Spatial analysis for assessing soil organic carbon stocks in southern Spain

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Introduction

Soils are the largest C sinks in terrestrial ecosystems. Soils have the ability to store C for long periods of time; thus, changes in the size of the soil carbon pool could significantly modify the atmospheric CO_2 concentration. The global soil organic C (SOC) pool of 2,500 gigatons (Gt) includes about 1,550 Gt of SOC. SOC pools contain approximately 1,550 Gt of organic C in the first 100 cm (from a total of approximately 2,500 Gt), 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. Reports of C stocks are required under the Kyoto Protocol to the United Nations framework Convention on Climate Change to estimate C emissions. Inventories and analysis of SOC distribution constitute an essential tool for modelling the effects of the different factors involved on SOC sequestration potential. SOC pools at global scales are difficult to assess due to high spatial variability and the different factors affecting soil C dynamics. Among these factors, land use has a strong influence on SOC stock, altering the balance between C losses and carbon sequestration. SOC estimates are commonly uncertain in areas with heterogeneous land uses and a high variety of climate and site patterns as Mediterranean environments.

Most studies are restricted to the topsoil, although vertical processes have a considerable effect on SOC variability. The few existing studies that compare the dynamics of SOC in the upper horizons and the subsurface, suggest a variation with depth in the factors that control the dynamics of SOC, a hypothesis that has not been thoroughly investigated. Vertical distribution is one of the features of the organic carbon pool that is not clearly understood together with the relationships with climate and vegetation.

Several studies have estimated SOC stocks at large scale by using national and global soil maps and a certain amount of representative soil profiles, or by combining soil/land use spatial datasets, which makes possible to determine patterns in SOC variability. But reliability depends on the quality and resolution of soil/land use information.

This research is part of a global project for developing a land evaluation tool for evaluating soil capacity for C sequestration, as a new component of the MicroLEIS Decision Support System. **The objectives of the present study were to estimate current soil organic carbon (SOC) stocks for each land use and soil type, studying relationships between SOC stocks and selected environmental variables (elevation, temperature and rainfall).** 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.

Methods

STUDY AREA. The study area is **Andalusia (S Spain; Figure 1).** Monthly rainfall ranges between <300 and >2000 mm year^{-1}). Mean temperature varies between <10 and 18 ºC. Elevation ranges from 0 to 3479 masl. Main soil types are Cambisols (33%), Regosols (20%), Luvisols (13%) and Leptosols (11%).

Most of natural vegetation is Mediterranean forest and shrubland (Figure 2), and 45.7 and 9.6% of soil is dedicated to farming 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.: wheat, rice, sugar beet, cotton and sunflower) and greenhouse crops. In the coastal area the decline of traditional crops has been imposed mainly by massive urbanization and tourist infrastructures.

Figure 1. Study area.

SOIL DATABASES. Data from about 2000 geo-referenced soil profiles have been used to estimate SOC. Soil variables used were soil depth (cm), organic carbon content (g 100 g^{-1} soil), sand (%), silt (%) and clay content (%) and bulk density (g cm^{-3}). Data were homogenized and re-sampled for 0-25, 25-50 and 50-75 cm.

SPATIAL DATASETS. Land use classification for this study was based on the Land Use and Land Cover Map of Andalusia (LULCMA) for 2007 at scale 1:25,000 and minimum map unit 0.5 ha, obtained after the analysis of satellite images (Landsat TM, IRS/PAN and SPOT-5) and digital aerial photographs. Land cover classes of LULCMA were reclassified into standard CORINE Land Cover (CLC) nomenclatures. Land use and land cover changes (LULCC) were examined and gaps/errors were substituted with revised data from different origins or direct observations. Spatial distribution of soil types was extracted from the soil map of Andalusia (S 1:400,000; CSIC-IARA, 1989). Elevation was extracted from the 100 m resolution digital elevation model derived from the topographic map of Andalusia (S 1:10,000).

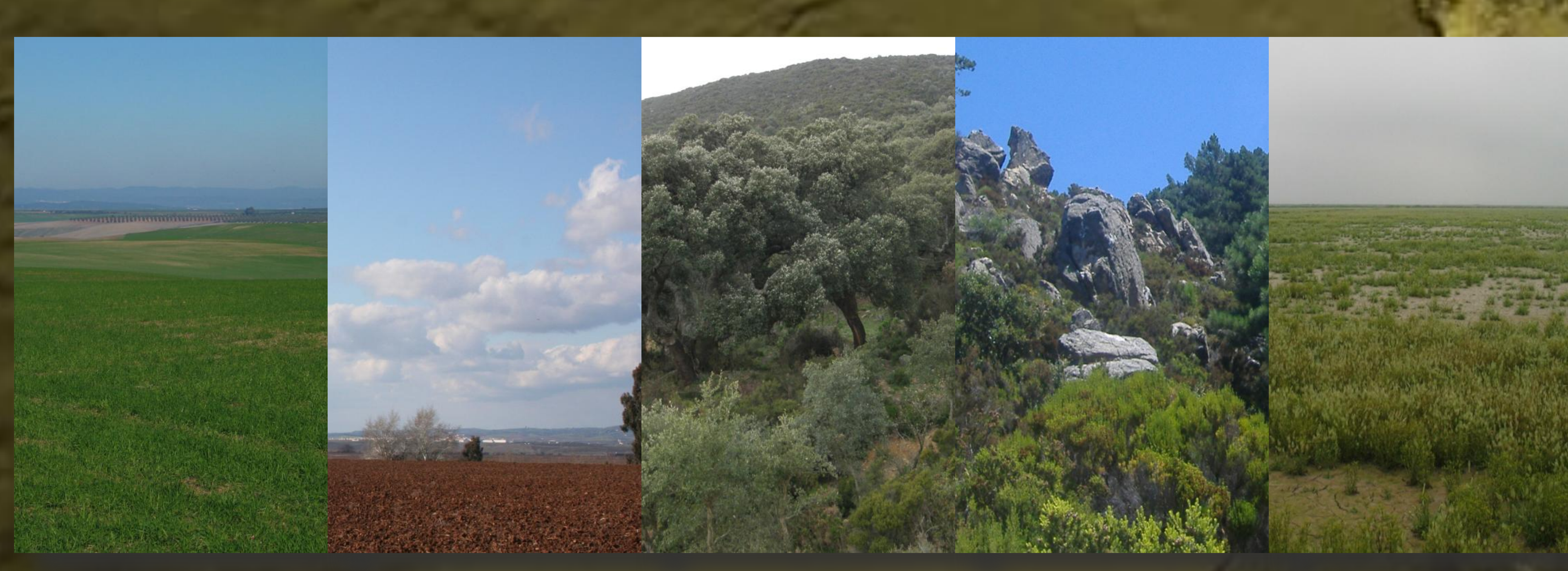


Figure 2. Different soil/land use units in the study area.

CLIMATE VARIABLES. Rainfall and temperature data were obtained from the 1971 – 2000 time series of the Environmental Information Network of Andalusia (REDIAM).

SOC STOCKS CALCULATION.
For every soil layer of the 1736 soil profiles, soil organic carbon density (SOCD) was estimated as follows:

$$\mathrm{SOCD} = \mathrm{SOC} \quad \mathrm{BD} \quad \mathrm{D}$$

where SOCD is soil organic carbon density (Mg ha^{-1}), SOC is soil organic content (g 100^{-1} g^{-1}), BD is bulk density (g cm^{-3}), and D is the thickness of the studied layer (cm). Soil profiles were grouped according to original soil profile descriptions, into 10 soil classes (FAO) and 7 CLC land use types ("Arable land", "Permanent crops", "Heterogeneous agricultural area", "Forest", "Scrub and/or vegetation associations", "Open spaces with little or no vegetation", and "Maritime wetlands").

SOCs for each soil class within every land cover type, the study area was divided into "land use-soil association units" using a topological intersection of the LULCMA for 2007 and the SMA. The overlay of both maps resulted in 85,4925 new polygons, defined by one soil class (dominant unit) and one aggregated land cover type. Mean values of SOCD of each land use-soil class was assigned to all the new polygons. SOC stock for each soil class was determined by multiplying SOCD mean values by the area of each land use-soil unit.

RELATIONSHIPS BETWEEN SOC AND ENVIRONMENTAL VARIABLES. Linear multiple regressions were performed to find the best predictive equation for SOC. Only natural areas ("Agroforestry", "Broad-leaved forest", "Coniferous forest", "Mixed forest", "Grassland", "Sclerophyllous vegetation" and "Transitional woodland-scrub") were considered.

Discussion of results

SOC STOCKS. Figure 3 shows the SOC map of Andalusia. Our estimates (Table 1) are in agreement with the results obtained in Mediterranean areas by other authors. Figure 4 shows the cummulative SOC stock for each soil type. The largest SOC are found in Calcisols, and Vertisols. Most of Calcisols occur under "Scrub and/or herbaceous associations" and values of SOC stocks for Calcisols obtained in this research are in general larger than those found by several authors. 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. Low SOC contents are observed for coarse textured Arenosols.

Cambisols are the predominant soil type in the study area together with Regosols. 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 SOC stocks under agricultural land uses.

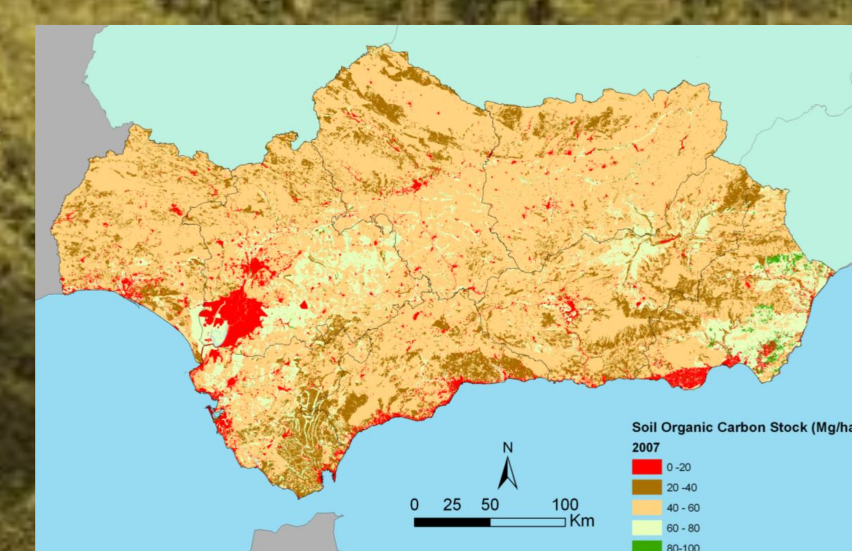


Figure 3. Map of soil organic carbon content (0-75 cm) in Andalusia.

SOC stocks for Regosols in this study are larger than values reported by other authors in Spain and other Mediterranean regions, as the Iberian Peninsula or France.

We found similar values of SOC stocks in Luvisols and Fluvisols, although larger values for Fluvisols were encountered under agricultural uses opposite to Luvisols which presented higher SOC stocks 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.

Planosols and Solonchaks occupy 4,742.75 and 4,224.74 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 lands 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 other authors. Figure 5 shows the SOC stock for each CORINE land cover class.

More than 50% of the OC 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 (Figures 6 and 7). Leptosols, which are commonly shallow soils with limited pedogenic 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 SOC stocks obtained in this research for Leptosols were lower than values reported by other areas in similar regions.

Table 1. Area (km^2) and SOC stocks (SOCS, Gg) under main land uses and soil types.

	Arable land		Permanent crops		Heterogeneous agricultural areas		Forests		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	215.39	19.23	62.48	17.66	88.72	158.95	527.60	150.77	655.34	12.40	21.12	43.10	0.00	477.12	1570.66
Calcisol	418.44	2754.74	118.92	661.63	323.62	2659.63	35.34	342.49	823.90	5463.85	15.52	0.00	1.66	0.00	1737.40	11882.35
Cambisol	4513.96	21328.30	7296.52	43692.96	6.351.18	21934.10	7990.29	26414.11	9352.92	49295.52	205.01	0.00	16.21	0.00	35726.09	162664.99
Fluvisol	1454.13	7969.70	961.37	5913.48	613.15	3772.10	435.89	2054.75	775.91	2972.40	23.49	0.00	65.62	706.39	4329.57	23388.82
Leptosol	255.75	987.41	542.77	1503.48	352.12	1322.69	1755.01	7191.84	4175.28	16872.29	91.67	408.71	0.00	0.00	7172.58	28286.40
Luvisol	1522.38	8086.08	2389.15	13689.13	866.75	4422.00	982.42	5844.76	1193.73	6090.40	20.50	0.00	8.81	0.00	6983.74	38132.36
Planosol	722.15	4.221.14	416.67	0.00	171.06	0.00	374.67	0.00	206.29	521.61	9.20	0.00	16.15	0.00	1916.20	4742.75
Regosol	2040.71	12991.90	3888.70	19577.74	1.637.16	6809.04	3616.00	20088.98	5150.77	31849.11	152.03	567.00	32.81	62.16	16518.18	91945.94
Solonchak	923.80	1464.13	11.89	0.00	80.23	0.00	42.91	0.00	64.12	343.75	17.39	0.00	341.36	2416.86	1481.70	4224.74
Vertisol	3542.16	24569.57	1630.43	9552.42	973.77	7261.86	519.88	5132.26	668.29	1851.86	8.23	0.00	1.39	0.00	7344.15	48367.97
Total	15468.49	84588.35	17275.66	94653.32	11.386.70	48270.14	15911.37	67596.79	22561.98	115916.14	555.43	996.83	527.12	3185.41	83686.74	415206.98

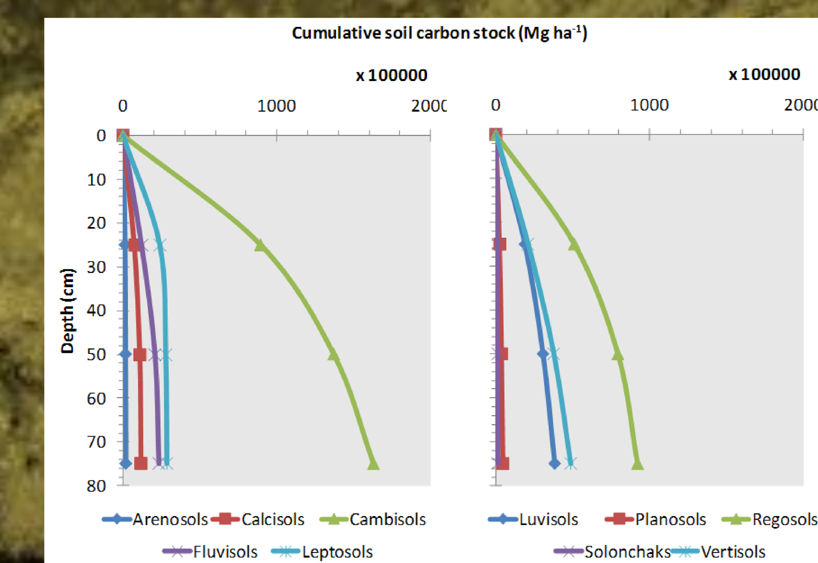


Figure 6. Cumulative soil organic carbon stock in depth for each soil type.

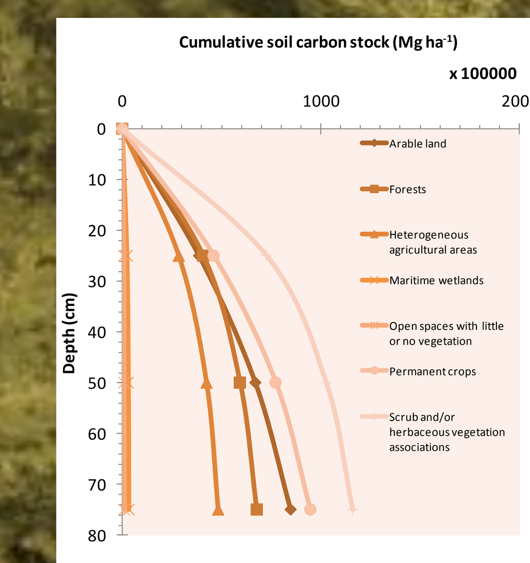


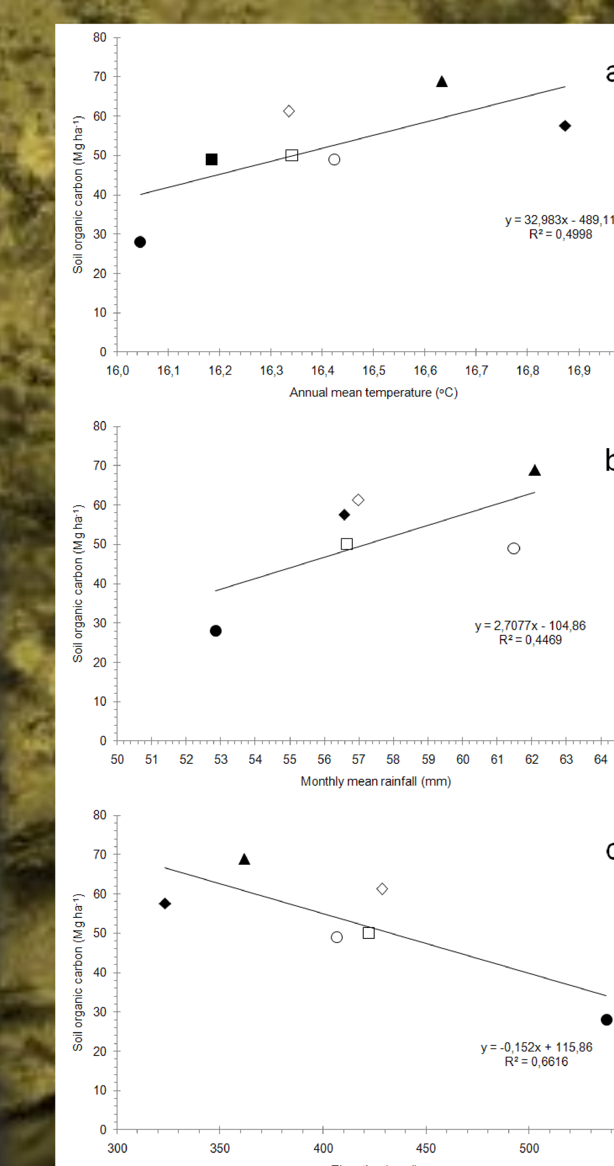
Figure 7. Cumulative soil organic carbon stock in depth for each CORINE land cover class.

RELATIONSHIP BETWEEN SOC STOCK AND ENVIRONMENTAL VARIABLES. 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). Although SOC contents for the different soil types and land uses vary widely, mean SOC stocks from land use types show good correlations with mean temperature, rainfall and elevation.

The correlation between SOC and temperature (Figure 8) was positive, in contrast with negative correlations reported by other authors. SOC contents use to be higher in cold environments, where decomposition rates are low. However, the range of temperatures in the studied area is not as wide as those observed in broad scale studies, and local processes can be significant. High SOC contents were observed in soils under mixed forests (16.6 ºC and 68.9 Mg ha^{-1} SOC, on average) or sclerophyllous vegetation (16.3 ºC, 61.3 Mg ha^{-1}), and lower contents were observed under transitional woodland-scrub (1.2 ºC and 49.0 Mg ha^{-1}), broad-leaved forest (16.4 ºC and 49.0 Mg ha^{-1}) and agroforestry soils (16.0 ºC and 28.0 Mg ha^{-1}).

The SOC content in Andalusia increases with precipitation, in agreement with the results of previous studies, although values presented in this work are higher than others reported in Spain.

Finally, **SOC stocks showed a high negative correlation with elevation** (Figure 8). Major SOC stocks were observed mainly under land use types distributed through lowlands ("grassland" and "mixed forest", for example). On the other hand, **soils under "agroforestry", with mean elevation 537.7 masl, showed the lowest mean SOC content**. Therefore, larger SOC stocks seem to be related with high temperatures and precipitations accompanied by low altitude.



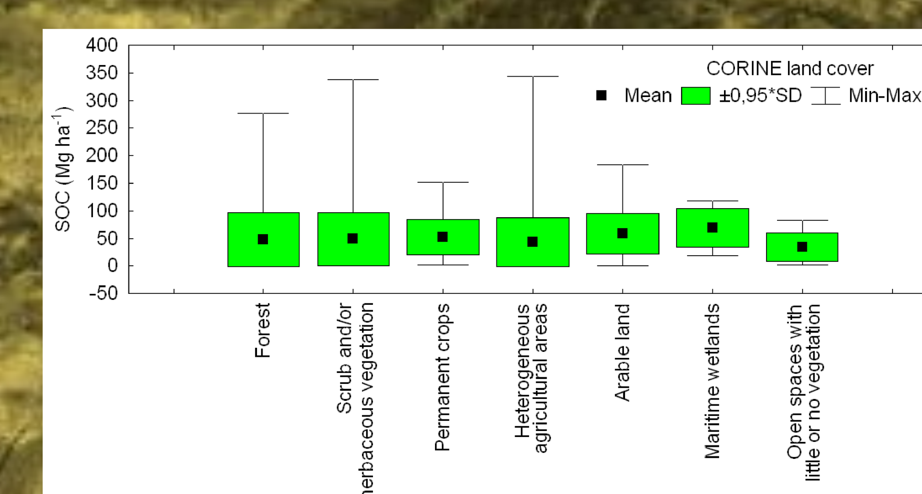


Figure 4. Soil organic carbon stock for each soil type.

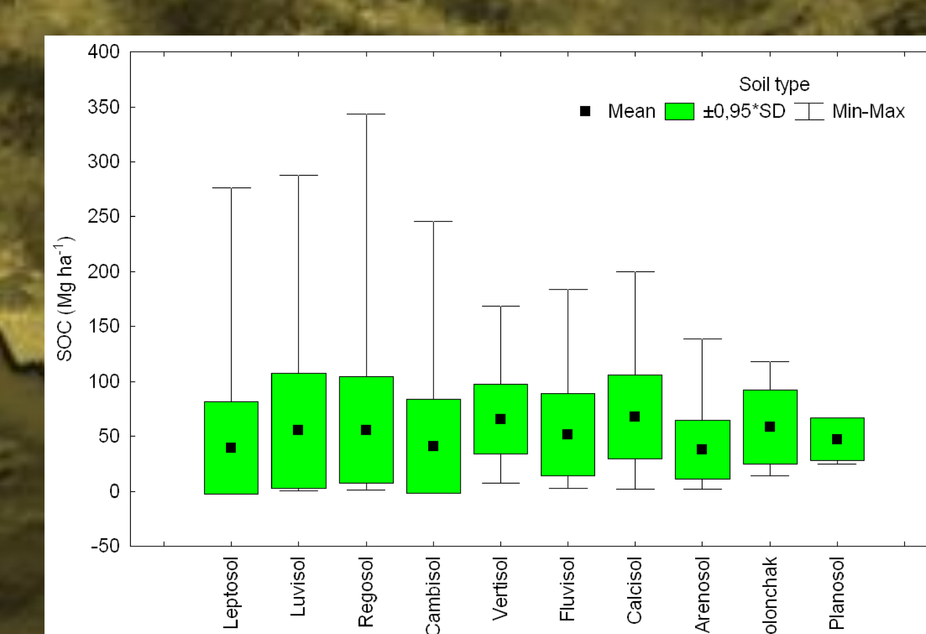


Figure 5.Soil organic carbon stock for each CORINE-land cover class.

Figure 8. a: Relationship between mean soil organic carbon content and mean temperature for natural land use types; b: relationship between mean soil organic carbon content and mean monthly rainfall for natural land use types; c: relationship between mean soil organic carbon content and mean elevation for natural land use types. Legend: ● agroforestry; ○ broad-leaved forest; ■ transitional woodland-scrub; □ coniferous forest; ◆ grassland; ◇ sclerophyllous vegetation.

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