Soil organic carbon along an altitudinal gradient in the Despeñaperros nature reserve, Southern Spain

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Abstract

Soil organic C (SOC) is extremely important in the global C cycle as C sequestration in non-disturbed soil ecosystems can be a C sink and mitigate greenhouse gas driven climate change. Soil organic C changes in space and time are relevant to understand the soil system and its role in the C cycle, and this is why the influence of topographic position on SOC should be studied. Seven topographic positions from a toposequence between 607 and 1168 m were analyzed in the Despeñaperros Natural Park (Jaén, SW Spain). Depending on soil depth, one to three control sections (0-25, 25-50 and 75-cm) were sampled at each site. The SOC content in studied soils is below 30 g kg^{-1} and strongly decreases with depth. These results were related to the gravel content and to the bulk density. The SOC content from the topsoil (0-25 cm) varied largely through the altitudinal gradient ranging between 27.3 and 39.9 g kg^{-1}. The SOC stock (SOCS) varied between 53.8 and 158.0 Mg ha^{-1} in the studied area been clearly conditioned by the topographic position. Therefore, results suggest that elevation should be included in SOCS models and estimations at local and regional scales.

1 Introduction

Soils are an important C reservoir (Barua and Haque, 2013; Yan-Gui et al., 2013). In fact, the primary terrestrial pool of organic carbon (OC) is soil, which accounts for more than 71% of the Earth's terrestrial OC pool (Lal, 2010). In addition, soils have the ability to store C for a long time (over the last 5000 years) (Brevik and Homburg, 2004). Soils play a crucial role in the overall C cycle, and small changes in the soil organic carbon stock (SOCS) could significantly affect atmospheric carbon dioxide (CO_2) concentrations, and through that global climate change. Within the C cycle, soils can be a source of greenhouse gases through CO_2 and methane (CH_4) emissions, or can be a sink for atmospheric CO_2 through C sequestration in soil organic matter (OM) (Breuning-Madsen et al., 2009; Brevik, 2012).

Climate, soil use and soil management affect to soil OC variability, particularly in soils under Mediterranean type of climate, characterized by low OC content, weak structure and readily degradable soils (Hernanz et al., 2002). In temperate climates, recent studies show differences in C sequestration rates in soils depending on use and management (Muñoz-Rojas et al., 2012a and 2012b), climate and mineralogical composition (Wang et al., 2010), texture, slope and elevation (Hontoria et al., 2004), and tillage intensity and no-till duration (Umakant et al., 2010). Soil conservation strategies are being seen as a strategy to increase soil OM content (Barbera et al., 2012; Batjes et al., 2014; Jaiarree et al., 2014; Srinivasarao et al., 2014; Fialho and Zinn, 2014).

Several studies have been carried out to estimate differences in soil organic carbon (SOC) dynamics in relation to soil properties, land uses and climate (Eshetu et al., 2004; Lemenih and Itanna, 2004; Muñoz-Rojas et al., 2013). Although the impact of topographic position on soil properties on SOC content is widely recognized (Venterea et al., 2003; Fu et al., 2004; Brevik, 2013), relatively few studies have been conducted to examine the role of topographic position (Fernández-Romero et al., 2014; Lozano-García et al., 2014).

The spatial variation of soil properties may also be significantly influenced by aspect (which may induce microclimate variations), physiography, parent material, and vegetation (López-Vicente et al., 2009; Brevik, 2013; Ashley et al., 2014; Bakhshandeh et al., 2014; Dingil et al., 2014; Gebrelibanos et al., 2014; Kirkpatrick et al., 2014). Ovales & Collins (1986) evaluated soil variability due to pedogenic processes across landscapes in contrasting climatic environments and concluded that topographic position and variations in soil properties were significantly related. McKenzie and Austin (1993) and Gessler et al. (2000) found that variations of some soil properties could be related to the slope steepness, length, curvature and the relative location within a toposequence. Both studies suggest that the assessment of the hillslope sequence helps to understand variations of soil properties in order to establish relationships among specific topographic positions and soil properties. Asadi et al. (2012) found that the integrated effect of topography and land use determined soil properties.

Topography is a relevant factor controlling soil erosion processes through the redistribution of soil particles and soil OM (Cerdà and García Fayos, 1997; Ziadat and Taimeh, 2013).

The topographic factor has been traditionally included in the study of the spatial distribution of soil properties (Fernández-Calviño et al., 2013; Haregeweyn et al., 2013; Ozgoz et al., 2013; Wang and Shao, 2013). Over time, many researchers have quantified the relationships between topographic parameters and soil properties such as soil OM and physical properties such as particle size distribution, bulk density and depth to specific horizon boundaries (McKenzie and Austin, 1993; Gessler et al., 1995; Gessler et al., 2000; Pachepsky et al., 2001; Ziadat, 2005). Soil OM content has been negatively correlated with the topographic gradient (Ruhe and Walker, 1968), and slope gradient (Nizeyimana and Bicki, 1992). However, quantitative relationships between soil topography and soil physical-chemical properties are not well established for a wide range of environments (Hattar et al., 2010).

Research along altitudinal gradients has shed light on the effects of climate on soil properties. Ruiz-Sinoga et al. (2012) found a strong relationship between soil OM and elevation, which was due to reduced decomposition rates with lower temperatures. High erosion rates have been found under dry climates and low altitudes in Israel (Cerdà, 1998a; Cerdà, 1998b), which support the idea of high OM losses due to soil erosion in dry areas.

In this line, in Mediterranean natural areas there is no information about the soil variability, also little data is available related to the control topography exerts on soil properties (Lozano-García and Parras-Alcántara, 2014). Therefore, the aims of this study are: (i) to quantify SOC contents and their vertical distribution in a natural forest area, (ii) to assess the SOCS differences in soils along an altitudinal gradient and (iii) their relationship with soil depth in a Mediterranean natural area.

2 Material and Methods

2.1 Study site

The Despeñaperros Natural Park (76.8 km^2) is one of the best-preserved landscapes in southern Europe. It is located within the Eastern Sierra Morena (province of Jaén, southeastern Spain), at coordinates 38º20’ - 38º27’N, 3º27’ - 3º37’W. The study area is characterized by warm dry summers and cool humid winters and climate is temperate semiarid with continental features due to elevation. Average extreme temperatures range between -10 ºC (winter) and 42 ºC (summer), with mean temperature 15 ºC. The moisture regime is dry Mediterranean, with average annual rainfall is 800 mm. High temperatures and long drought periods cause water deficits up to 350 mm annually.

It is a mountainous area, with an altitudinal range of 540 m.a.s.l. in the Despeñaperros River valley to 1250 m.a.s.l at Malabrigo Mountain. The relief is steep with slopes ranging from 3% to 45%, and the parent materials are primarily slates and quartzites. Most abundant soils in the area are Phaeozems (PH), Cambisols (CM), Regosols (RG) and Leptosols (LP), according to the classification by IUSS Working Group WRB (2006). Well-preserved Mediterranean woodlands and scrublands occupy the study area and large game habitat is the main land use.

2.2 Soil sampling and analytical methods

Seven sites were selected along a topographic gradient in a south-facing slope in the Despeñaperros Natural Park (Table 1). Soil samples were collected at each site following a random sampling design according to FAO (2006). Each selected point was sampled using soil control sections (SCS) at different depths (S1: 0-25, S2: 25-50 and S3: 50-75 cm). SCS were used for a uniform comparison between studied soils. Four replicates of each soil sample were analyzed in laboratory (17 sampling points × 1, 2 or 3 SCS × 4 replicates).

Soil samples were air-dried at constant room temperature (25 °C) and sieved (2 mm) to discard coarse particles. The analytical methods used in this study are described in Table 2.

Statistical analysis was performed using SPSS Inc. (2004). The physical and chemical soil properties were analyzed statistically for each SCS of different soil groups (PH, CM, RG and LP), including the average and standard deviation (SD). The statistical significance of the differences in each variable between each sampling point and soil type were tested using the Anderson-Darling test at each control section for each soil type. Differences with $p<0.05$ were considered statistically significant.

3 Results and discussion

3.1 Soil properties

The studied soils were classified as Phaeozems, Cambisols, Regosols and Leptosols (IUSS Working Group WRB, 2006) (Table 1). The soils are stony soils, acidic, with low base concentrations, oligotrophic and with slightly unsaturated complex change and located in areas of variable slopes ranging between 5% and 38%. Phaeozems are the most developed soils in the study area. They are deep, dark, and well humidified with high biological activity and high vegetation density on gentle slopes and shady side foothills. Cambisols are developed and deep soils; however, Leptosols are the least developed and shallowest soils.

Phaeozems are the most pedogenically developed soils in the study area. They are found on gentle slopes (<3%), usually in shaded areas on Ordovician sandstones. The gravel content is variable, ranging between 7% and 31% (weight). Texturally they are sandy soils at the surface and silty-clay-loam or silty-clay soils at depth, with a horizons sequence A0/A1/AB/Bt/C1. These soils show luvic (lv) characteristics (luvic-Phaeozems (lv-PH)) and are >1 m in depth with pH along the profile ranging from 6.3 to 5.6 at depth and about 4.3% OM content (Table 1 and 3).

Cambisols are less developed soils than luvic-Phaeozems, however, these soils are more developed and deeper than Regosols and Leptosols. They appear in areas of variable slope (3-38%) and are >1 m in depth characterized by a cambic horizon (Bw) on Ordovician quartzites (Table 1) with approximately 20% gravel content. At the surface they are sandy soils (<60% sand content) with high clay content in the Bw horizon and increasing clay content with depth (Table 3). The horizon sequences were A0/A1/AB/BW/BC/C1 or A0/A1/AB/BW. These soils are characterized by low OM content at depth. Gallardo et al. (2000) showed that the low OM content could be explained by the semiarid Mediterranean conditions. In addition, Parras-Alcántara et al. (2013a) found there is less OM and fewer mineral aggregates in sandy soils, thus favoring high levels of OM transformation. Because of this, Hontoria et al. (2004) suggested that physical variables determine soil development in the driest areas of Spain to a greater degree than management or climatic variables. The Cambisols topsoil has humic (hu) characteristics, with >5% OM content (Table 3) due to plant debris accumulation in the A0 horizon. This OM is poorly structured and partially decomposed, thereby reducing the amount and increasing the OM evolution degree with depth. In this line, Bech et al. (1983) reported that the free OM concentration in the surface horizon was higher than 90%, while humic and fulvic acid concentrations were less than 2% in soils with *Quercus ilex spp*. ballota vegetation. Free OM was reduced and humidification increased up to 30% in deeper layers.

Regosols can be found in steeply sloping areas (>8%) characterized by high water erosion and subject to rejuvenation processes. We found eutric (eu), dystric (dy) and umbric (um) Regosols (Table 1) on sandstone and quartzite parent materials with >25% gravel content in surface layers that eventually disappeared in depth in some cases. These soils are sandy-loamy in surface layers and silty-clay in deep layers, with different horizon sequences (A0/A1/AB/BC/C1, A0/A1/AC/C1 and A1/AC/C1). Eutric-Regosols are deeper soils (>80 cm) that are loamy with high gravel content (25.1-32.2%) at the surface decreasing with deep, acid pH (5.9) and high OM content (6.7%) at the surface. The dystric-Regosols are stony soils that are shallow (<40 cm), loamy at the surface and sandy at depth with high gravel content (>40%) at the surface, acid pH (6.2) and high OM content (7.3%) in the surface horizon (Table 3). The umbric-Regosols are also stony, they are deep soils (>70 cm) that are loamy with high gravel content (40%) in the surface decreasing to 11% at depth, acid pH (5.6) and high OM content (6.5%) (Table 3).

Leptosols are the least developed soils of the study area. Lithic (li), mollic (mo) and eutric (eu) Leptosols were identified (Table 1) formed in sandstones, quartzites and slates on variable slopes (1.5-46%). Horizon sequences A1/AC/C1, A1/AC, and AC/C1 and A1 were found. The gravel content was variable (>40% in the topographically elevated areas and decreasing with depth) with high sand content (>50%) in the surface layers. One characteristic of these soils is that the clay content increased with depth, reaching up to 30%. According to Recio et al. (1986), the physical-chemical properties of the soils in the study area are due to lithology, while their low edaphic development is conditioned by age. According to Nerger et al. (2007), the alteration and pedogenesis processes taking place in these soils usually occur on low slopes. The lithic-Leptosols are the least developed soils at this study site, with thicknesses ranging between 10 and 15 cm in areas of steep slope. In flat areas, their low development is due to their extreme youth. These soils are loamy with a high gravel content (>28%), acid pH and >4% OM content. Mollic-Leptosols are characterized by mollic surface horizons (thick, well-structured, dark, high base saturation and high OM content), on variable slopes (18.5%-38.5%). According to Corral-Fernández et al. (2013) these soils are characterized by organic residue accumulation in the surface horizons; this OM is poorly structured and partially decomposed at the surface with increasing decomposition rate with depth. Umbric-Leptosols are characterized by high OM content, are shallow, and either loamy with high stony content (>20% gravel content) or sandy (>55% sand content), have low bulk density conditioned by the OM content, high porosity and acid pH (Table 3).

3.2 Distribution of soil organic carbon

Generally, soils in the study area are characterized by >3% OC content, making them part of the 45% of the mineral soils of Europe that have between 2 and 6% OC content (Rusco et al., 2001). Soil OM content decreased with depth at all topographic positions (A, B, C and D positions) (Table 4). However, this property cannot be observed in the lowest topographic positions (E, F and G positions) due to the low edaphic development (umbric-Leptosols, lithic-Leptosols and mollic-Leptosols) as only one SCS exists (S1: 0-25 cm) (Tables 1 and 4).

The soils in this study are characterized by high sand content at the surface (S1) varying between 59.2 and 34.2% for C and F positions respectively, and reduced sand content with depth in all studied soils (Table 3), affecting to OM development. With respect to clay content reaches 45% in C: S3. In addition, the mineral medium may play an important role in soil humidification processes, so we can explain low soil OM concentrations with depth due in part to soil texture, because soil OM tends to decrease with depth in virtually all soils, regardless of textural changes. Clays over sands would have a decrease in soil OM with depth also, and probably a more marked decrease. In addition, the formation of aggregates made up of OM and the mineral fraction is reduced, thus favoring high OM levels in sandy soils at depth (González and Candás, 2004). Furthermore, Gallardo et al. (2000) argued that the relatively low concentrations of OM in depth could be explained by the climate (Mediterranean semiarid). Similar results have been found by Corral-Fernández et al. (2013), Parras-Alcántara et al. (2014) and Lozano-García and Parras-Alcántara (2013a) in the Pedroches Valley, near the study area.

Another key issue is that the clay fraction increased with depth in the B and C positions (reaching a clay content of as high as 45% (C: S3)) and its relation with soil OM at depth (S2: 25-50 cm), which was characterized by high OM contents as compared to S3 (B:2.0/0.6%; C:1.8/0.06%) (Table 4). Burke et al. (1989) and Leifeld et al. (2005) have shown high OM levels in soils with high clay content in depth indicating clay stabilization mechanisms in the soil. This effect can be observed in the B and C topographic positions, where an increase in clay content was observed at depth as compared to the upper horizons (B:S1-17.2%/S2-22.1%; C:S1-16.1%/S2-35.7%). This OM increase may be due to carbon translocation mechanisms (dissolved organic carbon), soil biological activity and/or the root depth effect (Sherstha et al., 2004).

Soil OM appears to be concentrated in the first 25 cm (S1) due to OM, where the mineralization and immobilization C processes should be slightly active. In the surface layer (S1), OM was variable along the toposequence studied ranging between 39.9 and 27.3 g kg^{-1} at the B and F positions, respectively (Table 4). In this regard, it is important to point out that the S1 layer can reach over 60% of the total soil organic carbon (T-SOC) values documented, corresponding to 60, 64.4 and 63% for the B, C and D positions respectively as compared to the rest of the soil profile (S2 or S2+S3). Batjes (1996) states that for the 0 to 100 cm depth approximately 50% of soil organic carbon (SOC) appears in the first 30 cm of the soil. Jobbágy and Jackson (2000) showed that 50% of SOC is concentrated in the first 20 cm in forest soils to 1-m depth. Civeira et al. (2012), showed that SOC in the upper 30 cm of soils in Argentina is much higher than in the 30-100 cm interval. Data provided by these authors and the results obtained in this study may be comparable because in this study we used a 75 cm depth and the mentioned authors used a 1m depth. Furthermore, Jobbágy and Jackson (2000) indicated that changes in SOC were conditioned by vegetation type (which determines the vertical distribution of roots) and to a lesser extent the effect of climate and clay content. Despite this, climatic conditions can be a determining factor in the SOC concentrations for surface horizons, whereas clay content may be the most important element in deeper horizons, also, clay contributes to stabilize OM by protecting physically of microbial activity and reducing C outputs, this effect is important under homogeneous climate conditions (as those in the study area). At the regional-global scale, the precipitation contributes to maximize SOC and temperature accelerates mineralization process decreasing the SOC (Post et al., 1982).

Results of T-SOC analysis in the studied area did not show great along the toposequence. T-SOC depended on the degree of development of the soil that appeared at each topographical position. The T-SOC was highest at the B (66.5 g kg^{-1}), D (58.1 g kg^{-1}) and C (52.3 g kg^{-1}) positions, corresponding to Cambisols-Regosols-Leptosols, Regosols, and Phaeozems-Cambisols-Regosols respectively. Leptosols showed the lowest T-SOC content with 27.3 g kg^{-1}, 31.9 g kg^{-1}, 32.7 g kg^{-1} and 38.1 g kg^{-1} at the F, G, E and A topographic positions, respectively. Similarly, >60% of SOC concentrated in the S1 layer of deeper soils (B, C and D).

Precipitation and temperature varied through the studied toposequence, where precipitation increases and temperature decreasing with increasing elevation. T-SOC content was not affected by climatic variations, but depended on the soil development in each landscape position. Reduced T-SOC contents were observed at the lowest topographic positions, where soils were shallower. This is in agreement with Power and Schlesinger (2002) who concluded that topographic position affects T-SOC, due to low OM decomposition rates under low temperatures.

3.3 Soil organic carbon stocks

SOCS in the study area showed a reduction with depth in all topographic positions (Table 4). This SOCS reduction along the profile is linked to OM reduction with depth, this reduction in SOCS also depended on the gravel content and the bulk density (Table 3).

When the upper SCS was analyzed we observed high SOCS values as high as 91.1 Mg ha^{-1} in the elevated topographic positions (highest value at the B position). The lowest SOCS values were found at the G position (53.8 Mg ha^{-1}), the lowest site in the toposequence. This trend of decreasing SOCS with decreasing elevation is constant except at the A and E positions. Both are poorly developed soils with high OM content in the surface horizon).

We observed that at the D and B topographic positions between 53.8 and 58.0% of SOCS, respectively, occurred in the S1 SCS. This constituted 63.0% and 60.0% of T-SOC in these topographic positions. This shows that the gravel content and bulk density affects the SOCS in the surface horizons of the toposequence studied, and, therefore, SOCS decreases when SOC increases. In the most developed soil, similar SOC and SOCS concentrations (B: 60%-SOC; 58%-SOCS) were observed in the S1 layer, conditioned by bulk density and gravel content. In addition, SOCS decreased in depth conditioned by reduction of gravel content and increasing bulk density. This is not in agreement with Tsui et al. (2013) and Minasny et al. (2006), who suggested a negative relation between bulk density and depth as a consequence of high OM content at the surface, linked to low clay concentrations (Li et al., 2010). In this sense, we observed that high SOCS depended on the SOC concentration and the clay content.

However, the SOC concentration affected the SOCS to a lesser degree so that in S2 (25-50 cm) we found >10% of SOCS related to SOC (C position).

In contrast, low SOCS can be found in S3 except at the B topographic position (19.1 Mg ha^{-1}). This situation could be due to the fact that pedological horizons were generally different than the SCS divisions (S1: 0-25 cm; S2: 25-50 and S3: 50-75 cm) (Hiederer, 2009); in other words, the SCS divisions often led to the mixing of two or more soil horizons (depending on thickness horizon) in any given SCS division.

In all studied soils, the clay content increased with depth. This clay content increase is associated to higher values of SOC (B: S2 and C: S2). In this line, we can explain high SOCS concentrations in clayey soils caused by clay stabilization mechanisms on SOC, this effect can observed at the A topographic position which has higher clay content with respect to the B and D positions. However, a SOCS increase can be observed. This is the case at the D and C topographical positions with SOCS values of 52.1 and 50.1 Mg ha^{-1} respectively in the S2 sampling layer (Table 4), showing a correlation between S1 and S2, due to carbon translocation processes as dissolved organic carbon, bioturbation and/or deep rooting (Sherstha et al., 2004).

3.4 Soil organic carbon stocks along the altitudinal gradient

The SOCS results along the toposequence were also studied. It is important to point out that total SOCS (T-SOCS) were influenced by topographical position in the toposequence analyzed. T-SOCS increased linearly with elevation from G (607 m.a.s.l.) to B site (1009 m.a.s.l.), with the exception of the highest topographic position, A (1168 m.a.s.l.), with a linear regression relationship (Figure 1). Similar results were found by Ganuza and Almendros (2003), Leifeld et al. (2005) and Fernández-Romero et al. (2014). These studies showed that the T-SOCS increased with elevation. However, Avilés-Hernández et al. (2009) found that T-SOCS from forest soils decreased with elevation in a toposequence in Mexico due to variations in the OM decomposition rate and Lozano-García and Parras-Alcántara (2014) found that T-SOCS decreased with elevation in a traditional Mediterranean olive grove due to erosion. With respect to the A position in this study, the lower T-SOCS (72.9 Mg ha^{-1}) values with respect to the rest of the studied toposequence may be due to soil loss caused by erosion processes in soils with a low level of development. Similar results have been found by Parras-Alcántara et al. (2004) and Durán-Zuazo et al. (2013). Parras-Alcántara et al. (2004)

explained their findings as a consequence of high soil erosion rates, caused by high erosivity of rainfall, high erosionability, steep slopes, low vegetation cover and the lack of conservation practices in the studied area. Durán-Zuazo et al. (2013) explained this effect by low vegetation densities in the upper parts of mountain areas that can cause high erosion with strong water runoff. Martínez-Mena et al. (2008) have emphasized the effects of erosion on soil OM loss, especially under semi-arid conditions. In this context, a low vegetation ratio can accelerate OM decomposition, weakening soil aggregates (Balesdent et al., 2000; Paustian et al., 2000). Cerdà (2000) indicated that this effect could occur regardless of climatic conditions.

As can be seen in Table 4, T-SOCS decrease was not homogeneous. In some cases, rapid changes were found, while in other situations gradual changes were noted. Abrupt changes in T-SOCS occurred between the B/C and D/E topographic positions, showing T-SOCS differences of 38 Mg ha^{-1} and 44 Mg ha^{-1} respectively. Gradual changes in T-SOCS occurred between the C/D, E/F and F/G topographic positions with variations of 3 Mg ha^{-1}, 13 Mg ha^{-1} and 6 Mg ha^{-1} respectively. Many authors have concluded that the SOCS reduction can be explained by soil physical properties - mainly texture (Corral-Fernández et al., 2013; Parras-Alcántara et al., 2013b). The studied soils are sandy at the surface, with clay increasing with depth, except in E, F and G sites (soils that have S2 and/or S3 SCS), therefore, OM stabilizing mechanisms are produced, reducing the aggregate formation between SOC and mineral fraction at depth. As a result, the SOCS content is lower with sandy soils (Nieto et al., 2013). González and Candás (2004) and Parras-Alcántara et al. (2013a) obtained similar results, the first in sandy-loamy soils and the second in Mediterranean clayey soils. In addition, low SOC levels are conditioned by the climatic characteristics of southern Europe (Gallardo et al., 2000).

Conclusions

Soils found in the Despeñaperros nature reserve include Phaeozems, Cambisols, Regosols and Leptosols. Phaeozems are the deepest and most developed soils, and Leptosols are the least developed and shallowest soils. These soils are characterized by low OM content with depth due to the semiarid Mediterranean conditions and the high sand content. The studied soils are characterized by organic residue accumulation in the surface horizons.

The SOC content decreased with depth at all topographic positions and the clay fraction increased with depth. The mineral medium played an important role in soil humidification processes. In addition, the SOC in the S2 layers is characterized by high SOC values with respect to the S3 layers indicating clay stabilization mechanisms in the soil. We can explain this increase due to carbon translocation mechanisms (dissolved organic carbon), soil biological activity and/or the root depth effect.

With respect to T-SOC content, there is not a large difference between T-SOC along the toposequence. The T-SOC of these soils depends on the degree of development of the soils found at each topographic position. We can observe a T-SOC reduction at the lowest topographic positions for less developed soils and a T-SOC increase at the highest topographic positions in the more developed soils. SOCS in the study zone show a reduction with depth in all topographic positions. This SOCS reduction along the profile is linked to OM and gravel content reduction and an increase in bulk density with depth. The T-SOCS increased with altitude, due to the higher turnover of organic material (plants) and the lower decomposition rate due to lower temperatures.

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Table 1. Soil groups of the study area at each of the seven topographic positions with properties. The key refers to the reference soil groups of the IUSS Working Group WRB (2006) with lists of qualifiers.

Topographic position	m.a.s.l.[a]	Slope %	Parent material	Vegetation	Soil groups	Qualifiers	n[b]
A	1168	15.3	Quartzite - Sandstone	Maritime pine (*Pinus pinaster*) Holm oak (*Quercus ilex*) Gum rockrose (*Cistus ladanifer*)	Leptosols - LP	Mollic - mo	2
B	1009	16.5	Quartzite - Sandstone	Holm oak (*Quercus ilex*) Cork oak (*Quercus suber*) Strawberry tree (*Arbutus unedo*) Gum rockrose (*Cistus ladanifer*)	Regosols - RG Leptosols - LP Cambisols - CM	Eutric - eu Mollic - mo Humic - hu	3
C	945	20.8	Quartzite - Sandstone	Stone pine (*Pinus pinea)* Mastic (*Pistacia lentiscus*)	Cambisols - CM Regosols - RG Phaeozems - PH	Humic - hu Dystric - dy Luvic - lv	3
D	865	5.5	Quartzite	Portuguese oak (*Quercus faginea*) Strawberry tree (*Arbutus unedo*) Gum rockrose (*Cistus ladanifer*)	Regosols - RG	Umbric - um	2
E	778	10.7	Quartzite - Slates	Holm oak (*Quercus ilex*) Strawberry tree (*Arbutus unedo*) Gum rockrose (*Cistus ladanifer*)	Leptosols - LP	Umbric - um	3
F	695	12.0	Quartzite	Cork oak (*Quercus suber*) Holm oak (*Quercus ilex*) Strawberry tree (*Arbutus unedo*) Gum rockrose (*Cistus ladanifer*)	Leptosols - LP	Litic - li	2
G	607	18.5	Slates	Holm oak (*Quercus ilex*) Mastic (*Pistacia lentiscus*)	Leptosols - LP	Mollic - mo	2

[a] Metres above sea level; [b] Sample size

Table 2. Methods used in field measurements, laboratory analysis and to make calculations from study data.

Parameters	Method
Field measurements	
Bulk density (Mg m^{-3})	Cylindrical core sampler* (Blake and Hartge, 1986)
Laboratory analysis	
Particle size distribution	Robinson pipette method (USDA, 2004)**
pH – H_2O	Volumetric with Bernard calcimeter (Duchaufour, 1975)
Organic C (%)	Walkley and Black method (Nelson and Sommers, 1982)
Parameters calculated from study data	
SOC stock (Mg ha^{-1})	(SOC concentration×BD×d×(1-δ_{2mm}%)×0.1)*** (IPCC, 2003)
Total SOC stock (Mg ha^{-1})	$\Sigma_{horizons}$ SOC Stock$_{horizon}$ (IPCC, 2003)

* 3 cm diameter, 10 cm length and 70.65 cm^3 volume.

** Prior to determining the particle size distribution, samples were treated with H_2O_2 (6%) to remove organic matter (OM). Particles larger than 2 mm were determined by wet sieving and smaller particles were classified according to USDA standards (2004).

*** Where SOC is the organic carbon content (g Kg^{-1}), d the thickness of the soil layer (cm), δ2mm is the fractional percentage (%) of soil mineral particles >2 mm in size in the soil, and BD the soil bulk density (Mg m^{-3}).

Table 3. Properties of the soils evaluated (average ± SD*) in the Despeñaperros Nature Reserve.

Topographic position	m.a.s.l. m	SCS	Depth cm	Gravel %	Sand %	Silt %	Clay %	B.D. Mg m^{-3}	O.M. g kg^{-1}	pH H_2O
A	1168	S1	0-25	33.1±13.8 aA	56.5±1.1 aA	22.3±3.0 aA	21.2±4.1 aA	1.1±0.19 aA	64.5±8.9 aA	6.3±0.7 aA
		S2	25-50	7.0±3.1 bA	39.3±0.81 bA	30.7±4.2 aA	30.0±6.1 aA	1.5±0.21 bA	0.99±0.21 bA	5.3±0.5 bA
B	1009	S1	0-25	17.0±10.0 aB	52.9±29.8 aA	29.9±30.6 aA	17.2±5.3 aA	1.1±0.10 aA	68.6±5.2 aA	5.9±0.4 aA
		S2	25-50	27.1±6.4 bB	58.7±20.1 aB	19.1±12.2 bB	22.1±8.0 aB	1.3±0.12 aB	35.3±3.4 bB	5.6±0.7 aA
		S3	50-75	14.3±16.9 aA	41.6±18.1 bA	25.7±15.2 aA	32.6±2.9 bA	1.5±0.12 bA	10.5±2.8 cA	5.7±0.5 aA
C	945	S1	0-25	34.0±5.5 aA	59.2±7.2 aA	24.7±3.1 aA	16.1±6.2 aA	1.2±0.10 aA	58.0±9.5 aA	5.9±0.8 aA
		S2	25-50	14.4±7.2 bC	36.1±12.2 bA	28.2±2.5 aA	35.7±14.1 bA	1.3±0.06 aB	30.9±6.3 bB	5.5±0.4 aA
		S3	50-75	14.9±11.9 bA	24.4±15.9 cB	30.4±9.8 aA	45.2±16.2 cB	1.5±0.05 aA	0.99±0.12 cB	5.2±0.6 aA
D	865	S1	0-25	39.9±6.2 aA	47.6±19.3 aB	38.1±7.5 aB	14.3±2.1 aA	1.1±0.09 aA	62.9±10.4 aA	5.6±1.0 aA
		S2	25-50	24.0±4.5 bB	46.6±18.2 aC	36.2±7.9 aA	17.2±5.4 aB	1.3±0.10 aB	35.9±7.6 bB	5.7±0.8 aA
		S3	50-75	11.9±10.2 cA	30.9±11.1 bB	47.1±5.4 bB	22.0±6.8 aC	1.5±0.13 bA	1.0±0.30 cB	4.5±0.4 bB
E	778	S1	0-25	25.5±6.8 aC	52.2±7.2 aA	30.2±5.1 aA	17.6±2.4 aA	1.2±0.13 aA	56.3±8.9 aA	5.7±0.7 aA
F	695	S1	0-25	28.2±7.4 aC	34.2±5.3 aC	41.0±9.8 aB	24.8±2.8 aA	1.2±0.14 aA	46.9±7.4 aB	6.3±0.5 aA
G	607	S1	0-25	42.9±19.3 aD	54.9±4.1 aA	27.7±2.5 aA	17.3±6.6 aA	1.3±0.13 aB	54.9±9.2 aB	6.2±0.7 aA

m.a.s.l.: Metres above sea level; SCS: Soil control section; BD: Bulk density; O.M.: Organic matter.

*Standard deviation.

Numbers followed by different lower case letters within the same column have significant differences ($P<0.05$) at different depths, considering the same topographic position. Numbers followed by different capital letters within the same column have significant differences ($P<0.05$) considering the same SCS at different topographic position.

Table 4. Soil organic carbon (SOC) content and soil organic carbon stock (SOCS) (average ± SD*) in the Despeñaperros Nature Reserve.

Topographic position	Elevation m.a.s.l.	SCS	SOC g kg^{-1}	T-SOC g kg^{-1}	SOCS Mg ha^{-1}	T-SOCS Mg ha^{-1}
A	1168	S1	37.5±16.8 aA	38.1±8.4 A	70.8±33.5 aA	72.9±17.0 A
		S2	0.58±0.09 bA		2.1±0.57 bA	
B	1009	S1	39.9±10.3 aA	66.6±8.2 B	91.1±13.2 aB	158.0±15.8 B
		S2	20.5±6.4 bB		49.8±14.9 bB	
		S3	6.1±7.8 cA		19.1±19.2 cA	
C	945	S1	33.7±8.6 aA	52.3±5.9 C	67.4±9.7 aA	119.3±10.9 C
		S2	18.0±9.1 bB		50.1±22.4 bB	
		S3	0.58±0.09 cB		1.8±0.26 cB	
D	865	S1	36.6±7.9 aA	58.1±5.7 C	62.1±8.9 aA	116.1±8.6 C
		S2	20.9±9.0 bB		52.1±16.7 bB	
		S3	0.57±0.09 cB		1.9±0.30 cB	
E	778	S1	32.7±13.2 aA	32.7±13.2 A	72.6±25.0 aA	72.6±0.65 A
F	695	S1	27.3±15.1 aB	27.3±15.1 A	59.3±27.3 aC	59.3±27.3 A
G	607	S1	31.9±13.1 aB	31.9±13.1 A	53.8±18.3 aC	53.8±18.3 A

m.a.s.l.: Metres above sea level; SCS: Soil control section; SOC: Soil organic carbon; T-SOC: Total SOC; SOCS: Soil organic carbon stock; T-SOCS: Total SOCS.

*Standard deviation.

Numbers followed by different lower case letters within the same column have significant differences ($P<0.05$) at different depths, considering the same topographic position. Numbers followed by different capital letters within the same column have significant differences ($P<0.05$) considering the same SCS at different topographic position.

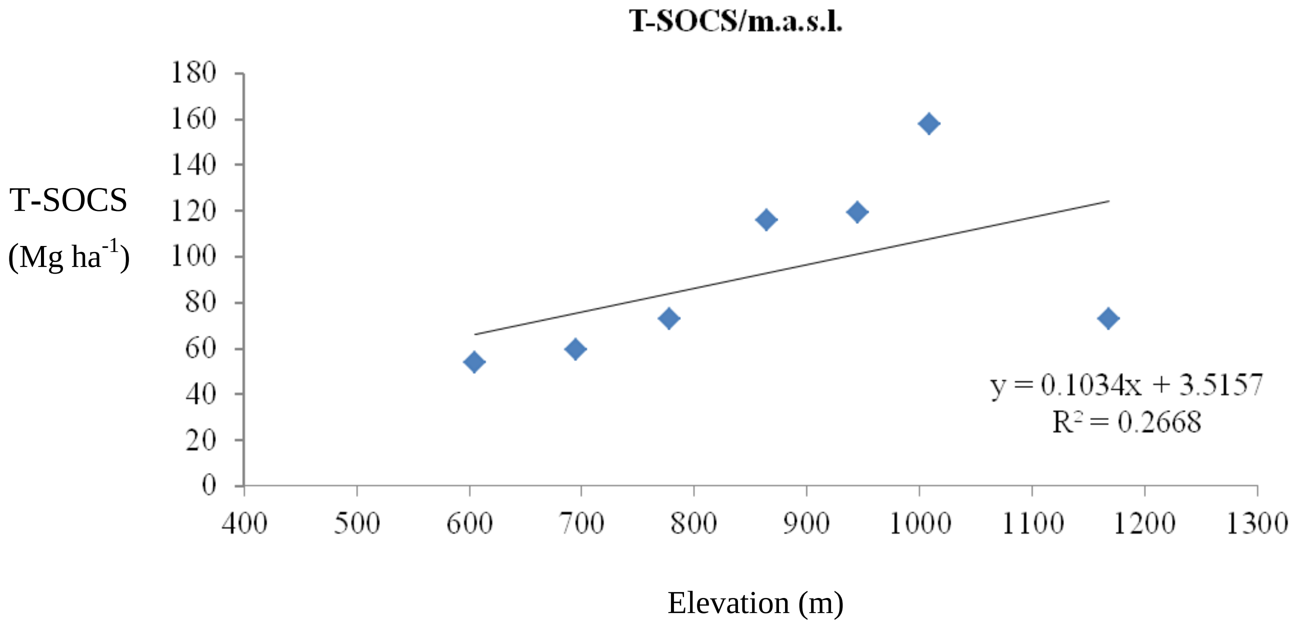

Figure 1. Linear regresion model for T-SOCS versus altitudinal gradient.

T-SOCS: Total soil organic carbon stock