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Soil carbon stock in relation to soil properties and landscape position in a forest ecosystem of southern Italy (Calabria region)

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Abstract

Carbon (C) storage in forest soils is of great importance both to forest ecosystems and to reduce the CO_2 in atmosphere. Knowledge of spatial pattern of soil organic carbon (SOC) and the factors influencing it in various soil-landscapes are essential for understanding global C cycle.

The objective of this study was to investigate at profile scale SOC stock in a forested area of southern Italy (Calabria) in relation to soil properties and landscape position. Twenty-eight soil profiles were sampled to cover all soil types and physiographic units of the study area and each horizon was sampled and characterized for its physical-chemical properties (bulk density, texture, pH, SOC, and nitrogen). Moreover, the organic horizon (O) was sampled and SOC concentration was determined. Then, the SOC stock for the organic layer and mineral horizons was calculated.

Soils developed in the study area belong to the Inceptisol and Entisol orders varyring from very shallow to moderately deep, and chemical and physical characteristics mainly controlled by granitic parent rock. SOC stock for the organic layer varied from 3 Mg ha^{-1} to 6 Mg ha^{-1} whereas for mineral horizons ranged between 20.2 Mg ha^{-1} and 310.9 Mg ha^{-1}.

The results showed a different behaviour of physical-chemical properties and carbon store for coarse-textured soils and more fine-textured soils. In addition, soil types and topographic features such as slope gradient, slope curvature and landscape position controlled SOC stored in mineral horizons through changes in both in-depth variability of SOC concentration and profile thickness. In particular, higher SOC stocks were recorded in flat areas than on steep slopes, and Inceptisols developed on slopes with concave morphology exhibited higher values than Entisols located on convex slope.

Key words: Forest soils, landscape position, soil properties, carbon stock, Calabria, Southern Italy.

1. Introduction

Forest ecosystems cover large parts of the land surface and play an important role in the terrestrial carbon (C) cycle (Lorenz and Lal, 2010). Particularly, forest ecosystems accumulate organic compounds in vegetation through photosynthesis, and return C to the atmosphere by auto- and heterotrophic respiration, and fix C into stable soil organic carbon (SOC) pools (Post and Kwon, 2000; IPCC, 2003; Wilson and Daff, 2003; Depro et al., 2008; McKinley et al., 2011; Pan et al., 2011).

Small variations in SOC can significantly affect the global C cycle, climate change, and soil properties (Lal, 2005; Powlson et al., 2011). There is a clear consensus that sustainable use of forest and soil resources is one of the ways to manage climate change and mitigate global warming. That requires a deeper understanding of the spatial distribution of C storage to support management policies of the forest ecosystems. Consequently, it is crucial quantifying and understanding the spatial variation of soil C stocks in forests, and identifying the environmental factors controlling its dynamics (Batjes, 1996; Six et al., 2002a).

In forest soils, the continuous addition of decaying plant residues to the soil surface and root growth and decay represent the main sources of SOC. The decomposition of the plant litter is one of the main processes of formation and evolution of forest soils showing organic and mineral horizons (O and A horizon) characterized by a high content of humic substances, representing the major components of the global carbon budget (Šnajdr et al., 2008).

Therefore, the amount of SOC is calculated by the net balance between the rate of above and below ground organic matter input and SOC mineralization (Golchin et al., 1994; Gregorich and Janzen, 1996). Many studies on soil carbon storage have generally focused only on the organic horizons and on the first 20 cm of soil profile (e.g. Wallace and Freedman, 1996; Yanai et al., 2003; Olsson et al., 1996; Taylor et al., 2007; Teklay and Chang, 2008; Innangi et al., 2015), often neglecting the deeper mineral soil horizons (Diochon et al., 2009). In the last years, several studies have nevertheless highlighted the importance of subsoil in the total SOC storage (Wang et al., 2010), especially in forest ecosystems (e.g. McCallister and Del Giorgio, 2012; Rumpel and Kögel-Knabner, 2011; Tarnocai et al., 2009; Marty et al., 2015; Kirsten et al., 2016). In addition, studying SOC distribution along soil profile is important since content and stability of SOC strongly varies among soil horizons due to changes in soil chemical and/or physical properties (Rumpel and Kögel-Knabner, 2011; Parras-Alcántara et al., 2015).

Several authors highlighted how the amount of SOC stored in soil is not only controlled by organic carbon concentration but also by physical, chemical, and biological soil properties (Christensen, 1992; Trumbore et al., 1995; Hassink 1997; Six et al., 2002a), among which bulk density, stone content, and soil depth are the most important (Batjes, 1996; IPCC, 2003; Salomé et al., 2010). The variations of chemical-physical properties are greatly influenced by slope morphology and landscape position which affect soil depth, profile development, texture and structure in relation to erosional and depositional processes (Costantini, 1993; Telles et. al., 2003; Houben, 2008; Costantini et al., 2013; Lucà et al., 2014).

Moreover, assumed that at large scales climate is one of the main factors explaining SOC distribution, at local scale, SOC stocks can vary significantly due to the influence of anthropogenic factors such as land use or management practices (Tan et al., 2004; Lal, 2005; Mou et al., 2005; Von Lützow et al., 2006), as well as environmental factors like parent material, soil properties and topography (e.g. Callesen et al., 2003; García-Pausas et al., 2007; Bruun et al., 2015; Nadeu et al., 2015). In particular, topography has been identified as an important variable for explaining SOC stocks since it influences the distribution of organic matter and soil nutrient (Abrams et al., 1997), the rates of litter decomposition (Sariyildiz et al., 2005), the stability of SOC between landform positions (Chaplot and Poesen, 2012) as results of transport and selectivity of geomorphic processes (Nadeu et al., 2015).

In this context, the main objective of the study was to analyse soil carbon stocks at profile scale in a forest ecosystem of southern Italy (Calabria region) in relation to soil properties and landscape attributes. Furthermore, as factors controlling SOC dynamics may vary vertically along the profile, the variation of soil properties with depth was also analyzed. Given that parent material and tree cover do not vary across the study area, the work allowed to constrain the influence of changes in soil chemical-physical properties and topography even within a limited area.

2. Material and methods

2.1 Study area

The study area, large about 33.2 hectare, was located within the Biogenetic Natural Reserve "Marchesale" (Calabria region, southern Italy), at 38° 30′ 7″ N to 38° 29′ 31″ N of latitude and 16° 14′ 10″ E to 16° 14′ 42″ E of longitude (Fig. 1a). The study area is covered by a beech forest (*Fagus sylvatica L.*) with sporadic silver fir trees. The elevations range from 1137 to 1212 m a.s.l., whereas slope gradients range between 0 to about 45 degrees, with an average of 11.2 degrees, and the prevalent slope exposure is west and north.

The area has a typical Mediterranean upland climate (*Csb*, *sensu* Köppen 1936). Thermo-pluviometric data coming from the station of Mongiana (38°29'55'' N, 16°19'11''E, 921 m a.s.l.) showed an average annual precipitation equal to 1,810 mm and an average annual air temperature of 10.7 °C. The average maximum air temperature (summer) is 28.3 °C, whereas the average minimum air temperature (winter) is -3.7 °C. The soil moisture regime is udic and the soil temperature regime is mesic (ARSSA, 2003).

The study area is located within the Serre Massif which represents the central sector of the Calabrian–Peloritan arc (Amodio-Morelli et al., 1976), where Hercynian granitoid rocks, mainly represented by granodiorite, locally intruded by pegmatite dikes, crop out. These rocks in outcrop appear intensely fractured and characterized by chemical and/or physical weathering processes, which produced rock fragmentation into large blocks or microgranular disintegration.

The bedrock, locally, is mantled by thick regolith and/or colluvial deposits (Borsi et al., 1976; Calcaterra et al., 1996; Conforti et al., 2013). In particular, colluvial deposits, with variable thickness can be observed in concave areas and at the foot of the slopes (Fig. 1b).

The geomorphology of the area is characterized by a mountains landscape, generally, with V-shaped valleys, assuming a concave shape when partly filled by colluvial deposits (Fig. 1b). Summit paleosurfaces (Sorriso-Valvo, 1993; Calcaterra and Parise, 2010; Lucà et al., 2011), representing the residual flat or gently-sloping highlands, often bordered by steep slopes and deep incisions also occur. In some places, especially on the residual paleosurfaces where the regolith has been removed, subspherical corestones and boulders of unweathered or less weathered rock, have been exhumed and outcrop on the ground surface (e.g. Le Pera and Sorriso-Valvo, 2000; Scarciglia et al., 2005).

2.2 Field survey and soil sampling

Through the interpretation of topographic map at 1:5,000 scale and field survey, a detailed geomorphological analysis was performed in order to map the landscape units of the study area. In particular, four landscape units were identified: summit paleosurface, steep slope, gentle slope, and valley floor (Fig. 1c). Moreover, some terrain attributes, such as slope gradient, aspect and curvature, were extracted by a digital elevation model (DEM) with a cell size of 5 m and used as support for landscape unit mapping and pedological survey.

Twenty eight pedons (9 soil profile and 19 hand auger drilling, using 'Edelman auger') were chosen and described, during summer 2014, trying to cover all landscape units of the study area (Fig. 1c). All soil profiles were dug down to the parent material or Cr horizon, and a detailed field description based on standard international guidelines (FAO, 2006; Schoeneberger et al., 2012) was made. Both bulk and undisturbed (core) soil samples were collected in each mineral horizon for laboratory physical and chemical analyses. The Cr horizon was always sampled for a thickness of 20 cm to obtain comparable results in all pedons, also because the auger did not always allow to exceed this depth in the parent material. Undisturbed soil samples were extracted using a stainless steel cylinder of 100 cm^3 in volume, and bulk density (BD) was evaluated considering the volume of stones if present. BD cores were sampled near the midpoint of each horizon in each profile and at each auger hole.

Moreover, for each soil profile, the entire organic horizon (O) was sampled neglecting sublayers within a frame of 20 cm x 20 cm and SOC and total nitrogen (N) contents were determined.

2.3 Physical and chemical analyses

The collected soil samples from the mineral (80 samples) and organic horizons (28 samples) were first dried for 48 hours at 40°C in a ventilated oven then were gently crushed using pestle and mortar removing the visible roots, and passed through a 2 mm sieve. Particle size distribution was determined by the hydrometer method (Bouyoucos, 1962; Patruno et al., 1997), based on dispersion and sedimentation principles, using sodium hexametaphosphate as a dispersant. The soil particle size distribution (sand, silt and clay) was classified in accordance with the USDA soil texture triangle. In order to evaluate the BD of mineral horizons, each soil core was oven dried at 105°C and the dry weight of the soil was divided by the volume of the core, reduced considering the skeleton content (Holmes et al., 2011).

The pH was measured by mixing soil with deionized water at a soil: water ratio of 1:2.5 followed by shaking the suspension for 1 hour and using a pH meter (HI 92240®, Hanna Instruments, Woonsocket, RI, USA). SOC concentration was determined by means of dry combustion, using a Shimadzu TOC-L analyzer with a SSM-5000A solid sample module (Shimadzu Corporation, Kyoto, Japan). Since all soil samples were carbonate-free, SOC was assumed to equal total carbon.

Nitrogen (N) concentration was determined by combustion of microsamples (5 mg of soil) in an Elemental Analyzer NA 1500 (Carlo Erba Instruments, Milan, Italy).

Dry and weighted samples of organic horizons were pulverized through a cutting mill and a mortar, and SOC and N were measured using the methods described above.

Finally, the soil carbon/nitrogen ratio (C/N) was calculated. Moreover for each sample, dry soil color was evaluated by using the Munsell soil color chart.

2.4 Calculation of SOC stock and statistical analysis

SOC stock (Mg ha^{-1}) for the organic horizon (SOC $stock_o$) was calculated using the equation of Baritz et al. (2010):

$$SOC\ stock_O = \frac{SOC \times R}{100} \quad (1)$$

where SOC is the soil organic carbon contentration (g kg^{-1}) and R (kg m^{-2}) is the ratio between dry weight of the organic horizon and the size of the sampling frame.

The SOC stock for the mineral soil ($SOC\ stock_m$) of each soil profile was calculated using the equation of Batjes (1996):

$$SOC\ stock_m = \sum_{i=1}^{n} \frac{D_i \times BD_i \times SOC \times (1\text{-}SC/100)}{10} \quad (2)$$

where n is the number of soil horizons, D_i is the depth (cm) of i^{th} soil horizon, BD_i is the soil bulk density (g cm^{-3}), and SC is the skeleton concentration expressed as percentage in volume.

To detect if physical-chemical properties vary with soil depth and soil texture, and to evaluate the effect of different source of variation (soil texture, soil type, slope gradient, slope curvature landscape position) on SOC stock, the non-parametric Mann-Whitney test was used. The test allowed assessing significant differences in the medians of two considered categories, using a threshold for significance of 0.05. If $p < 0.05$, differences were considered statistically significant.

All statistical analysis were carried out using SPSS 19.0.

3. Results and discussion

3.1 Soil properties

The site characteristics of the investigated soil profiles as well as the main morphological features were reported in Table 1. The distribution and development of soil profiles in landscape units were generally influenced by the alteration grade of the granitic rock and by topographical features (Table 1). Field survey showed that parent rock in the study area varied from highly to slightly weathered (Table 1), following the International Association of Engineering Geology (IAEG, 1995) classification. The highly weathered granitic rocks with a sandy-gravelly grain distribution were sometimes coupled with colluvial deposits.

According to the USDA (2014) classification, the soils of the study area belong to Inceptisols (*Humic Dystrudept*) and Entisols (*Lithic Udipsamments*). All the pedons were shallow to moderately deep, with thickness varying from 13 to 125 cm (Table 1). Profile thickness was related to landscape position; in particular, shallow soils developed onto convex slopes with slope gradient generally greater than 20° where parent rock was slightly weathered. On the contrary, moderately deep soils were found on the summit paleosurface, gentle slopes and valley floors, with moderately to highly weathered parent rock. In some topographic depressions, as well as along the footslope, severe reworking and accumulation of colluvial soil eroded from upslope areas lead to the formation of thicker soil as observed in other contexts (Lucà et al., 2014). Many Entisols were often developed in fairly steep slopes or on areas where bedrock crop out. Entisols were typically shallow, with an average thickness around 30 cm, and exhibited minimal horizon development (O-A-Cr/R) while the common horizonation of Inceptisols was O-A-Bw-Cr, O-A-AB-Bw-Cr. The organic horizon (O), with thickness generally around 3-5 cm, had a characteristic black or dark brown color (10YR 2/1 -2/2) and consisted mainly of Oi-Oe and secondly by Oa sublayers, that correspond to OL-OF and OH horizons, respectively (Zanella et al., 2011; Sicuriello, 2015). Based on these characteristics the humus form were mainly Moder and more rarely Mor.

Table 2 summarizes the summary statistics of mineral horizons. The A horizons had thickness varying from 5.0 to 61.5 cm and exhibited a very dark brown colour (10YR 3/2-3/3) due to the accumulation of organic matter (umbric epipedon, USDA, 2014) without its downward migration within the profile, in response to progressive decomposition of plant residues. The AB, Bw and BC horizons were characterized mainly by dark yellowish brown (10YR 4/4) and/or yellowish brown (10YR 5/4-5/6) colours, whereas Cr were typically brownish yellow.

Soil structure of surface horizons generally varied from granular to sub-angular, with some variations in size of peds (mean size 1 cm) and a consistence from very weak to weak; in the deep horizons, the structure was weakly to moderately developed with sub-angular peds. Roots, mostly found in the first 40-50 cm of depth, were mainly very coarse and coarse. Within soil profiles, skeleton constituted by parent rock fragments showed shapes from sub-rounded to sub-angular and diameters ranging approximately from 0.5 to 5 cm. The percentage of skeleton varied from 1 to 54% and significantly increased with soil depth passing from Bw to BC and from BC to Cr horizons (data not shown).

Particle size distribution of mineral soils was dominated by sand and silt (about 70-80%) for all the horizons (Table 2). Statistical analysis revealed that sand content did not vary significantly ($p>0.05$) between consecutive horizons apart from Bw to BC and BC to Cr layers (data not shown). Soils were coarse and medium-textured and, following USDA soil texture triangle, were classified as loamy sand, sandy loam and loam.

Soil BD varied between 0.23 g cm^{-3} and 1.66 g cm^{-3} and a tendency to increase gradually with depth (Fig. 2a). The particularly low BD values in A horizons (Table 2) could be related to the partial volcanic contribution to the soil and associated andic properties, as documented in another pedon very close to the study area (Vingiani et al., 2014), and presumably also to the typical, highly aerated and porous structure of andic-like topsoils (cf. Scarciglia et al., 2005, 2008).

Significant differences of BD values in consecutive horizons were observed for AB-Bw and BC-Cr horizons (Fig. 2a). Other studies in forest soils confirmed the increase in bulk density with increasing depth (De Vos et al., 2005; Schrümpf et al., 2011) and according to Grüneberg et al. (2014) high BD values in deeper soils are due to weight of the overlying horizons.

The comparison of BD within soil texture classes showed that for loamy sand soils significantly higher values than those of the other classes whereas the lowest values were recorded by loam soil (Fig. 3a). The higher bulk density of loamy sand soils may be related to the lower soil porosity and soil compaction than loam soils.

Soil pH varied from moderately to strongly acid, with values ranging between 4.0 and 5.3 (Table 2) and it showed no trend with depth nor significant differences among soil horizons, as also observed by Costantini (1993), and Vingiani et al. (2014) in other mountain sites of Calabria. The high acidity of forest soils resulted from the granitic acid parent rock, the high rainfalls of the study area and from considerable amount of litter accumulation. As suggested by Hagen-Thorn et al. (2004), low pH values may result from the production of organic acids and the delay of return of base cations to the soil combined with slow beech litter decomposition.

SOC concentration in O horizons ranged between 217.0 and 369.8 g kg^{-1}, with a mean value of 284.9 g kg^{-1} (Table 3) and, as expected, it was statistically higher (approximately four times) than mineral horizons (Fig. 2b). High concentration of SOC in the organic horizon was related to the abundance of beech litterfall (Guckland et al., 2009) and the continuous supply of carbon provided by the decomposition of plant detritus and roots. Such phenomena are generally favoured by high precipitation which lead to low rates of litter decomposition and therefore SOC accumulation (Hagen-Thorn et al., 2004; Guckland et al., 2009). In addition, Trumbore et al. (1996) highlighted how low temperatures could reduce SOC breakdown, increasing SOC accumulation and weakening the positive effect of precipitation. Therefore, the accumulation of SOC was also favoured by the cool and wet climate of the study area, due to its effects on the quantity of organic residue soil inputs and on the rates of soil organic matter mineralization and litter decomposition.

For mineral horizons, SOC concentration varied from 1.0 to 132.2 g kg^{-1} (Table 2) and it showed, as expected, a significant decreasing with depth (Fig. 2b). The highest values of SOC for mineral horizons (69 g kg^{-1}, Table 2) was detected for the A horizon, confirming the results of Vingiani et al. (2014) for soil profiles located nearby the study area. Similar to other studies (Don et al., 2007; Schrümpf et al., 2011), it was found an opposite trend of SOC concentrations and bulk density. Moreover, it was observed that SOC concentration was statistically higher for loam soils than other texture classes (Fig. 3b). That was probably due to the higher amount of clay and silt in loam soils, which have the ability to adsorb organic matter, protecting it from microbial decomposition, promoting soil structure thus stabilizing SOC (Six et al., 2002b; Telles et al., 2003).

The same differences within soil texture classes were detected for N (Fig. 3c) whose concentration ranged from 12.1 to 20.4 g kg^{-1} for organic layers (Table 3), and from 0.3 to 7.2 g kg^{-1} for mineral horizons (Table 2). The vertical distribution of N across soil profiles followed the same trend of SOC (Fig. 2c).

The C/N ratio ranged between 17.3 and 24.8 in the organic layer (Table 3) whereas for mineral horizons varied from 3.1 to 22.2 (Table 2), and it was statistically higher for the organic layers

(Fig. 2d). Furthermore, it showed no significant variation across soil profiles apart from Cr horizons. In addition, no significant difference in C/N ratio occurred between loam and sandy loam soils whereas it was statistically lower for loamy sand soils compared to the other textural classes (Fig. 3d). The low values of C/N ratio for Cr horizons may be therefore attributed to the influence of soil texture. Moreover, the low C/N ratio observed in these horizons could indicate a higher degree of degradation and humification of the SOC, than in overlying soil horizons (Callesen et al., 2007).

3.2 Soil carbon stock along soil profiles

The results of SOC stock calculation for each soil profile are reported in Table 4. SOC stock for the organic horizons (SOC $stock_o$) varied from 3 Mg ha^{-1} to 6 Mg ha^{-1}, whereas a large variation resulted from SOC stock of mineral horizons (SOC $stock_m$) with values ranging between 20.2 Mg ha^{-1} and 310.9 Mg ha^{-1} (Table 4). The maximum value (214.5 Mg ha^{-1}) of SOC stock was observed in the A horizons accounting for about 30% of the estimated total SOC stock along soil profile (Fig. 4). The significant lowest values were recorded in the organic horizon, which stored approximately 2% of total SOC stock. Similar results were observed for soils developed under beech forest in northern and central Italy (Piovesan et al., 2010), as well as in other countries (e.g. Lecointe et al., 2006; Grüneberg et al., 2014). Vertical distribution of SOC stock (Fig. 4) highlighted that even though there was less variability in SOC stock across A-Bw horizons, a significant decrease with depth was observed towards BC and especially Cr layers. The results revealed that the sampling thickness of 20 cm for Cr layers can be considered reliable because of the above quoted decreasing trend of SOC stock in depth. This behaviour is consistent with the evidence that more than 96% of SOC was stored in the overlying soil horizons. In addition, a similar decreasing trend of the weathering degree of the parent rock down-profile suggests a possible corresponding decrease in the storage capacity of SOC.

Statistically, there was no significant difference in SOC $stock_o$ (data not shown) in relation to the considered soil types and morphological features (slope gradient, slope curvature, landscape position). A possible explanation for such finding is that SOC $stock_o$ is dependent on carbon and the main factor influencing at local scale carbon in the organic horizon are tree species (Vesterdal et al., 2008). Since land cover is the same for the whole study area, then SOC $stock_o$ is not affected by site characteristic. Nevertheless, minor, statistically not-significant differences between SOC stock and topographic positions were observed at local scales. In particular, low values of SOC stock (< 4 Mg ha^{-1}) along some steep slopes and high values (≥ 6 Mg ha^{-1}) in summit paleosurfaces or in valley floors could be explained by the effects of geomorphic dynamics, such as erosion and deposition processes, respectively.

A different behaviour was instead detected for mineral horizons. Figure 5 shows the effect of soil texture, soil type and relief attributes on SOC $stock_m$.

SOC $stock_m$ increased from loamy sand to loam soils (Fig. 5a). Results highlighted that SOC stock is related to soil texture and they are consistent with the literature (Borchers and Perry, 1992; Six et al., 2002b) showing a different ability of soils to store carbon varying particle size, therefore, the soils with high contents of silt and clay are more able to storing SOC (Callesen et al., 2003). Carbon stocks of coarse-textured soils was expected to be lower in relation to the lower fertility due to low production of litter and root and to slowly active decomposition (Baritz et al., 2010).

SOC $stock_m$ was statistically higher in Inceptisols than Entisols (Fig. 5b). Such expected finding resulted probably from the greater thickness of Inceptisols (Table 1), since SOC stock is dependent on profile depth (Eq. 2), which in turn may be strongly controlled by the interplay between the deepening of the pedogenetic front and geomorphic dynamics.

SOC $stock_m$ differed significantly with slope gradient. In particular, soils located in areas with slope gradient less than 10° were found to have SOC $stock_m$ higher than soils developed on steeper slopes (Fig. 5c). This result is consistent with other studies, which have indicated a relationship between slope and SOC accumulation (Liu et al., 2006; Wang et al., 2010). In addition, SOC $stock_m$ was typically higher for soil profiles located along concave slope, compared to those situated along slopes with convex morphology (Fig. 5d). The higher SOC $stock_m$ in concave morphology may be related to higher deposition and accumulation of SOC promoted by convergent landscape positions. On the contrary divergent landforms with convex curvature enhance water and sediment losses (Gregorich et al., 1998).

Figure 5e shows SOC storage for different landscape units. The lowest SOC $stock_m$ occurred along steep slopes, followed by gentle slopes while significant differences were not observed in summit paleosurface and valley floor showed the highest values (Fig. 5e). Differences in SOC $stock_m$ with landscape position may be attributed to processes of erosion and deposition controlling soil and SOC distribution along slopes as well as the amount of labile organic matter (Gregorich et al., 1998). Several studies developed under different environmental conditions (Pennock and Van Kessel, 1997; Arrouays et al.,1998) found greater SOC stocks in valley floor, for the high sedimentation of carbon-enriched deposits (Gregorich et al., 1998) or the lower mineralization processes (Janzen, 2006). On the contrary, lower SOC stocks along midslope might be due to higher potential for erosion processes compared to summit position and valley floor which lead to soil thinning. Such hypothesis is consistent with field survey that showed shallow, less developed Entisols profiles located on fairly steep slopes. In addition, for the study area the lack of significant differences in SOC $stock_m$ stored in summit paleosurfaces and valleys may be primarily related to the low slope angle of both landscape unit (<10°) which allowed soil accumulation.

The findings of this study showed complex patterns of SOC stock for mineral horizons in relation to relief features, soil types and physical-chemical properties. SOC stock and its spatial distribution (both laterally across landscape units and in-depth through the soil profiles) revealed to be very sensitive to local topography, as a response to the major soil-forming processes, degree of soil development and related features, as well as their strict interplay with landscape dynamics (erosion, deposition and/or reworking phenomena). Further research is needed to better understand the main local environmental characteristics controlling SOC dynamics, given the complexity of interacting factors.

4. Conclusions

The interactions of SOC stocks with soil characteristics and landscape position in soil profiles located in a woodland area of Calabria region (southern Italy) covered by beech forest, were studied. This research focused on the potential effects of soil texture, soil type and topography features, as slope gradient, slope curvature and landscape units, on the SOC storage.

The morphological, chemical and physical soil properties were analysed for samples all genetic horizon taken from 28 pedons, which were chosen within the main landscape units (summit paleosurface, steep slope, gentle slope and valley floor) detected in the study area.

Our results showed that the spatial distribution and formation of soils were generally influenced by the weathering level of the granitic rock and by topographic features. Soil depth exhibits high spatial variability ranging from shallow to moderately deep, and the soils were classified as Inceptisols and Entisols. These soils were coarse and medium-textured and were classified as loamy sand, sandy loam and loam.

Due to the acid nature of the parent material, coupled with the high rainfall and from considerable amount of litter accumulation, all soils analysed showed a moderately to strongly acid pH. Moreover, the continuous input of fresh organic material favoured the formation of surface organic layers and organic-rich A horizons.

We found that SOC concentration significantly decreased with depth from the surface. In agreement with previous works, the mean concentration of SOC and SOC stock were significantly related to soil texture. In particular, the mineral soils with highest values of SOC and SOC stock were the loamy soils, which contain high contents of fine fractions (silt plus clay) than the other soils. In addition, it was observed that the spatial distribution of N across soil profile followed the same trend of SOC.

The finding of this study also showed that SOC stock along the soil profiles are sensitive to soil types and topographic features. Variance in SOC stored among the two soil types developed in the study area, confirmed that Inceptisols sequestered increasingly greater quantities of SOC than Entisols. Both results are consistent with the different thickness of soil types. In fact, an increase of SOC stocks was observed as the soil thickness increased. Therefore, the Entisols, which are characterized by thin soil horizons and shallower depths, have the lowest SOC stocks, while the Inceptisols with thicker soil horizons and deeper showed the highest values of SOC stock.

From a topographic point of view, the SOC stocks varied with slope gradient, slope curvature and landscape position. Valley floor and summit paleosurfaces had significantly higher SOC stock compared to gentle and steep slopes. This may be caused of topography's effect on soil formation, and erosion/deposition processes. In addition, the comparison between slope curvature and SOC stocks showed that the latter differ markedly ($p < 0.05$) among the different slope curvature. The mean SOC stock in the soil profiles located on the concave slopes was 223.6 Mg ha^{-1}, while in the areas with flat morphology was 124.8 Mg ha^{-1}, and only 71.5 Mg ha^{-1} of SOC stock was evaluated along slope with convex curvature.

Finally, the results proved that the stock of SOC at soil profile scale, under similar parent material, land use and climate conditions is significantly influenced by soil type, soil texture and landscape features. SOC storage is important not only because of its role in the global C cycle, but also because it affects forest productivity. Hence, the results obtained could also be used in the future for a sustainable management of forest ecosystem, which in Calabria cover about 40% of the region.

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Table 1
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Table 1. Site characteristics and main morphological features of soil profiles (P1–P28). Slope gradient, aspect and slope curvature were derived from a 5 m DEM.

Soil profile	Coordinates (WGS84 UTM33N) E (m)	Coordinates (WGS84 UTM33N) N (m)	Parent rock	Landscape unit	Aspect	Slope gradient (°)	Slope curvature	Soil type (USDA, 2014)	Horizons	Depth (cm)
P1	608,493	4,261,986	mwg	Summit paleosurface	W	7	Concave	Inceptisol	O-A-AB-Bw-Cr	125.0+
P2	608,223	4,262,111	hwg	Summit paleosurface	N	8	Concave	Inceptisol	O-A-AB-Bw-Cr	85.4+
P3	608,383	4,262,056	swg	Steep slope	W	18	Convex	Entisol	O-A-R	17.8
P4	607,972	4,261,936	swg	Summit paleosurface	N	6	Flat	Inceptisol	O-A-AB-Bw-R	43.4
P5	608,068	4,261,911	hwg	Valley floor	N	8	Concave	Inceptisol	O-A-AB-Bw-Cr	105.5+
P6	608,153	4,261,943	swg	Gentle slope	W	15	Concave	Inceptisol	O-A-Bw-R	54.8
P7	608,028	4,261,711	mwg	Summit paleosurface	E	4	Concave	Inceptisol	O-A-BC-Cr	103.5+
P8	608,272	4,261,426	hwg	Valley floor	N	9	Concave	Inceptisol	O-A- AB-BC-Cr	139.0+
P9	608,357	4,261,733	hwg	Valley floor	W	9	Concave	Inceptisol	O-A-Bw-BC-Cr	117.8+
P10	608,167	4,262,206	hwg	Summit paleosurface	N	9	Concave	Inceptisol	O-A-AB-Bw-Cr	118.0+
P11	608,405	4,261,820	hwg	Summit paleosurface	N	5	Concave	Inceptisol	O-A-AB-Bw-Cr	97.0+
P12	608,160	4,261,494	hwg	Summit paleosurface	N	4	Concave	Inceptisol	O-A-AB-Bw-Cr	109.3+
P13	608,051	4,261,768	swg	Gentle slope	E	13	Convex	Entisol	O-A-R	35.0
P14	608,256	4,261,810	mwg	Summit paleosurface	N	3	Flat	Inceptisol	O-A-Bw-BC-Cr	78.0+
P15	608,530	4,261,886	swg	Summit paleosurface	W	6	Flat	Inceptisol	O-A-AB-R	48.0
P16	608,188	4,262,029	hwg	Summit paleosurface	W	4	Concave	Inceptisol	O-A-Bw-BC-Cr	103.4+
P17	608,320	4,261,885	mwg	Summit paleosurface	W	3	Flat	Inceptisol	O-A-Bw-Cr	78.0+
P18	608,322	4,261,730	swg	Steep slope	N	29	Convex	Entisol	O-A-R	13.0
P19	608,223	4,261,886	swg	Steep slope	W	24	Convex	Entisol	O-A-R	16.0
P20	608,245	4,261,723	hwg	Valley floor	W	1	Concave	Inceptisol	O-A-AB-Bw-Cr	108.0+
P21	608,360	4,261,576	swg	Summit paleosurface	W	6	Flat	Inceptisol	O-A-AB-Bw-R	43.0
P22	608,161	4,261,621	swg	Gentle slope	N	7	Convex	Entisol	O-A-R	46.0
P23	608,231	4,261,472	mwg	Summit paleosurface	E	8	Flat	Inceptisol	O-A-Bw-Cr	81.0+
P24	608,097	4,261,948	swg	Valley floor	W	3	Concave	Entisol	O-A-R	45.0
P25	608,391	4,262,016	hwg	Valley floor	W	4	Concave	Inceptisol	O-A-Bw-Cr	110.0+
P26	618,148	4,261,736	swg	Steep slope	N	23	Convex	Entisol	O-A-R	18.0
P27	608,225	4,261,398	swg	Summit paleosurface	N	5	Flat	Inceptisol	O-A-Bw-R	41.0
P28	608,206	4,261,813	swg	Gentle slope	N	16	Convex	Inceptisol	O-A-Bw-Cr	56.5+

hwg= highly weathered granite; mwg= moderately weathered granite; swg= slightly weathered granite

Table 2
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Table 2. Summary statistics of soil properties for the mineral horizons of the 28 soil profiles. (SC= skeleton concentration; BD= bulk density; S.D.= standard deviation).

Mineral horizon		Depth (cm)	SC (%)	Sand (%)	Silt (%)	Clay (%)	BD (g cm^{-3})	pH (-)	SOC (g kg^{-1})	N (g kg^{-1})	C/N (-)
A (28 samples)											
	Min	5.0	1.0	37.1	16.8	8.2	0.23	4.0	30.5	2.2	12.7
	Max	61.5	21.3	72.3	45.0	24.9	0.91	5.1	132.2	7.2	22.2
	Mean	23.1	7.7	54.2	29.4	16.4	0.54	4.7	69.0	4.2	16.3
	Median	18.0	7.0	52.9	30.3	16.9	0.51	4.7	61.5	4.3	16.5
	S.D.	13.6	6.2	9.1	6.7	4.2	0.16	0.3	25.2	1.4	2.1
AB (13 samples)											
	Min	7.4	1.0	33.0	21.0	10.8	0.44	4.2	19.6	1.5	13.1
	Max	46.0	11.9	61.0	45.3	23.0	0.93	4.9	71.1	4.3	18.1
	Mean	26.4	5.7	49.7	31.6	18.8	0.63	4.6	48.3	3.0	15.8
	Median	26.0	6.0	50.3	28.6	19.0	0.56	4.9	51.6	3.2	16.2
	S.D.	9.7	3.6	8.4	6.3	3.5	0.18	0.2	15.0	0.9	1.5
Bw (18 samples)											
	Min	18.0	2.0	42.5	16.0	11.0	0.63	4.3	14.2	1.0	11.7
	Max	59.5	27.0	67.2	36.6	22.8	1.19	5.1	43.7	3.0	21.1
	Mean	33.7	9.7	55.8	27.8	16.4	0.87	4.7	26.2	1.6	16.0
	Median	30.0	8.3	57.7	28.6	16.3	0.88	4.7	23.7	1.4	16.3
	S.D.	12.2	6.2	7.0	5.4	3.5	0.15	0.2	8.8	0.5	2.2
BC (5 samples)											
	Min	15.0	9.2	50.7	16.3	8.6	0.86	4.4	9.1	0.5	11.0
	Max	34.0	28.5	71.2	34.7	17.7	1.30	4.8	20.1	1.4	20.0
	Mean	25.9	16.7	64.1	21.9	14.0	1.03	4.6	14.1	1.1	14.2
	Median	30.0	15.0	67.9	20.2	14.6	1.1	4.7	13.3	1.1	13.3
	S.D.	8.0	7.1	8.3	7.4	3.3	0.18	0.2	4.2	0.4	3.7
Cr (16 samples)											
	Min	-	37.1	63.4	11.5	7.1	1.51	4.4	1.0	0.3	3.1
	Max	-	54.0	80.2	22.7	13.9	1.66	5.0	8.4	0.9	9.6
	Mean	20	46.2	72.1	17.5	10.4	1.56	4.7	5.3	0.7	7.1
	Median	-	44.6	71.1	18.3	10.7	1.56	4.7	5.6	0.7	7.8
	S.D.	-	5.2	4.9	3.4	2.2	0.04	0.2	2.5	0.2	2.2

Table 3
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Table 2. Summary statistics of soil properties of organic horizons. (W=dry weight organic horizon; S.D.= standard deviation)

Organic horizon (28 samples)	Soil properties			
	W (g)	SOC ($g\ kg^{-1}$)	N ($g\ kg^{-1}$)	C/N (-)
Min	46.5	217.0	12.1	17.3
Max	90.0	369.8	20.4	24.8
Mean	67.1	284.9	15.4	18.5
Median	64.3	282.5	15.3	18.1
S.D.	9.4	40.2	2.1	1.7

Table 4
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Table 4. SOC stocks in the organic and mineral horizons, and in the whole profile of the 28 pedons. Summary statistic are also reported (numbers in italic report the minimum values of SOC stock, whereas in bold the maximum values; S.D.= standard deviation).

Landscape Unit	Soil profile	SOC stock ($Mg\ ha^{-1}$)							
		Horizon						Mineral soil	Whole profile
		O	A	AB	Bw	BC	Cr		
Summit paleosurface	P1	4.5	50.3	73.2	88.5	–	10.8	222.8	227.3
Summit paleosurface	P2	4.3	45.1	66.4	78.8	–	12.7	203.0	207.3
Steep slope	P3	5.2	60.0	–	–	–	–	60.0	65.2
Summit paleosurface	P4	5.1	20.2	*24.9*	71.5	–	–	116.6	121.7
Valley floor	P5	5.1	133.9	**110.1**	53.0	–	13.9	**310.9**	**316.0**
Gentle slope	P6	5.9	83.9	–	35.9	–	–	119.8	125.7
Summit paleosurface	P7	6.0	**214.5**	–	–	33.3	11.0	258.9	264.9
Valley floor	P8	5.8	133.3	52.3	–	26.1	9.7	221.3	227.1
Valley floor	P9	4.7	110.2	–	44.9	**33.7**	*1.9*	190.7	195.4
Summit paleosurface	P10	5.2	126.9	88.4	73.5	–	8.0	297.4	302.6
Summit paleosurface	P11	4.9	113.7	68.3	59.5	–	4.3	245.8	250.6
Summit paleosurface	P12	3.5	70.8	110.1	61.7	–	3.4	246.0	249.5
Gentle slope	P13	5.2	39.4	57.3	–	–	–	96.7	101.8
Summit paleosurface	P14	4.5	49.8	–	49.0	*16.1*	2.7	117.6	122.1
Summit paleosurface	P15	4.4	58.4	75.5	–	–	–	133.9	138.2
Summit paleosurface	P16	3.7	95.2	–	**97.1**	29.5	**14.1**	236.0	239.7
Summit paleosurface	P17	4.3	34.6	–	83.1	–	8.7	126.4	130.6
Steep slope	P18	4.8	20.2	–	–	–	–	*20.2*	*25.0*
Steep slope	P19	4.8	38.3	–	–	–	–	38.3	43.1
Valley floor	P20	4.0	63.4	56.6	81.4	–	13.9	215.3	219.3
Summit paleosurface	P21	4.5	*15.5*	61.1	41.0	–	–	117.6	122.1
Gentle slope	P22	4.0	57.9	46.8	–	–	–	104.7	108.7
Summit paleosurface	P23	4.8	28.1	–	92.0	–	8.9	129.0	133.8
Valley floor	P24	4.6	110.7	–	–	–		110.7	115.2
Valley floor	P25	**6.5**	101.7	–	78.0	–	6.2	185.9	192.4
Steep slope	P26	*3.0*	60.6	–	–	–	–	60.6	63.6
Summit paleosurface	P27	4.5	60.8	–	37.8	–	–	98.7	103.1
Gentle slope	P28	5.3	44.7	–	*34.4*	–	8.6	87.7	93.0
	Mean	4.8	72.9	68.6	64.5	27.7	8.7	156.2	160.9
	Median	4.8	60.3	66.4	66.6	29.5	8.8	127.7	132.2
	SD	0.8	44.9	24.0	20.8	7.2	4.0	79.0	79.0

Figure 1
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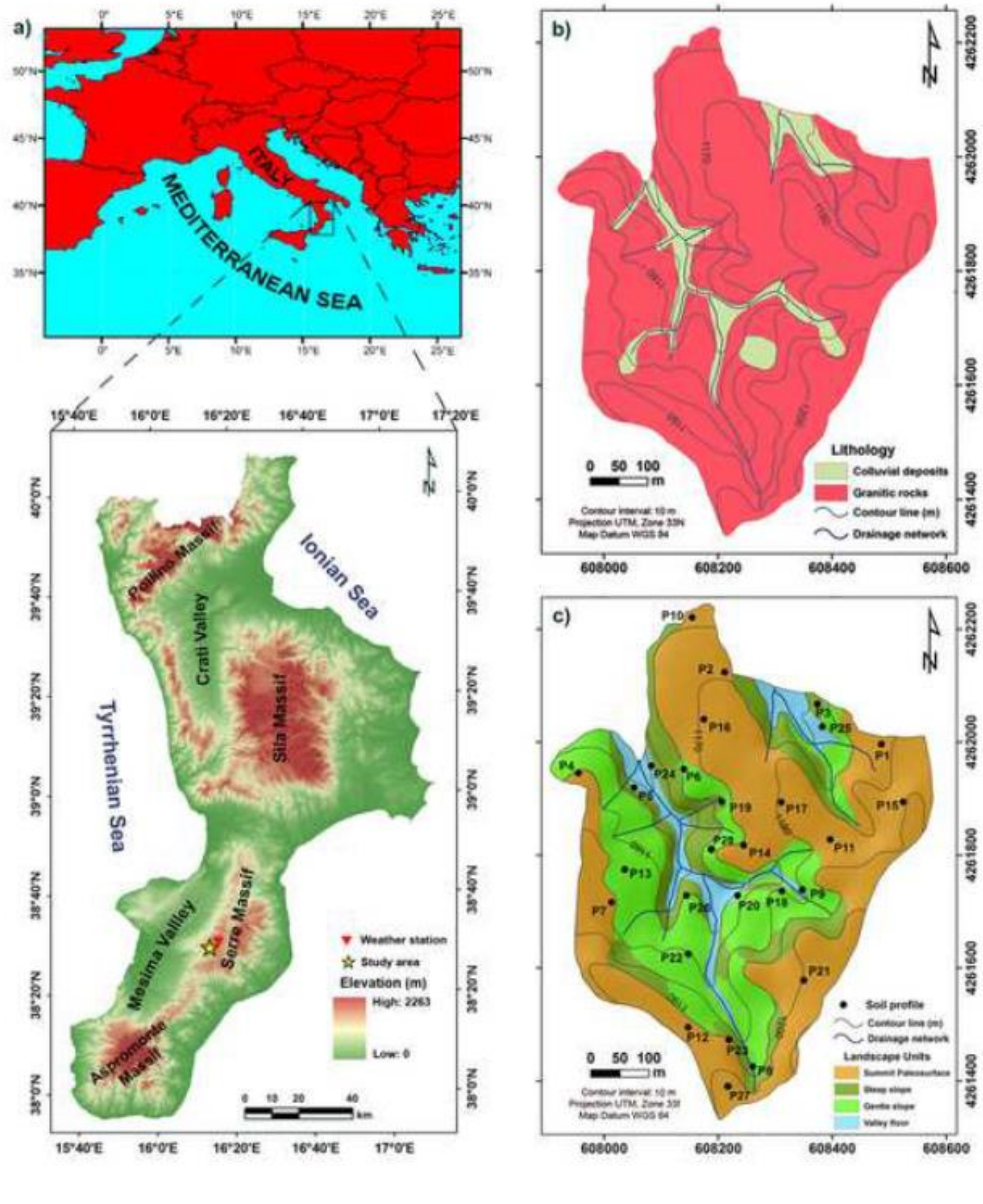

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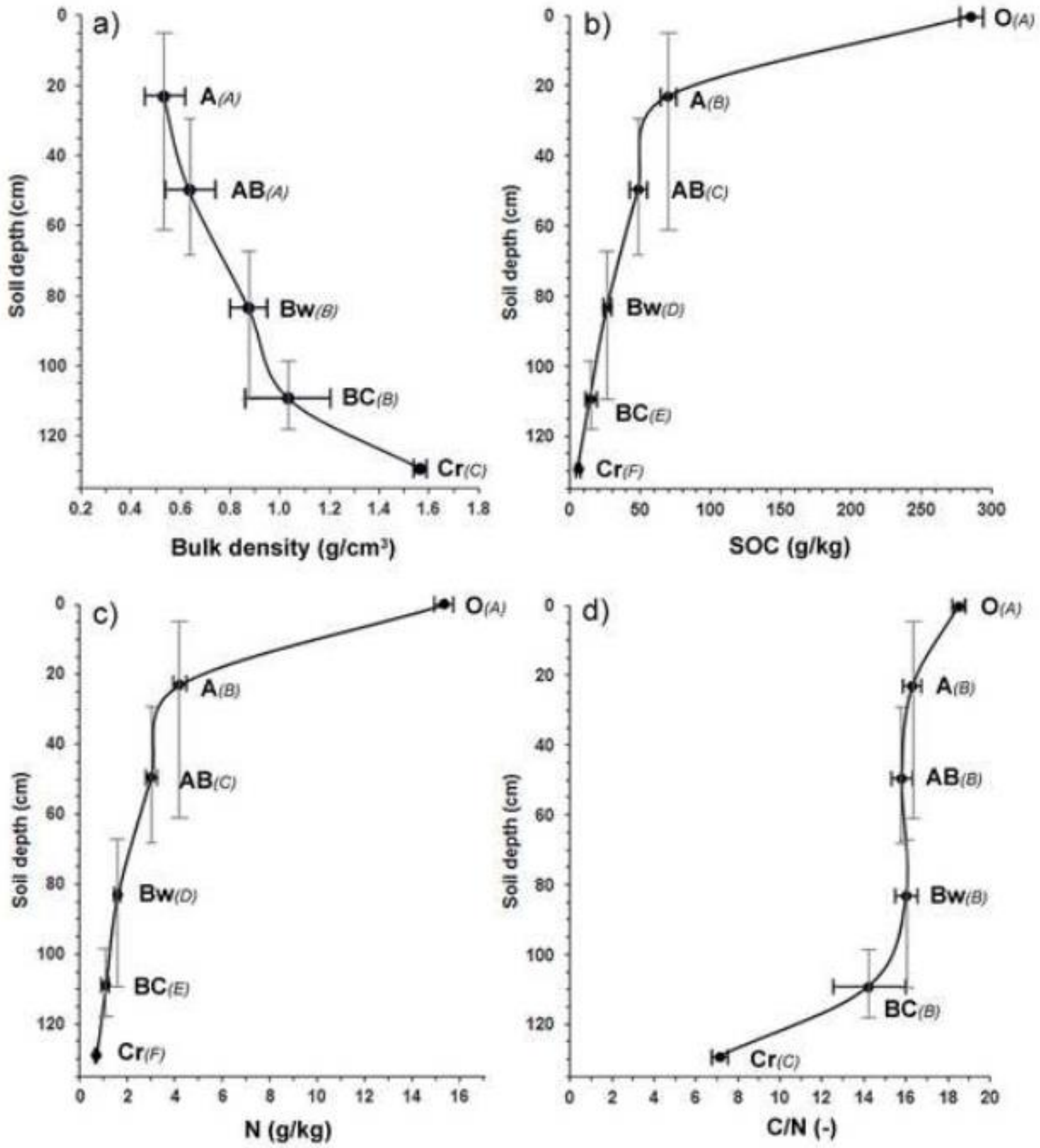

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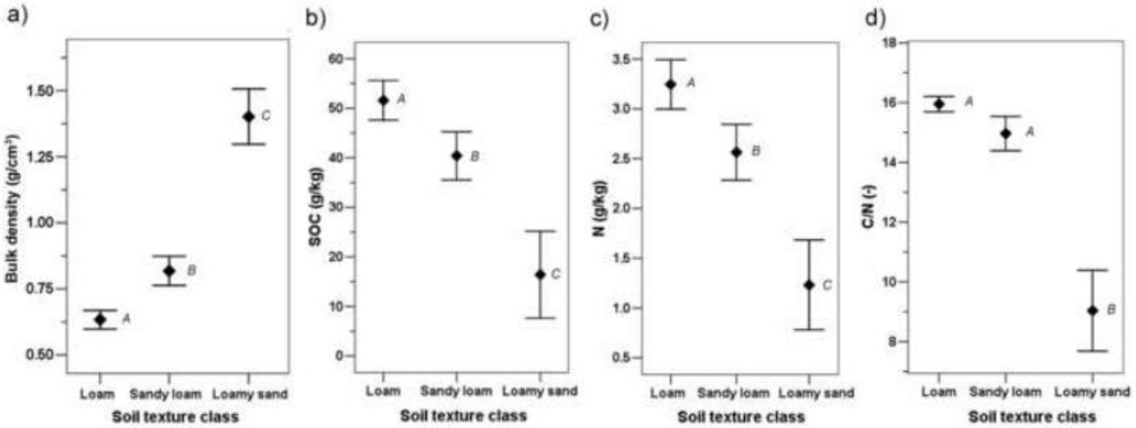

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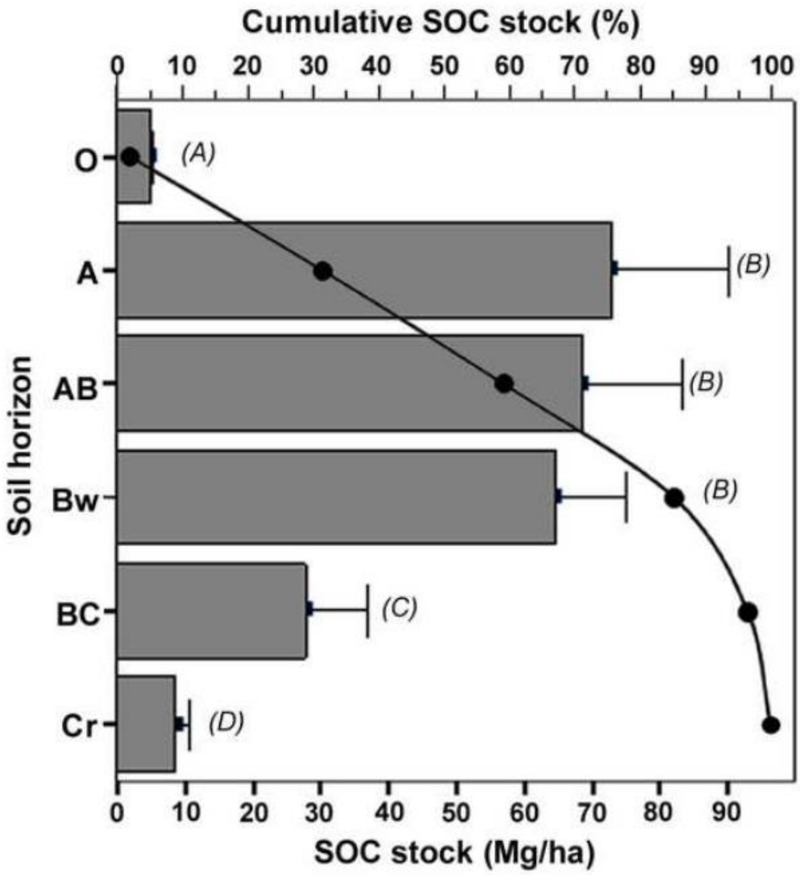

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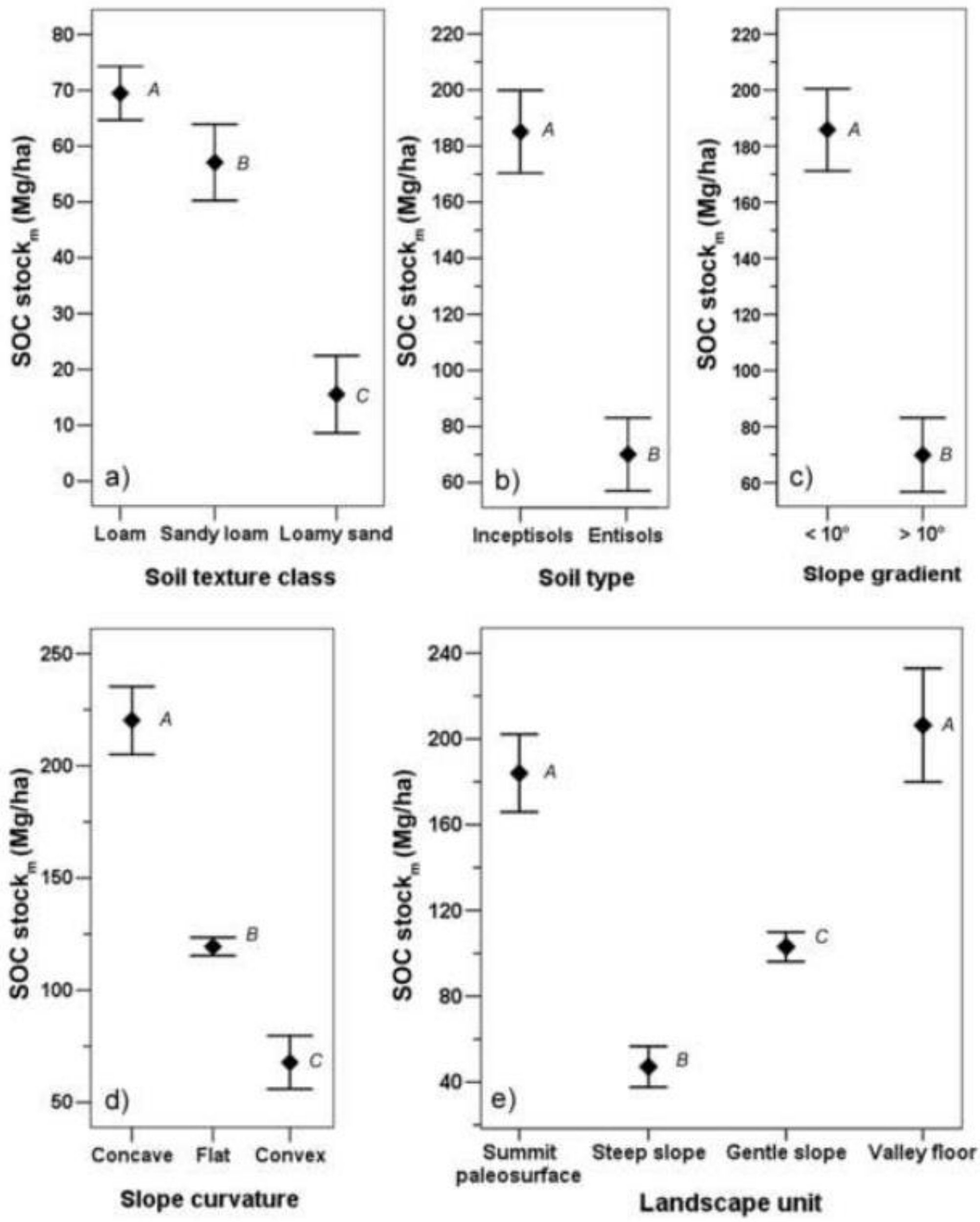

Figure captions

Figure 1- a) Location of study area; b) geolithologic map; c) landscape units and location of studied soil profiles.

Figure 2 – Vertical distribution of bulk density (a), SOC concentration (b) and C/N ratio (c) in the horizons of the 28 soil profiles. Horizontal bars are standard errors of the mean (black dot). Grey vertical bars refer to the thickness of each horizon. Horizons followed by the same letter in brackets are not significantly different according to the studied soil property.

Figure 3 – Mean values (black dot) and standard errors (vertical bars) of bulk density (a), SOC (b), N concentration (c) and C/N ratio (d) within different soil texture classes. Classes with the same capital letters are not significantly different according to the studied soil property.

Figure 4 –SOC stock across soil profile and cumulative percentage of SOC stock within soil horizon. Horizons followed by the same letter in brackets are not statistically significant.

Figure 5 – Mean values (black dot) and standard errors (vertical bars) of SOC stockm for soil texture classes (a), soil types (b), slope gradient (c), slope curvature (d), and landscape units (e). Capital letters indicate significant differences for different classes.