Organic carbon stocks in Mediterranean soil types under different land uses (Southern Spain)

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Abstract

Soil C sequestration through changes in land use and management is one of the sustainable and long-term strategies to mitigate climate change. This research explores and quantifies the role of soil and land use as determinants of the ability of soils to store C along Mediterranean systems. Detailed studies of soil organic C (SOC) dynamics are necessary in order to identify factors determining fluctuations and intensity of changes. In this study, SOC contents from different soil and land use types have been investigated in Andalusia (S Spain). We have used soil information from different databases, as well as land use digital maps, climate databases and digital elevation models. The average SOC content for each soil control section (0-25, 25-50 and 50-75 cm) was determined and SOC stocks were calculated for each combination of soil and land use type, using soil and land cover maps. The total organic C stock in soils of Andalusia is 415 Tg for the upper 75 cm, with average values ranging from 15.9 Mg C ha^{-1} (Solonchaks under “Arable land”) to 107.6 Mg C ha^{-1} (Fluvisols from "wetlands"). Up to 55% of SOC accumulates in the top 25 cm of soil (229.7 Tg). This research constitutes a preliminary assessment for modelling SOC stock under scenarios of land use and climate change.

1 Introduction

Soil organic C (SOC) plays an important role in the global C cycle. It is generally assumed that soils are the largest C sinks in terrestrial ecosystems. Soils act as a source or a sink of atmospheric CO_2 and contain approximately twice the amount of C in the atmosphere, and about three times the amount in vegetation (IPCC, 2000, 2007, Lal, 2004). Soils have the ability to store C for long periods of time; thus, changes in the size of the soil C pool could significantly modify the atmospheric CO_2 concentration. Additionally, an adequate level of SOC stock is essential to decrease erosion and degradation risks, hold water and nutrients and improve soil structure (Lal, 2004).

Carbon sequestration is a crucial strategy for reducing atmospheric CO_2 concentration, contributing to climate change mitigation (Lal, 2003). Globally, soil C pools contain approximately 1,550 Gt of organic C in the top 1 m (from a total of approximately 2,500

Gt C), and SOC sequestration is estimated at 0.4 to 1.2 Pg C year $^{-1}$, equivalent to 6-20% of the annual release from fossil fuel combustion (Lal, 2004; Houghton, 2005).

On the other hand, the soil C pool is particularly difficult to quantify and in some cases it is assumed to be a fixed fraction or ignored due to lack of data or precise methodologies. During the last years, the need for accurate information on SOC content at the European, national or regional level has increased due to the importance of SOC stocks for sustainable use of natural resources.

In addition to the present concern about environmental problems such as soil degradation and soil contamination, information on SOC stocks is necessary to assess the potential role of soils as CO_2 sinks. Reports of national inventories of C stocks are required under the Kyoto Protocol by the United Nations Framework Convention on Climate Change (e.g., MARM, 2011) , to estimate C emissions to the atmosphere, which requires accurate and reliable estimates of current C stocks. Carbon inventories and analysis of SOC distribution constitute an essential tool for modelling the effects of different factors involved on SOC sequestration potential.

SOC pools at global scales are difficult to assess due to high spatial variability and different factors affecting soil C dynamics. Among these factors, land use has a strong influence on SOC stocks (Liebens and VanMolle, 2003; Meersmans et al., 2008; Smith, 2008), altering the balance between C losses and sequestration (Ostle et al., 2009). Nevertheless, there are further determinants influencing SOC variability, such as climate and topography (Schulp et al., 2008; Phachomphon et al., 2010). Consequently, SOC estimates are commonly uncertain in areas with heterogeneous land uses and a high variety of climate and site patterns (Leifield et al., 2005) such as the Mediterranean environments. At the same time, soil depth has an important influence on SOC stocks (Grüneberg et al., 2010). Most studies on SOC are restricted to the topsoil, although vertical processes have a considerable effect on SOC variability (VandenBygaart, 2006). The few existing studies that compare the dynamics of SOC in the upper horizons and the subsurface, suggest a variation in depth of factors controlling SOC dynamics, a hypothesis that has not yet been thoroughly investigated (Salome et al., 2010; Albadalejo et al., 2011). Vertical distribution is one of the features of the organic C pool that is not clearly understood together with the relationships with climate and vegetation (Jobbágy and Jackson, 2000).

Several studies have estimated SOC stocks on a large scale by using national and global soil maps and a certain amount of representative soil profiles, or by combining soil and land cover spatial datasets (Batjes, 1996; Batjes and Dijkshoorn, 1999; Arrouays et al., 2001; Morisada et al., 2004; Batjes 2005; Bradley et al., 2005; Leifeld et al., 2005). Commonly, inventories are based on a combination of soil-land use mapping units and assignment of mean SOC values from soil profiles, which makes it possible to determine patterns in SOC variability related to soil and land use features. However, the reliability of these estimates depends upon the quality and resolution of the land use and soil spatial databases. Moreover, due to the large spatial variability of SOC within the map units, an elevated density of soil sampling points is required to achieve accurate estimates (Liebens and VanMolle, 2003; Martin et al., 2011).

According to Bahn et al. (2009), a key item in future research in the terrestrial C cycle is an accurate assessment of SOC pool in ecosystems and regions that have so far been heavily under-represented. Whereas the SOC pool has been studied at global, continental (Eswaran et al., 1993, Liski et al., 2002; Smith, 2004) or regional scales in humid forest systems (Batjes and Dijkshoorn, 1999, Schwartz and Namri, 2002), there is a lack of information on Mediterranean systems. In addition, estimates of SOC stocks may be particularly inaccurate in areas with diverse land use patterns, such as Mediterranean landscapes. In Spain, for example, Rodríguez-Murillo (2001) assessed organic C contents under different types of land use and soil. Nevertheless, there are few studies providing accurate regional SOC estimates based on combined studies of soil land cover data. In general, there is a lack of national-scale studies on soil spatial variability in Spain (Ibáñez et al., 2005) and therefore detailed studies on SOC distribution in soils are necessary (Flores et al., 2007). Future studies on SOC pools need to be carried out in a comparable way, and the access to datasets needs to be facilitated (Bahn et al., 2009). This study comes to fill a gap in SOC assessment in Mediterranean soils.

The objectives of this study are [1] to quantify current SOC contents and SOC stocks in Andalusia (S Spain) for each land use and soil type at different soil depths, [2] to assess possible relationships between SOC stocks and environmental variables, and [3] to elaborate a SOC map of the studied area.

This research is part of a global project for developing a land evaluation tool for predicting SOC pool under scenarios of land use and climate change, as a new component of the MicroLEIS Decision Support System (Anaya-Romero et al, 2011; De la Rosa et al., 2004)

The Mediterranean area represents an important challenge to scientists and land managers because of its size, physical complexity, geological and anthropological history (Blondel and Aronson, 1995). The information generated in this study will be a useful basis for modelling SOC processes and designing of management strategies for stabilizing the increasing atmospheric CO_2 concentrations by preservation of C stocks and sequestration in other Mediterranean regions.

2 Materials and methods

2.1 Study area

Andalusia (S Spain) covers an area of approximately 87,000 km2 (Figure 1). The climate is Mediterranean, with dry, hot summers and mild, moderately rainy winters, showing local variations at a detailed scale. Western Atlantic areas are more rainy and humid, whereas the eastern portion has a dry to extremely dry Mediterranean climate. Average annual precipitation ranges between 500 and 700 mm. Average annual temperatures vary between <10 and 18 ^{o}C, although milder temperatures are observed at the coast border. Elevation varies between 0 and 3479 masl (Mulhacén Peak). According to CSIC-IARA (1989), the main soil reference groups are Cambisols, Leptosols, Luvisols, Regosols, and Vertisols.

Most of the natural vegetation is Mediterranean forest, predominantly evergreen trees such as oaks, pines and firs, with dense riparian forests and Mediterranean shrubland. Currently, 45.7% and 9.6% of soil is dedicated to farm uses and grasslands, respectively. Agriculture in Andalusia has traditionally been based on wheat crops, olive trees and vineyards. In recent decades, traditional crops have been substituted with intensive and extensive crops (e.g., rice, sugar beet, cotton and sunflower). Likewise, intensive greenhouse crops under plastic have spread through some areas. In the coastal area the decline of traditional crops has been imposed mainly by massive urbanization and tourist infrastructures.

2.2 Origin of data and treatment

2.2.1 Soil data

Data from 1479 geo-referenced selected soil profiles reported and described by Jordán and Zavala (2009) and the SEISnet soil database (http://www.evenor-tech.com/banco/seisnet/seisnet.htm) distributed through the study area have been used to estimate SOC content. These databases contain descriptive and analytical data, including site characteristics, horizon description, chemical and physical analysis. Selection of soil profiles was carried out considering homogeneous sampling and analysis methods.

Variables used in this study were soil depth (cm), organic C content (g 100 g^{-1} soil), bulk density (g cm^{-3}) and coarse fragments (mineral particles >2 mm in diameter; g 100 g^{-1}). Soil types were described and classified according to FAO (2006). Organic C was determined by dichromate oxidation using the Walkley-Black method (Walkley and Black, 1934). Bulk density was measured by the core method (Blake and Hartge, 1986).

In order to normalize information from soil profiles, data were re-coded and imported to the SDBm Plus Multilingual Soil Profile Database, a geo-referenced soil attribute database that contains a large number of descriptive and analytical data fields (De la Rosa et al., 2002). As soil profiles showed a range of depths, data were homogenised and re-sampled for 0-25, 25-50 and 50-75 cm. The SDBM Plus database incorporates a “control section” function, which allows determining the thickness of the layer to be analysed within the soil profile. This function allows calculating the weighted average value for each variable in standard control sections.

The spatialization of soil data was carried out following the spatial distribution of soil classes from the soil map of Andalusia (CSIC-IARA, 1989) at scale 1:400,000, which contains 2,707 polygons classified in 64 soil map units, according to the legend of the soil map of the world (IUSS Working Group WRB, 2006).

2.2.2 Climate data

Climate data were obtained from the time series of the CLIMA subsystem of the Environmental Information Network of Andalusia (REDIAM, Andalusian Regional Government) which integrates several databases from a set of over 2200 observatories since 1971. Selected variables were mean monthly temperature and mean annual precipitation.

2.2.3 Elevation and slope

Elevation and slope data were extracted from the 100 m resolution digital elevation model (DEM) of Andalusia (ICA, 1999) derived from the topographic map of Andalusia (S 1:10,000).

2.2.4 Land use and land cover data

Land use classification and land cover data for this study were taken from the Land Use and Land Cover Map of Andalusia (LULCMA) for 2007 at scale 1:25,000 and minimum map unit 0.5 ha (Moreira, 2007). This digital spatial dataset, obtained after the analysis of satellite images (Landsat TM, IRS/PAN and SPOT-5) and digital aerial photographs, is a result of the Coordination of Information on the Environment (CORINE) programme, promoted by the European Commission in 1985 for the assessment of environmental quality in Europe.

Within the CORINE programme, the CORINE Land Cover project (CLC) provides consistent information on land cover and land cover changes across Europe (Anaya-Romero et al., 2011). The LULCMA provides an updated version of the original maps at scale 1:100,000 and constitutes more detailed and accurate databases, both thematically and geometrically. Land use and land cover changes (LULCC) were assessed visually and gaps/errors were substituted with revised data from different origins or direct observations. Land cover classes of LULCMA were reclassified into CLC standard nomenclatures, in order to make the methodology available for other CORINE programme member countries and obtain easily comparable results (Muñoz-Rojas et al., 2011).

The standard CLC nomenclature includes 44 land cover classes, grouped in a three-level hierarchy. The 5 main classes (level 1) describe land patterns for use on a planet scale, comprising the following categories: 1) “Artificial surfaces”, 2) “Agricultural areas”, 3) “Forest”s and semi-natural areas”, 4) “Wetlands”, and 5) “Water bodies” (Heymann et al., 1994). Level 2 (15 classes) corresponds to physical and physiognomic entities at scales 1:500,000 and 1:1,000,000 (“Urban zones”, “Forests”, “Lakes”, etc). Finally, level 3 is composed of acutely defined 44 classes for use on scale 1:100000 and higher (“Residential areas”, “Airport”, “Commercial areas”, etc.). All national working groups adopted this standard nomenclature, although it has been improved over the years by introducing local subclasses.

2.3 Soil organic C stock calculation

For each soil layer (0-25, 25-50 and 50-75 cm) of the 1479 soil profiles, soil organic C content (SOCC) was estimated as follows:

$$SOCC = SOC \times BD \times D \times (1-G) \qquad (1)$$

where SOCC is soil organic C content (Mg ha-1), SOC is soil organic C percentage (g 100-1 g-1), BD is bulk density (g cm-3), D is the thickness of the studied layer (cm) and G is the proportion in volume of coarse fragments (g 100 g-1). Equivalent approaches at different scales were used by Rodríguez-Murillo (2001) in peninsular Spain and by Boix-Fayos et al. (2009) in Murcia (SE Spain). Soil profiles were classified according to original soil profile descriptions, into 10 soil reference groups (IUSS Working Group WRB, 2006): Arenosols, Calcisols, Cambisols, Fluvisols, Leptosols, Luvisols, Planosols, Regosols, Solonchaks and Vertisols, and 7 land use types (following CLC nomenclature at level 2: “Arable land”, “Permanent crops”, “Heterogeneous agricultural areas”, “Forest”, “Scrub and/or vegetation associations”, “Open spaces with little or no vegetation”, and “Maritime wetlands”).

Data analysis was performed using SPSS (SPSS, 2009) and ArcGIS (ESRI, 2006) software packs. To determine SOC for each soil class within every land cover type, the study area was divided into “land use-soil association units” (landscape units) using a topological intersection of the LULCMA for 2007 and the Soil Map of Andalusia. The overlay of both maps resulted in 85,492 new polygons, defined by 1 soil class (dominant unit) and one aggregated land cover type.

Mean values of SOCC of each land use- soil class was assigned to all the new polygons. Soil organic C stocks for each soil class were determined by multiplying SOCC mean values by the area occupied by the land use-soil unit in the overlay map.

2.4 Relationships between soil organic C content and environmental variables

In order to identify the influence of environmental factors (climate and site factors) on SOC, correlation analyses were performed using Statistica (StatSoft, 2001). The following variables were considered: mean annual precipitation (mm), mean winter (December-February) and summer (June-August), temperature, elevation and slope.

Analyses were carried out for the total set of soil profiles, and for different soil types and land use classes. A number of soil profiles, classified as Planosols, Solonchaks and soils from “Maritime wetlands” were not considered in the analysis because of the absence of SOC variation with environmental variables.

Elevation and slope data for each profile was extracted from the DEM, and climate variables (mean annual rainfall and mean summer and winter temperature), were obtained from the Climate Spatial Datasets in raster format. Data Analysis was performed using ArcGIS Spatial Analyst extension tool (ESRI, 2006).

3 Results

3.1 Soil organic C contents from main land use and soil types

The total area of soils under “Arable land”, “Permanent crops”, “Heterogeneous agricultural area”, “Forest”, “Scrub and/or vegetation associations”, “Open spaces with little or no vegetation”, and “Maritime wetlands”, identified using the Soil Map of Andalusia and LULCMA, was 83,686.74 km^2 (Table 1). Ten major soil groups occur in the study area. Cambisols (42.7% of the studied area) and Regosols (19.7%) are most common, followed by Vertisols (8.8%), Leptosols (8.6%), and Luvisols (8.3%). These five major groups account for about 73,744.74 km^2 (88.1% of the studied area).

Soil organic C content (SOCC) and coefficient of variation (CV) were calculated for each land use and soil type combination/association in the study area (Table 2). Values are shown for 0-25, 25-50, 50-75 and 0-75 cm depths.

On average, Calcisols, Regosols and Solonchaks have the highest SOCC values, above 55 Mg C ha^{-1} while Arenosols and Leptosols show the lowest amounts, below 40 Mg C ha^{-1} (Table 2, Figure 2). Likewise, SOCC is considerably lower in “Open spaces with little or no vegetation” compared to the other land use types, and “Maritime wetlands” have the highest SOCC of all land use classes (Table 2, Figure 3).

The highest SOCC values in the first 25 cm of soil were observed in Fluvisols and Solonchaks under “Maritime wetlands”, which store more than 50 Mg C ha^{-1} (Table 2). Calcisols under “Heterogeneous agricultural areas” and “Forest” stored 50.1 and 50.7 Mg C ha^{-1} respectively. Solonchaks under “Arable land” and Vertisols under “Scrub and/or herbaceous vegetation associations”, have the lowest SOCC values, storing less than 14 Mg C ha^{-1}. The average SOCC distribution with depth is similar in all land use-soil class combinations, decreasing rapidly with increasing soil depth and tending to near-zero values below 50 cm for soils under "Open spaces with little or no vegetation" (Arenosols, Leptosols and Regosols). Calcisols under "Forest" store high amounts of SOC at larger depths comparing to other soil groups with SOCC values above 27 Mg C ha^{-1} and 15 Mg C ha^{-1} in the layers 25-50 cm and 50-75 cm.

Values of SOCC in the entire depth down to 75 cm range between 107.6 Mg C ha-[1] for Fluvisols under "Maritime wetlands" and 15.9 Mg C ha^{-1} for Solonchak under "Arable land". A large variation in SOC exists within each land use-soil class association with CV ranging between 3.8% for Solonchaks under "Arable land" and 152.7% for Luvisols under "Heterogeneous agricultural areas".

3.2 SOC stocks from main land use and soil types

Total stocks per land use class and soil type (in absolute terms) are given in Table 1. "Scrub and /or vegetation associations" contain 115.92 Tg C in 22,561.98 km^2, "Permanent crops" 94.65 Tg C in 17275.66 km^2, "Arable land" 84.59 Tg C in 15,468.49 km^2 and "Forest"67.60 Tg C in 15,911.37 km^2. Soils with the largest SOC stock are Cambisols (162.66 Tg), Regosols (91.95 Tg) and Vertisols (48.37 Tg).

The estimated SOC stock in the upper 75 cm is 415 Tg (Table 1). Accumulated C stocks for each soil type and land use class are shown in Figure 4 and Figure 5, respectively. All soil groups store more than 50% of total C in the first 25 cm, except Vertisols which accumulates less than 45%. The proportion of SOC stock in the 0-25 cm layer is on average about 55% (229.69 Tg) of the total SOC stock in the upper 75 cm, around 30% (122.89 Tg) in the 25-50 cm layer and 15% (62.62 Tg) in the deepest layer (50-75 cm) (Figures 4 and 5). Among all land use types, agricultural uses such as "Arable land" and "Permanent crops" show low percentages of SOC stock in the first layer (below 50%).

Current spatial distribution of SOCC per land use-soil association unit (Mg C ha-1) in Andalusia is shown in Figure 6.

3.3 Relationships between SOC and environmental data

Statistical analysis of correlations between SOC contents and environmental factors is shown in Table 3. Mean values, standard deviation and correlation coefficients have been obtained for each variable and SOC in the total dataset and land use/soil type groups.

Considering all the soil profiles, SOC was negatively correlated with slope (r = -0.2900). The analysis did not show significant correlations with other variables.

SOC was positively correlated with winter temperature in Cambisols and Luvisols (r = 0.9550 and r = 0.8249) and negatively correlated with summer temperature (r = -0.8291) in Fluvisols. In Vertisols, a significant negative correlation was found with elevation (r = -0.9511).

Among land uses, SOC showed a positive correlation with winter temperature in “Heterogeneous agricultural areas” (r = 0.9319) and a negative correlation with summer temperature in “Forest” (r = -0.8794). Elevation is also well correlated with SOC in “Heterogeneous agricultural areas” (r = -0.8818)

In both natural land use types (“Heterogeneous agricultural areas” and “Forest”), significant correlations were found with SOC and annual precipitation. However, whereas in “Forest” the correlation was positive (r = 0.7908), in “Heterogeneous agricultural areas” SOC was negatively correlated with precipitation (r = -0.7454).

4 Discussion

4.1 Soil C stocks

Studies on the spatial distribution of SOC in relation with soil types have been carried out by many authors. Liebens and VanMolle (2003), for example, evaluated different methodologies for assessing SOC stock in Flanders, Belgium, in which SOC densities were assigned to polygons on the digital soil map of Flanders. For the total area of Belgium, Lettens et al. (2005) used a topological intersection of CLC geo-data sets and a digitized soil association map and soil C data from different data sets to plot the distribution of soil C stocks in the country. Also, in France, Arraouays et al. (2001) took into account both forest soil types and vegetation cover. Then C densities were determined by soil/land use category using a combination of geo-referenced soil and CORINE land use databases. The same approach was used in Great Britain by Howard et al. (1995), who mapped the geographical distribution of SOC with estimates based on the dominant soil series and land cover class for 1 km × 1 km blocks.

Nevertheless, studies concerning both soil type and land use combined data are scarce, especially in Mediterranean areas. Different soil types show a range of capacities for C sequestration due to soil inherent potential (based on texture, mineralogy, etc) to retain organic C (Gibson et al., 2002) and therefore, both soil and land use data should be used in determining soil C stocks.

A number of studies have been carried out in different regions of Spain concerning SOC stocks under main land uses and/or soil types (Boix-Fayos et al., 2009; Diaz-Hernández et al., 2003; Ganuza and Almendros, 2003; Jordán et al., 2007). One of the most complete is the work conducted by Rodríguez-Murillo (2001), in which stock and spatial distribution of SOC in peninsular Spain was determined using soil profile descriptions available in literature.

Our estimates are in agreement with the results obtained in Mediterranean areas by other authors. Among the major soil types, the largest average SOCC is found in Calcisols, and Vertisols (Figure 2). Most of Calcisols occur under “Scrub and/or herbaceous associations” and values of SOC stocks for Calcisols obtained in this research are generally larger than those found by several authors (e.g., Rodríguez-Murillo, 2001). However, determined SOCCs are similar to those estimated by Diaz-Hernandez (2003) in South eastern Spain, with 52 Mg C ha^{-1} at 0.5 m depth and 70 Mg C ha^{-1} at 1 m depth.

A high SOC content in Vertisols which are naturally fertile soils may be explained by its high clay content and consequently high moisture storage capacity. Similar values of SOCCs for Vertisols were reported in Spain by Rodríguez-Murillo (2001), 68.9 Mg C ha^{-1}, and in Jordan by Batjes (2006), 37 Mg C ha^{-1} at 0.3 m depth and 75 Mg C ha^{-1} at 1 m depth with 59 Mg C ha^{-1} for “Arable land” and 68 Mg C ha^{-1} for “Forest” at 1 m depth. Moreover, in Tunisia, Brahim et al. (2010) estimated 45.6 Mg C ha^{-1} at 30 cm depth and 109.7 Mg C ha^{-1}at 1 m depth. Higher values were found in Central and Eastern Europe by Batjes (2002), with 82 Mg C ha^{-1} at 0.3 m and 236 Mg C ha^{-1} at 1 m depth.

A low SOC content is observed for coarse textured Arenosols. However, values encountered in this soil class are above those calculated by Rodríguez-Murillo (2001) and Batjes (2006), who estimated SOCCs of 22.2 Mg C ha^{-1} in Spain and 20.0 Mg C ha^{-1} in Jordan respectively. Nevertheless, calculations for SOC stocks estimated for Arenosols in this research are similar to values reported in France by Arrouays et al. (2001) which range between 28 Mg C ha^{-1} under “Arable land” to 44 Mg C ha^{-1} under “Forest”.

Cambisols are the most predominant soil type in the study area together with Regosols (Table 2). Cambisols are spread in a wide range of environments around the world and under all types of vegetation. Most of the European Regosols are found in the

Mediterranean region and are particularly common in arid areas. In the study area of this research, both soil types are used for agriculture and show high values of SOCCs under agricultural land uses.

We obtained lower SOCCs for Cambisols than those estimated by other authors in other Mediterranean areas such as Spain and Tunisia. In these areas, Rodríguez-Murillo (2001) and Brahim et al. (2010) calculations were 71.4 Mg C ha^{-1} and 101.8 Mg C ha^{-1} respectively at depth of 1 m. Larger values were obtained in Germany (114 Mg C ha^{-1}) and Central Europe (118 Mg C ha^{-1}) by Neufeldt (2005) and Batjes (2002). On the other hand, values of SOCCs for Cambisols lie between those proposed by Arrouays et al. (2001) ranging from 30 Mg C ha^{-1} for "Permanent crops" and 121 Mg C ha^{-1} for moors and heathlands. Moreover, Batjes (2006) found similar estimations in Jordan for Cambisols, with values of 23 Mg C ha^{-1} at 0.3 m depth and 45 Mg C ha^{-1} at 1 m depth.

Soil organic C content for Regosols in this study is larger than values reported by other authors in Spain and other Mediterranean regions. Rodríguez-Murillo estimated 48.7 Mg C ha^{-1} and Díaz-Hernandez (2003) obtained 35 Mg C ha^{-1} at 0.5 cm depth and 52 Mg C ha^{-1} at 1 m depth and in Jordan, Batjes (2006) reported 8 Mg C ha^{-1}. Comparing to France, SOCCs of Regosols under "Forest" are similar, around 50 Mg C ha^{-1} (Arrouays et al., 2001) but we estimated larger values under "Permanent crops".

We found similar SOCCs in Luvisols and Fluvisols, although larger values for Fluvisols were encountered under agricultural uses opposite to Luvisols which presented higher SOCCs under "Forest" and scrubs. The highest values among all soil classes and land use types in this study were those obtained for Fluvisols under "Maritime wetlands" (107.64 Mg C $ha-^{1}$) at 1m depth. Fluvisols are fertile soils and frequently occur under rice crops in wetlands. Most of the area covered by Luvisols, which have a great potential for a large number of crops when drainage is adequate, is under "Permanent crops" and "Arable land". Rodríguez -Murillo (2001) reported higher values for both Fluvisols and Luvisols in Spain, 75.8 Mg C $ha-^{1}$ and 66 Mg C $ha-^{1}$ respectively, nonetheless our estimations are within the values propose in France (Arrouays et al., 2001). They estimated SOCCs ranging from 27 Mg C $ha-^{1}$ under "Permanent crops" to 102 Mg C $ha-^{1}$ under Pastures for Fluvisols and 29 Mg C $ha-^{1}$ Mg C $ha-^{1}$ under "Permanent crops" to 84 Mg C $ha-^{1}$ under Pastures.

Planosols and Solonchaks occupy 1,916.20 and 1,481.70 km^2 respectively, mostly under "Arable land". Planosols are frequently used for grazing, nevertheless, under specific management they can be used for cultivation. Solonchaks are widespread in the arid and semi-arid climatic zones and land uses are limited by the salt content. Thus, in the study area low values are found under "Arable land" and relatively large under "Maritime wetlands" (15.85 Mg C ha^{-1} and 70.80 Mg C ha^{-1} respectively). These results are in agreement with those estimated in Spain by Rodríguez-Murillo (2001), with 76.3 Mg C ha-^{1}.

Generally, SOC contents are larger in the surface layer declining with depth. This is in agreement with previous studies (e.g.: Batjes, 1996; Salome et al., 2010). In arid soils from SE Spain, for example, Albadalejo et al. (2011) found that SOC from different soil types showed significant variations within the first 30 cm, and suggested that these variations were caused mainly by land use and precipitation. Nevertheless, the distribution of SOC with depth is likely to vary with different soil types (Schrumpf et al., 2008). More than 50% of the organic C of all studied soil groups was stored in subsoil horizons (0-25 cm), the layer more susceptible to change upon land use change especially agricultural and "Forest" management. These results are in line with Schöning et al. (2006) and Grüneberg et al. (2010). In particular, Leptosols, which are commonly shallow soils with limited soil development, accumulate 83.9% in the first 0.25 m (with 97.4% of the SOC content in the first 0.5 m). Most of the Leptosols are under scrub and/or herbaceous associations and "Forest", and SOCCs obtained in this research for Leptosols were lower than values reported by other areas in similar regions (Rodríguez-Murillo, 2001; Batjes, 2006). SOCC under "Forest" is below other land uses with similar areas, as "Arable land" or "Permanent crops". This may be explained as a consequence of the low degree of development of forest soils, where Cambisols, Leptosols and Regosols are dominant. Leptosols under "Forest", for example, occupy an area 6.9 and 3.2 times larger than under "Arable land" and "Permanent crops", respectively.

4.2 Relationship between SOCC and environmental variables

It is critical to determine the different factors explaining SOC stocks at different scales (Dai and Huang, 2006; Rodeghiero et al., 2010). According to Jenny (1941), climate is the main factor that influences the soil organic matter content through its effect on inputs (related to biomass production) and outputs produced by the microbial metabolism (influenced in turn by the climate and water availability). Natural or anthropic processes favouring increased biomass production (such as soil fertility, photosynthetic efficiency, fertilization, etc.) should be favourable to the decrease in atmospheric C content, by fixation in biomass or in soil (Macías et al., 2004).

The correlation between SOC content and winter temperature was positive for most soil types, although significant correlation coefficients were only observed for Cambisols and Luvisols. Correlation coefficients between SOC content and summer temperature were mostly negative, but significant correlations were only observed for Fluvisols. Other authors have reported negative correlations between temperature and SOC content (Hontoria et al., 1999; Ganuza and Almendros 2003; Dai and Huang, 2006). Concentrations of organic C are usually higher in cold environments, where decomposition rates are low (Paustian, 2002). However, the range of temperatures in the studied area is not as wide as those observed in broad scale studies (e.g.: Dai and Huang, 2006), and local processes can be significant. Our results suggest that extremely low winter and extremely high summer mean temperatures in the study area contribute to a decrease in SOC content.

Significant correlation coefficients were observed for precipitation and SOC content from "Forest" (r = 0.7908) and "Heterogeneous agricultural areas" (r = -0.7454), but contradictory results exist and a clear trend was not observed. Weak and no significant correlation was found when all soil profiles were considered. This is in contrast with results from other authors in Spain (Hontoria et al., 1999; Rodríguez-Murillo, 2001). Hontoria et al. (1999) obtained r = 0.55 for the whole country and Ganuza and Almendros (2003) estimated r = 0.5675 in the Basque Country (North Spain). Jobággy and Jackson (2000) analysed a large amount of soil profiles in the United States and elsewhere reporting values of r = 0.5 for 1 m depth. In a recent research, Ruiz Sinoga et al. (2012) have found that SOC sequestration in Mediterranean rangelands from southern Spain is reduced one order of magnitude from soil profiles under humid (59,9 Mg ha^{-1}) to semiarid (11.6 Mg ha^{-1}) climatic conditions.

High and significant negative correlations were observed between SOC content and elevation for Vertisols. Also, high (but non-significant) correlations were observed for Cambisols (r = -0.8775) and Fluvisols (r = -0.7219). Other soils showed weak and non-significant correlations. For LU types, elevation was significantly correlated to SOC content only in "Heterogeneous agricultural areas". When all groups were considered, weak and no significant correlations were observed between SOC and elevation, in contrast with other studies by Hontoria et al. (1999) and Rodríguez-Murillo (2001), although these authors considered soil data from the Iberian Peninsula.

4.3 Limitations of the methodology

It is known that soil properties have a high spatial variability and, according to many authors, organic C is one of the soil parameters with highest variability (Don et al., 2009; Hontoria et al., 1999; Schrumpf et al., 2008). We found relatively high CV among groups, particularly large in natural land uses such as forest and scrub, which is in accordance with many authors. Batjes (2006) obtained CVs over 150% for some soil groups in Central Europe and even larger values in his study of the total C in the soils of the world (Batjes, 1996). In Spain, for example, Rodríguez-Murillo (2001) reported CVs between 49.3 and 136.0% for SOC concentrations under the main land use types. Relatively high CV are usual for regional or national scale studies and the IPCC assume that there are uncertainties on absolute stock values calculations and therefore high quality data sets should be used to reduce estimation uncertainty. It is necessary to assume some uncertainty when using average values with high CV in small scale studies (as in national or regional inventories).

All soil types are not homogenously distributed. Cambisols, Fluvisols, Leptosols, Luvisols, Regosols, and Vertisols account for 93.29% of the study area, whereas Arenosols, Calcisols, Planosols and Solonchaks correspond to 6.71%. Consequently, when these soils are subdivided per LU class, the number of soil profiles per soil-LU combination is sometimes low. However, these combinations are representative of small areas which do not alter significantly global estimations.

Many empirical models have been proposed for explaining the relationship between SOC content and climatic factors. Global data show that organic C content increases in soils under high rainfall and low temperature (Oades, 1988). At detailed scales, anthropic transformation of ecosystems may strongly affect SOC content. Intensification of agricultural management, silviculture or afforestation, for example, may buffer the impact of climate on SOC. As a consequence, regional or local-scale studies may not show strong dependence between SOC content and climatic variables. Also, in the context of global change, other SOC redistribution or sequestration processes might be considered, as the increasing frequency of wildfires. At wide scale, wildfires are assumed to increase the organic C stock in soils, as reported by González-Pérez et al. (2004). At local scale, redistribution processes of soil organic matter by water erosion processes following wildfires may be substantial. It has been reported that erosion and the subsequent deposition after forest fires constitute a sink for C-rich sediments at the valley bottoms. In addition, C losses by soil erosion at the hillslopes may be replaced by the production of new biomass (Novara et al., 2011)

5 Conclusions

This study comprises the first comprehensive analysis of current organic C stocks for each soil type under present land use types in Andalusia, S Spain. In this research soil organic C pools and their distribution within the soil profile, are estimated under existing land uses, providing baseline information to assess the potential of the different soil types for SOC sequestration.

Soil organic C stocks are estimated at different depths (0-25, 25-50 and 50-75 cm) under different land use/soil type associations. Cambisols and Regosols are the most common soil types in Andalusia, but Calcisols and Vertisols show the highest SOCC values, above 65 Mg C ha^{-1}. In total, SOC stock is 415 Tg in the upper 75 cm and on average, with 55% stored in the first layer (0-25 cm). The amount of SOC in the first 75 cm was significantly correlated with annual mean temperature, annual mean precipitation and elevation in natural areas.

Regional studies for assessing soil organic C stocks are needed and should include information about LU/LC and soil class.

Nevertheless, large uncertainties in estimates of SOC stock prevail. These uncertainties can be also attributed to gaps in our understanding of both future land C content and quantification of the response of C sequestration according to land use change. Therefore, the role of future land use change in C stocks is considered in further research.

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Figure 1. Study area.

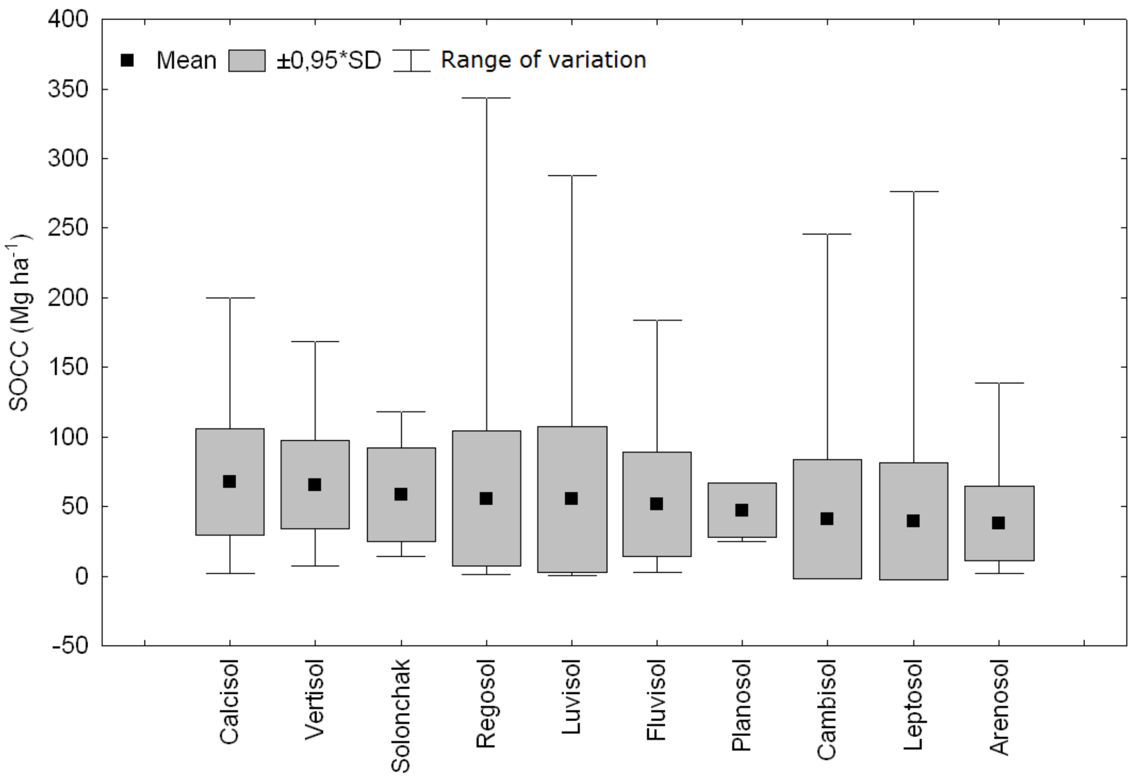

Figure 2. Soil organic carbon content (SOCC) for the major soil groups in the study area. SD: standard deviation.

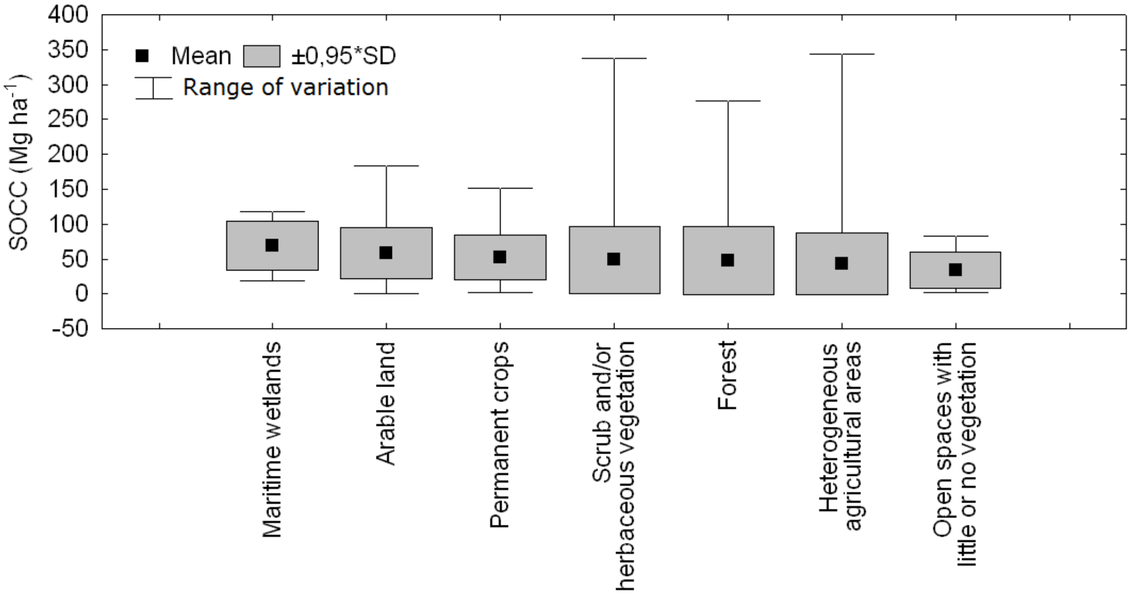

Figure 3. Soil organic carbon content (SOCC) for each land use type. SD: standard deviation.

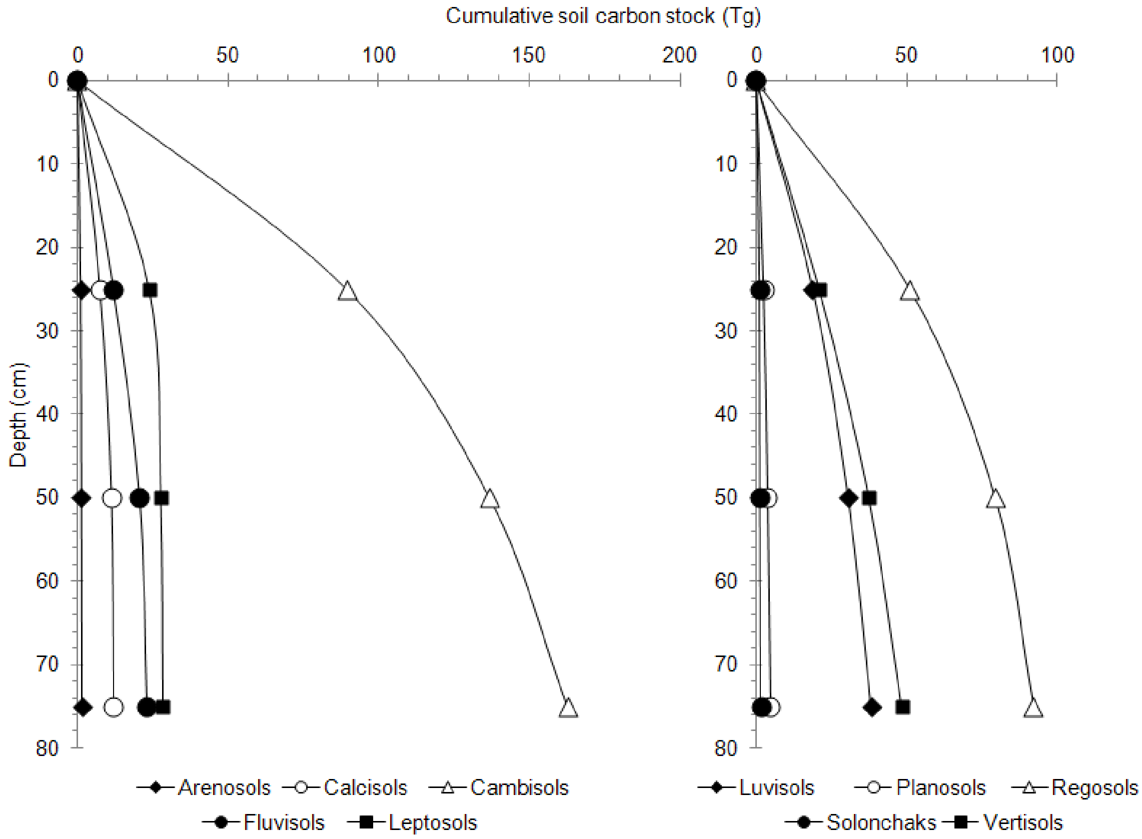

Figure 4. Cumulative soil organic carbon stock in depth for each soil class.

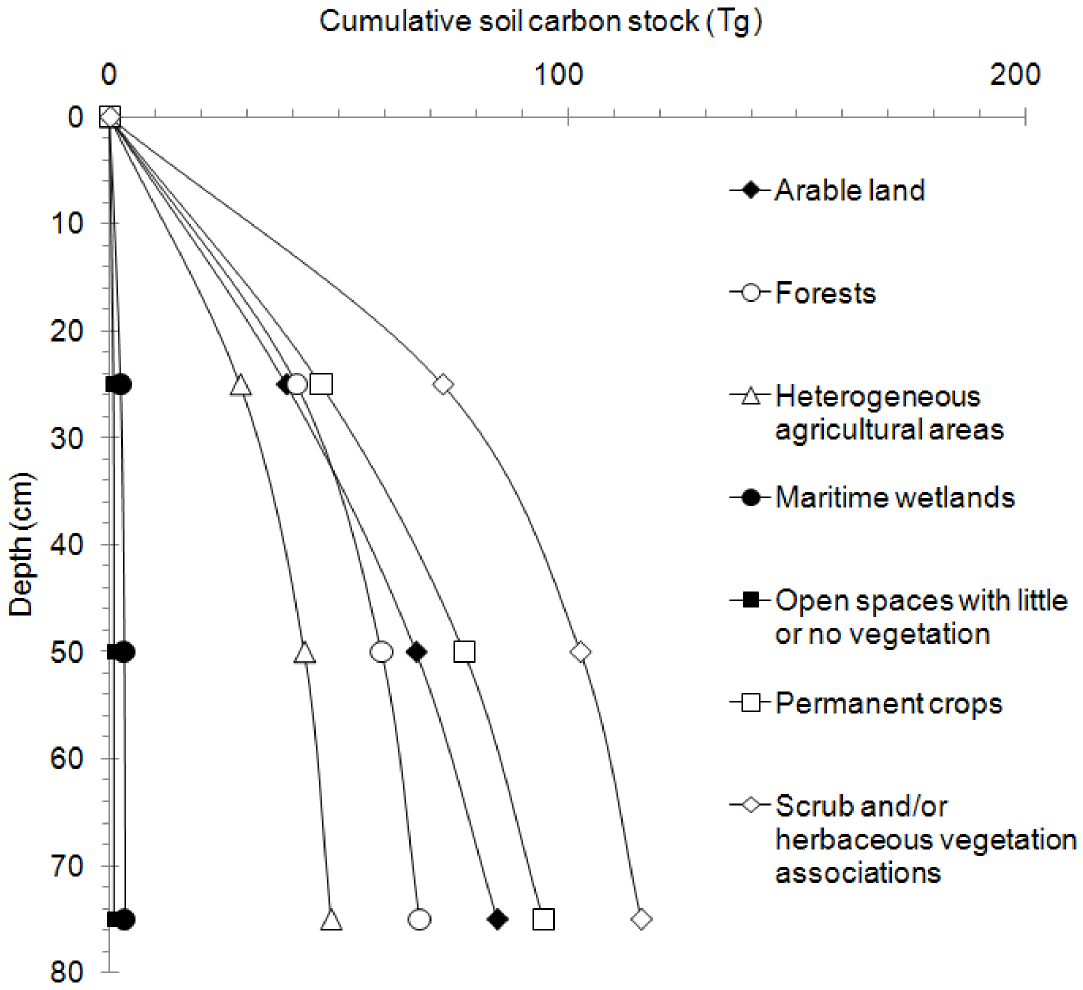

Figure 5. Cumulative soil organic carbon stock in depth for each land use type.

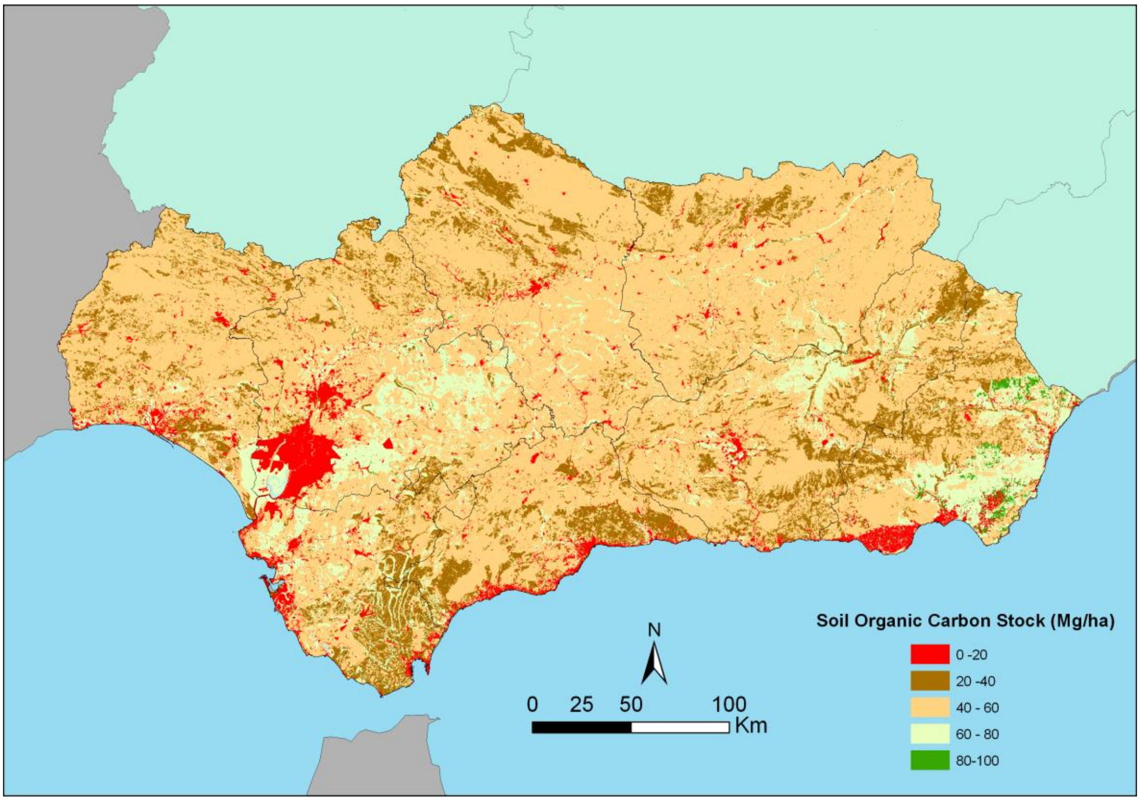

Figure 6. Map of soil organic carbon content (0-75 cm) in Andalusia.

Table 1. Area (km^2) and SOC stocks (SOC stock, Tg) under main land uses types and soil group.

Soil group	"Arable land"		"Permanent crops"		"Heterogeneous agricultural areas"		"Forest"		Scrub and/or herbaceous vegetation associations		"Open spaces with little or no vegetation"		"Maritime wetlands"		Total	
	Area	SOCS	Area	SOCS	Area	SOCS	Area	SOCS	Area	SOCS	Area	SOCS	Area	SOCS	Area	SOCS
Arenosol	75.00	0.22	19.23	0.06	17.66	0.09	158.95	0.53	150.77	0.66	12.40	0.02	43.10	0.00	477.12	1.57
Calcisol	418.44	2.75	118.92	0.66	323.62	2.66	35.34	0.34	823.90	5.46	15.52	0.00	1.66	0.00	1737.40	11.88
Cambisol	4513.96	21.33	7296.52	43.69	6351.18	21.93	7990.29	26.41	9352.92	49.30	205.01	0.00	16.21	0.00	35726.09	162.66
Fluvisol	1454.13	7.97	961.37	5.91	613.15	3.77	435.89	2.05	775.91	2.97	23.49	0.00	65.62	0.71	4329.57	23.39
Leptosol	255.75	0.99	542.77	1.50	352.12	1.32	1755.01	7.19	4175.28	16.87	91.67	0.41	0.00	0.00	7172.58	28.29
Luvisol	1522.38	8.09	2389.15	13.69	866.75	4.42	982.42	5.84	1193.73	6.09	20.50	0.00	8.81	0.00	6983.74	38.13
Planosol	722.15	4.22	416.67	0.00	171.06	0.00	374.67	0.00	206.29	0.52	9.20	0.00	16.15	0.00	1916.20	4.74
Regosol	2040.71	12.99	3888.70	19.58	1637.16	6.81	3616.00	20.09	5150.77	31.85	152.03	0.57	32.81	0.06	16518.18	91.95
Solonchak	923.80	1.46	11.89	0.00	80.23	0.00	42.91	0.00	64.12	0.34	17.39	0.00	341.36	2.42	1481.70	4.22
Vertisol	3542.16	24.57	1630.43	9.55	973.77	7.26	519.88	5.13	668.29	1.85	8.23	0.00	1.39	0.00	7344.15	48.37
Total	15468.49	84.59	17275.66	94.65	11386.70	48.27	15911.37	67.60	22561.98	115.92	555.43	1.00	527.12	3.19	83686.74	415.21

Table 2. Carbon stocks for land use-soil combinations at different soil depths (0-25, 25-50 and 0-75 m) (Mg ha-1). N: number of values, M: mean value, CV: coefficient of variation, na: insufficient number of samples to provide statistics (not available).

Soil group	Soil depth (cm)	"Arable land"			"Permanent crops"			"Heterogeneous agricultural areas"			"Forest"			Scrub and/or herbaceous vegetation associations			"Open spaces with little or no vegetation"			"Maritime wetlands"			Total		
		N	SOCC	CV	N	SOCC	CV	N	SOCC	CV	N	SOCC	CV	N	SOCC	CV	N	SOCC	CV	N	SOCC	CV	N	SOCC	CV
Arenosol	0-25	5	18.6	94.5	6	16.4	84.8	10	34.1	33.9	28	25.8	58.2	20	29.9	78.1	2	16.2	126.7	0	na	na	71	26.5	67.1
	25-50		3.5	101.3		15.2	107.7		10.3	75.5		5.2	151.3		8.3	173.6		0.8	141.4		na	na		7.3	150.1
	50-75		0.1	175.2		0.95	189.1		5.9	135.6		2.2	224.8		5.3	181.2		0.0			na	na		3.8	199.9
	Total		22.1	70.2		32.5	91.6		50.2	33.9		33.2	57.3		43.5	95.8		17.0	127.4		na	na		37.7	74.6
Calcisol	0-25	80	35.5	53.8	59	29.2	62.8	7	50.1	65.5	26	50.7	57.7	14	45.9	56.6	0	na	na	0	na	na	186	36.9	61.7
	25-50		23.3	84.4		18.7	89.6		25.5	62.6		27.5	58.8		19.2	113.6		na	na		na	na		22.2	83
	50-75		7.0	179.3		7.9	183.9		6.6	175.5		15.7	101.7		1.2	374.2		na	na		na	na		8.0	169.4
	Total		65.8	56.8		55.6	65.1		82.2	42.3		96.9	46.0		66.3	62.4		na	na		na	na		67.6	59.4
Cambisol	0-25	54	19.6	94.7	15	30.2	39.1	35	22.6	86.8	99	19.3	137.1	35	30.7	104.9	0	na	na	0	na	na	238	22.2	110.1
	25-50		16.3	98.3		18.3	63.9		8.3	113.1		8.9	151.9		15.5	136.5		na	na		na	na		12.0	126.5
	50-75		11.4	121.2		11.4	78.7		3.7	187.8		4.9	210.8		6.6	160.6		na	na		na	na		6.8	162.2
	Total		47.3	91.7		59.9	46.4		34.5	89.4		33.1	143.6		52.7	97.9		na	na		na	na		41.1	108.9
Fluvisol	0-25	28	26.7	68.5	1	29.5	nd	13	29.9	66.8	17	19.3	120.3	13	26.9	103.5	0	na	na	1	73.6	nd	73	26.3	84
	25-50		20.8	71.8		32.0	nd		21.7	65.3		18.3	117.8		5.8	118.7		na	na		20.3	nd		17.9	90.9
	50-75		7.3	167.4		0.0	nd		9.9	135.9		9.6	153.8		5.6	221.3		na	na		13.7	nd		8.0	160.4
	Total		54.8	53.0		61.5	nd		61.5	61.3		47.1	118.1		38.3	92.0		na	na		107.6	nd		52.1	75.6
Leptosol	0-25	19	27.7	98.9	14	20.2	82.5	54	33.6	97.6	143	33.6	111.0	105	34.5	100.3	2	44.6	122.0	0	na	na	337	33.1	104.7
	25-50		9.1	158.4		5.5	144.7		3.9	269.4		6.3	350.6		4.9	257.8		0.0			na	na		5.6	304.5
	50-75		1.8	435.9		2.1	195.3		0.0	734.9		1.1	512.7		0.9	471.8		0.0			na	na		0.9	512.8
	Total		38.6	94.3		27.7	67.0		37.6	94.3		41.0	126.3		40.4	100.2		44.6	122.0		na	na		39.6	111.2

Luvisol	0-25	34	25.1	82.6	30	25.6	70.7	15	24.8	143.3	41	33.9	103.1	24	28.7	132.1	0	na	na	0	na	na	144	28.2	104.7
	25-50		17.8	93.4		18.5	80.3		15.3	174.7		15.2	107.8		15.1	128.8		na	na		na	na		16.5	107.9
	50-75		10.2	124.5		13.3	99.8		11.0	227.6		10.4	115.1		7.3	191.9		na	na		na	na		10.5	137.7
	Total		53.2	78.45		57.3	73.8		51.0	152.7		59.5	100.5		51.0	127.7		na	na		na	na		55.2	100
Planosol	0-25	2	28.8	22.9	0	na	na	0	na	na	0	na	na	1	17.6	nd	0	na	na	0	na	na	3	25.1	31.8
	25-50		16.5	13.0		na	na		na	na		na	na		7.7	nd		na	na		na	na		13.5	39
	50-75		13.2	7.3		na	na		na	na		na	na		0.0	nd		na	na		na	na		8.8	86.9
	Total		58.5	16.6		na	na		na	na		na	na		25.3	nd		na	na		na	na		47.4	42.9
Regosol	0-25	56	31.9	66.4	53	24.8	73.2	33	21.5	112.7	111	34.6	87.7	71	35.5	80.9	4	29.9	32.5	1	19.0	nd	329	31.3	84.1
	25-50		22.1	70.5		17.8	79.1		12.5	196.5		16.5	131.6		16.9	147.1		7.4	165.9		0.0	nd		17.2	120.8
	50-75		9.7	150.6		7.7	162.2		7.7	286.3		4.5	198.1		9.4	222.2		0.0			0.0	nd		7.2	211.5
	Total		63.7	60.2		50.4	62.6		41.6	153.4		55.6	92.0		61.8	104.7		37.3	46.3		19.0	nd		55.7	92
Solonchak	0-25	2	11.1	65.8	0	na	na	0	na	na	0	na	na	8	30.1	44.8	0	na	na	10	50.4	50.5	20	38.4	61.7
	25-50		2.1	141.4		na	na		na	na		na	na		17.0	79.1		na	na		17.4	121.1		15.7	110.1
	50-75		2.6	141.4		na	na		na	na		na	na		6.5	163.7		na	na		3.0	290.8		4.3	207.2
	Total		15.9	3.8		na	na		na	na		na	na		53.6	60.0		na	na		70.8	49.8		58.4	60.5
Vertisol	0-25	51	28.4	48.7	13	25.2	54.8	2	38.5	8.5	5	42.4	18.9	7	13.1	127.9	0	na	na	0	na	na	78	27.6	53.3
	25-50		23.0	57.1		17.8	54.3		31.3	24.8		35.9	25.7		8.9	146.9		na	na		na	na		21.9	61.1
	50-75		18.1	81.7		15.7	67.4		4.8	141.4		20.4	64.1		5.7	189.6		na	na		na	na		16.4	85.2
	Total		69.4	44.8		58.6	43.3		74.6	3.1		98.7	14.9		27.7	146.3		na	na		na	na		65.8	50.1
Total	0-25	331	28.5	69.6	191	26.1	66.2	169	28.7	96	470	39.9	103.8	298	33.1	94.5	8	30.1	83.8	12	49.7	52	1479	30.1	91.1
	25-50		19.8	84.2		17.3	84.4		10.5	164.4		11.9	167		11.2	168.7		3.9	227		16.2	122		0.14	130.7
	50-75		10.0	137.9		8.8	144.1		4.7	294.7		4.9	208		4.9	264.8		na	na		3.6	234.5		6.5	193.6
	Total		58.3	65.4		52.2	65.3		43.8	106.2		47.8	51.9		49.1	103.6		34.1	79.8		69.6	53.5		50.6	91.2

Table 3. Mean soil organic carbon content (Mg ha-1) and standard deviation for each soil and land use type and correlation coefficients between soil organic carbon content and environmental variables. (*) p≤0,05; (**) p≤0,01; (***) p≤0,001. Non-significant correlation coefficients are not marked.

Type	Group	N	Mean	Std.Dev.	Winter Temperature	Summer Temperature	Total precipitation	Elevation	Slope
Soil	Arenosols	71	36.9188	8.0129	0.1320	0.1115	0.4624	-0.0808	-0.6201
	Calcisols	186	67.7720	8.0194	0.0123	-0.6355	0.4861	0.3360	0.3494
	Cambisols	238	41.4895	12.9810	0.9550 *	-0.4089	-0.2570	-0.8775	-0.0372
	Fluvisols	73	56.6057	30.4507	0.4650	-0.8291 *	-0.3751	-0.7219	-0.5153
	Leptosols	337	37.6295	15.61437	-0.4220	-0.699372	-0.6166	-0.1992	-0.5535
	Luvisols	144	50.7031	26.9051	0.8249 *	-0.5144	0.8041	-0.4060	0.6917
	Regosols	329	42.5729	22.5279	-0.6058	-0.0881	-0.0622	0.2386	-0.1990
	Vertisols	78	60.8834	10.4383	0.6370	0.9060	-0.9111	-0.9511 *	0.0175
Land use	“Arable land”	331	55.1962	12.13281	-0.0345	-0.0394	0.1300	0.0387	-0.0900
	“Forest”	470	45.2115	14.2694	-0.4833	-0.8794 **	0.7908 *	0.6795	-0.0399
	“Heterogeneous agricultural areas”	169	48.0900	21.4989	0.9319 ***	-0.5134	-0.7454 *	-0.8818 **	-0.1654
	“Open spaces with little or no vegetation”	8	16.9625	11.4580	-0.0078	-0.8816	-0.8009	-0.6594	-0.6894
	“Permanent crops”	191	43.1218	19.0391	-0.4130	0.5452	-0.3750	0.0440	-0.6657
	Scrub and/or herbaceous vegetation associations	298	55.2321	21.8231	-0.2346	-0.0902	0.4386	0.2303	0.5722
All groups		1456	47.9880	21.4769	0.1279	-0.2610	-0.0530	-0.2274	-0.2900 *