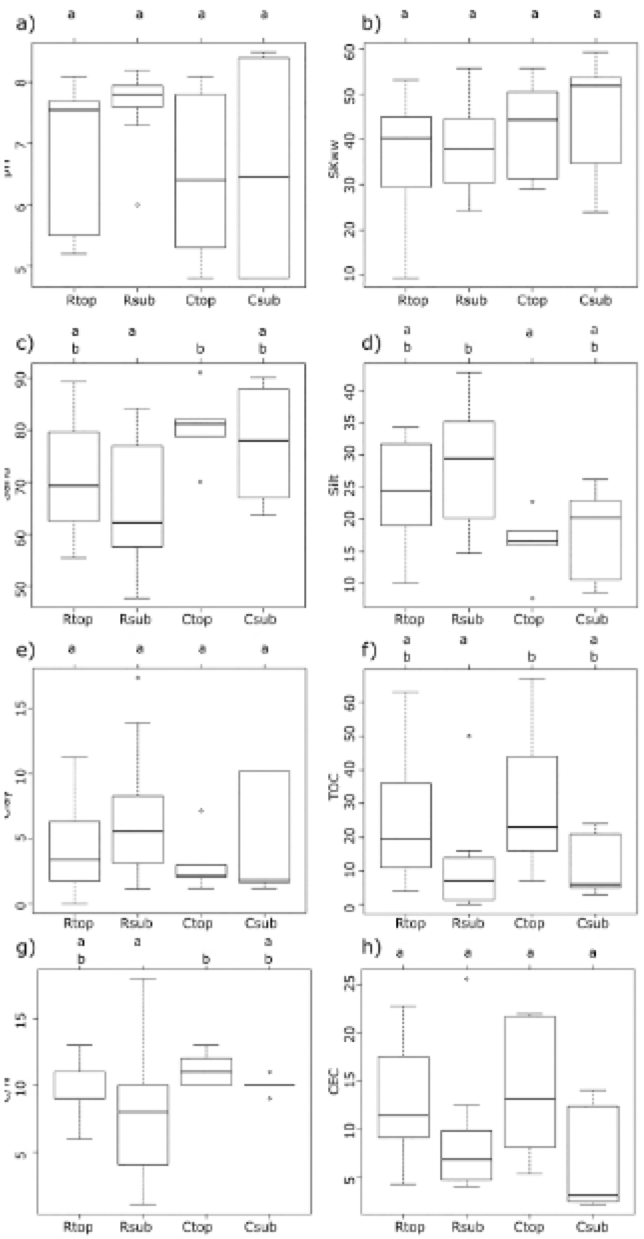

a)
pH
Rtop Rsub Ctop Csub
b)
SKww
c)
d)
Silt
e)
f)
TOC
g)
h)
CEC

Fig. 4. Total aggregates loss (a+b, from Equation 1) for topsoil samples (n=12), separated by study area.

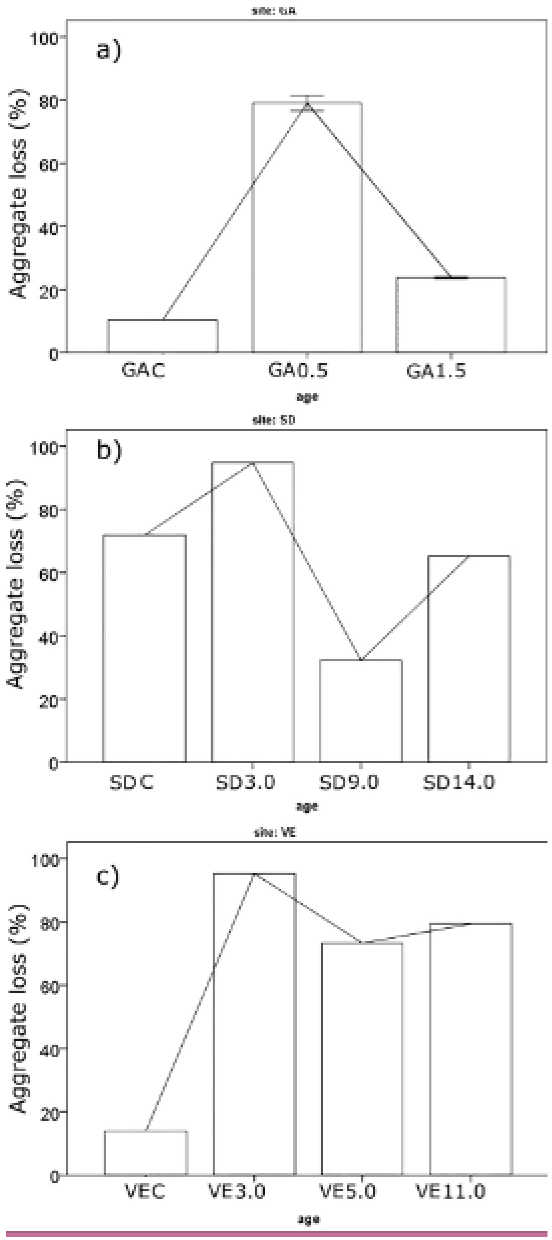

site: GA
a)
Aggregate loss (%)
100
80
60
40
20
0
GAC
GA0.5
GA1.5
age
site: SD
b)
Aggregate loss (%)
100
80
60
40
20
0
SDC
SD3.0
SD9.0
SD14.0
age
site: VE
c)
Aggregate loss (%)
100
80
60
40
20
0
VEC
VE3.0
VE5.0
VE11.0
age

Fig. 5. Example of aggregate breakdown curves in the GA site.

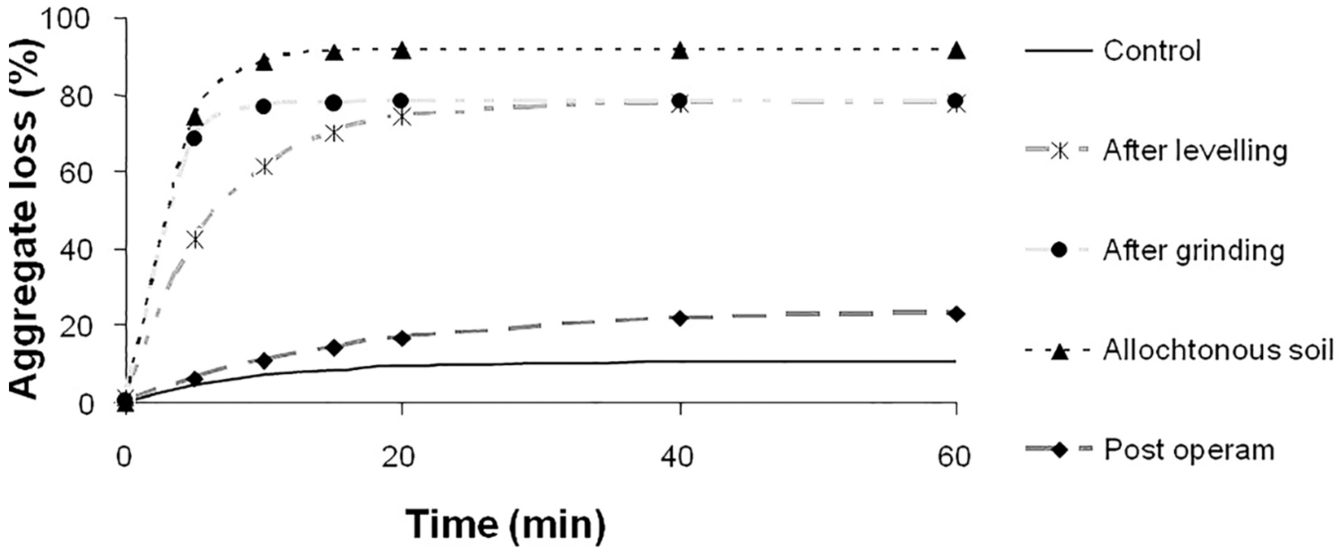
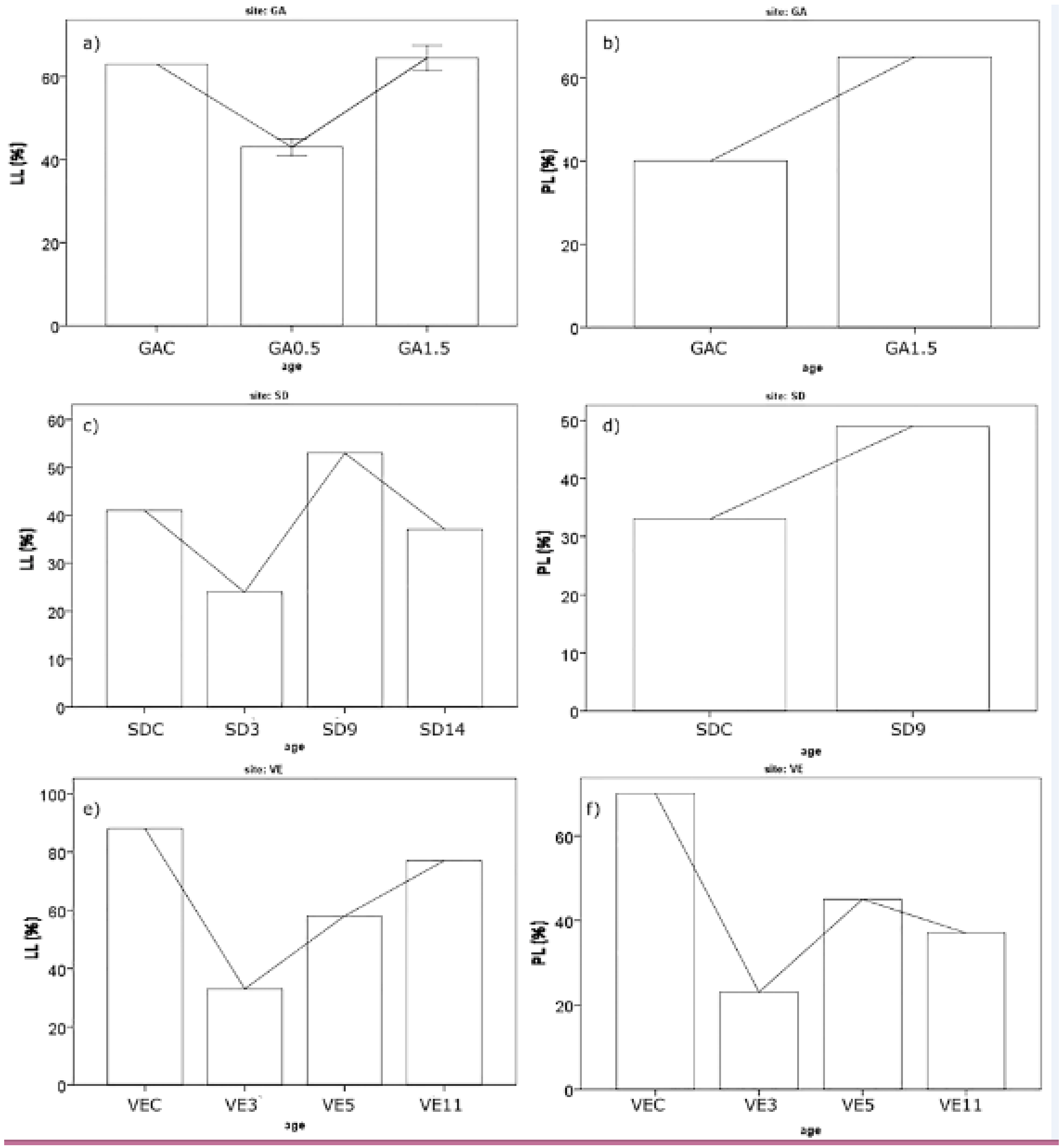
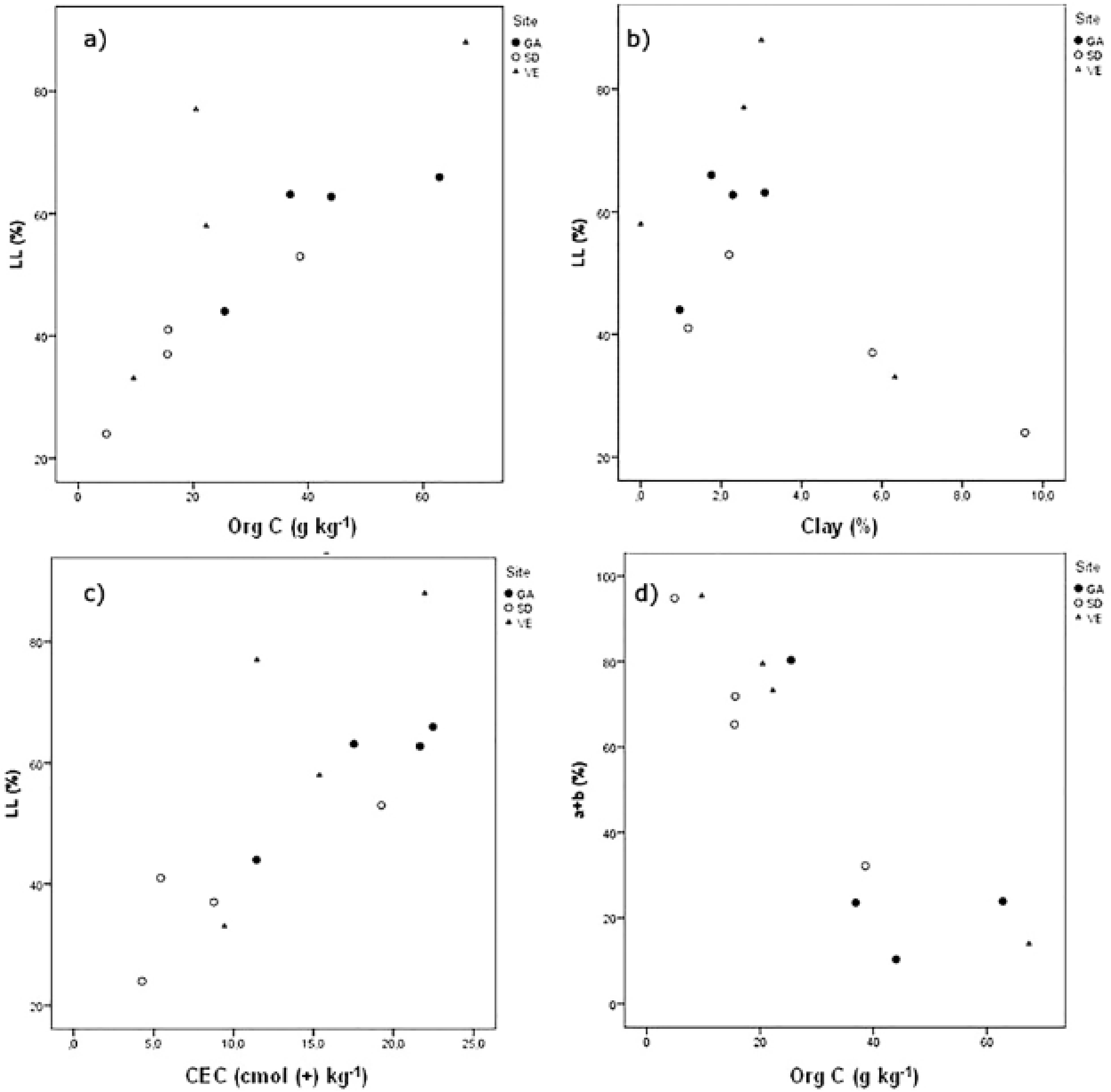


Fig. 6. Liquid limit and plastic limit (when determined) for topsoil samples, separated by study area.



site: GA
a)
LL (%)
GAC
GA0.5
GA1.5
age
site: GA
b)
PL (%)
GAC
GA1.5
age
site: SD
c)
LL (%)
SDC
SD3
SD9
SD14
age
site: SD
d)
PL (%)
SDC
SD9
age
site: VE
e)
LL (%)
VEC
VE3
VE5
VE11
age
site: VE
f)
PL (%)
VEC
VE3
VE5
VE11
age

Fig. 7. Relationships between the liquid limit (LL) and TOC (a), clay fraction (b), CEC (c) and between total aggregate loss (a+b) and TOC in topsoil samples (n=12).


a)
Site
GA
SD
VE
LL (%)
Org C (g kg-1)
b)
Site
GA
SD
VE
LL (%)
Clay (%)
c)
Site
GA
SD
VE
LL (%)
CEC (cmol (+) kg-1)
d)
Site
GA
SD
VE
a+b (%)
Org C (g kg-1)