Accuracy of soil organic carbon inventories in Mediterranean mountain areas.

Iolanda Simó [AB], Carmen Herrero [B], Jaume Boixadera [AB] and Rosa M. Poch [BC]

[A] Departament Agricultura, Ramaderia i Acció Rural. Generalitat de Catalunya, Catalonia (Spain). Email asara.dar@gencat.cat
[B] Departament de Medi Ambient i Ciències del Sòl, University of Lleida, Catalonia (Spain). Email rosa.poch@macs.udl.cat
[C] Centre Tecnològic Forestal de Catalunya, Solsona. Catalonia (Spain).

Abstract
With the objective to quantify the soil organic carbon content of the soils of a model area in the Catalan Pre-Pyrenees a detailed soil inventory was carried out. A nested sampling for organic matter and additional measurements of coarse elements and bulk density were needed to increase the accuracy of the estimations. Among the different profile site characteristics, land use and depth of SOC calculation affect the estimation of carbon stocks, in the sense that surface SOC in forests is higher than in agricultural land. More than half of the stored SOC is found in the first 30 cm, which indicates a high degradation susceptibility.

Key Words
Soil organic carbon, soil organic matter, soil mapping, geostatistics, Catalonia

Introduction
Soil properties play an important role in land use planning activities such as agriculture, erosion control, environmental protection and nature conservation. Soil organic matter is involved in processes like development and stabilization of the aggregates, in the biogeochemical nutrient cycles, and affects water and energy balances. The assessment of soil organic matter pools is essential for the evaluation of the ability of soil to sequester atmospheric carbon and to see whether soil changes induced by climate or land use may affect this ability. In order to do so with the required degree of precision, it is necessary to conduct soil surveys where organic matter contents, bulk densities, rock fragments and soil depths are determined and characterized without bias. Moreover, the sampling has to be georeferenced and be representative enough by working at adequate scales.

In Europe, the extrapolation of soil organic matter contents from the available data was not considered adequate because of lack of georeferences, of different survey methods and lack of standardization of analytical procedures (Jones *et al.,* 2005). As a consequence, the European Union defined (Stolbovoy *et al*., 2005) a protocol for the systematic soil sampling with the objective of detecting changes in soil carbon stocks.

Soil organic carbon content changes with depth. Generally, the highest levels are in the topsoil and they decrease with depth. The overall quantity of organic carbon in a given soil is determined largely by climate and organic inputs but can also be significantly affected by land use (McKenzie *et al.,* 2006).

The aim of this study is to obtain a detailed cartographic soil inventory and know the soil carbon stock in the main soils types and land uses, forest and farming lands, of a model area in the Iberian Pre-Pyrenees (Canalda river basin). This study wants to evaluate the incidence of land use changes on C storage in agro-silvo-pastoral ecosystems along climatic gradients through the determination of the soil potential for carbon storage, the quantification of this C reservoir, and to assess the precision of those estimations by means of (geo)statistical analyses.

Methods
The study area
The study area is located in a sub-basin from the Ribera Salada Basin (Catalan Pre-Pyrenees, NE Spain) called Canalda sub-basin, with an area of 10 km^2 and altitudes between 1100 and 2100 m, with predominant slopes between 10-50%. The parent materials are calcareous conglomerates, calcilutites and limestones. The annual rainfall is 500 to 750 mm, distributed along an altitudinal gradient. Agricultural uses include mainly cereals, potatoes and pastures, and the forest use varies from brook forest environments to subalpine and submediterranean vegetation. Soils are shallow, calcareous and stony, being most of them Inceptisols and Entisols. The area has been subjected to land use changes in the last 100 years, mainly the abandonment of agricultural land and its conversion to pastures or forest.

Cartographic soil inventory

The aim of the soil mapping is to know the soil carbon stock distribution. For this purpose, the CatSIS methodology (Boixadera *et al*., 1989), used in the soil map of Catalonia at a scale 1:25,000 has been applied. It has an intensity of 0.5 observations for cm^2 of final map. This working scale supposes 2 observations each 100 hectares, resulting in more than 20 pits in the model area. The soil classification used has been Soil Taxonomy (SSS 2006). The main steps developed in this soil survey were:

1. Application of photointerpretation and remote sensing;
2. Opening the soil pits in the units defined above;
3. Macromorphological field soil description;
4. Soil sampling and analyses (both physical and chemical);
5. Elaboration of the provisional map;
6. Rectification of the limits in the field by augerings;
7. Elaboration of the definite soil map.

Monitoring soil organic carbon

In each pit the routine soil physical characteristics were described, but in order to quantify carbon stocks some special measurements were carried out to characterize bulk density and coarse elements more in detail. These accompanying measurements are time consuming and rarely performed during routine soil testing (McKenzie *et al*., 2006), but are necessary, at least to depths of 300 mm, to quantify carbon (Porta *et al*., 2005).

Accordingly, the standard soil survey procedure used in the Soil Map of Catalonia was completed with the following determinations:

- Assessment of rock fragment volume. For each horizon, a 2 mm-mesh sieving was conducted in the field, the weight percentage of coarse fragments was measured, and it was converted to volume percentage using the density of quartz. Several kilograms of soil were taken for each horizon, down to a depth of 300 mm or to lithic contacts.
- The bulk density was measured by three methods: core sampling (Nacci *et al.*, 1999) and the aggregate method (Grossman *et al*., 2002) for each horizon; and the hole method (Nacci *et al*., 1999) for surface horizons.
- Organic carbon. It was determined by the standard wet oxidation method (Walkley-Black) and by a total carbon analyser (LECO).

The soil carbon stock was calculated for each soil mapping unit from the average of all pits in one unit. In order to achieve and compare soil carbon stock of different units, the following depth intervals were considered: 0 to 15 cm, 0 to 30 cm, 0 to 50 cm and 0 to 100 cm, disregarding organic horizons due to the low stability of organic matter. The 15 and 30 cm depths are chosen because they represent the stock of carbon susceptible to be influenced by anthropic action. SOC stocks are calculated adding up the SOC of each horizon until the given depth is achieved. The continuity of the profile is indispensable for the calculation of the SOC in depth. The following equation is used for the estimation of the SOC in each horizon (OCh):

$$OCh(Mg/ha) = Organic\ Carbon\ (\%)*Bulk\ density\ (kg/m^3)*Thickness\ (cm)*(1\text{-}Coarse\ elements)*0{,}001$$

The calculation of the SOC down to 15 and 30 cm is done by using the following equations (50 and 100 cm estimations follow the same procedure):

$$SOC\ (15\ cm) = OCh_1 + \left(\frac{OCh_2}{Depth\ h_2} \cdot (15 - Upper\ boundary\ h_2) \right)$$

$$SOC\ (30\ cm) = OCh_1 + OCh_2 + \left(\frac{OCh_3}{Depth\ h_3} \cdot (30 - Upper\ boundary\ h_3) \right)$$

In order to know the precision of the organic matter calculations for each unit, an additional sampling of soil organic matter following a nested design (Figure 1) was conducted around the modal profiles of each soil mapping unit. In this approach, we assumed the rest of the variables to be those of the modal profile.

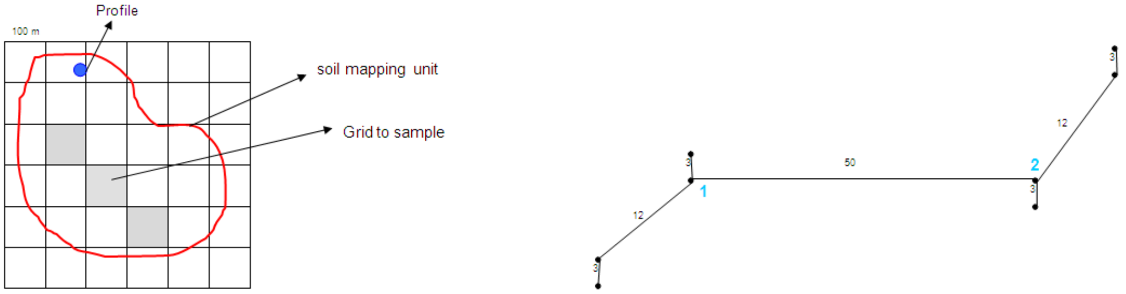

Figure 1. Nested sampling of soil organic matter. Two random starts points (1,2) are selected in each cell

Results

Only some of the results are presented. Table 1 shows some characteristics from the main modal profiles and the estimation of the carbon stocks. The depth is not the main factor that determines SOC, but the fact that many soils have buried horizons and a fluventic character.

Table 1. General characteristics to calculate SOC from some modal profiles. Coarse elements and bulk density are the interval values of the different horizons in each profile.

Modal profile	Depth	Horizon sequence	Coarse elements (%)	Bulk density (kg/m^3)	OCh (Mg/ha)	SOC (Mg/ha)
Typic Haplustepts	0-60	$A_1 - B_{w1} - B_{w2}$ - R	64.04 - 73.13	1487.2 - 1655.2	$A_1 - B_{w1} - B_{w2}$ 14 - 33.1 - 8.5	55.7
Typic Ustifluvents	0-110	$A_1 - A_2$ - AB - A_b - R	43.3 - 68.5	1352.3 - 1554.6	$A_1 - A_2$ - AB - A_b 27.2 - 26.7 - 33 - 39.6	126.7
Lithic Ustorthents	0-40	$O_i - O_a - A_1 - A_2$ - R	25 - 63.5	1000 - 1533.6	$O_i - O_a - A_1 - A_2$ 24.6 - 53.8 - 33.7 - 49.7	83.5
Udic Calciustepts	0-180	$A_{p1} - A_{p2} - B_w - B_k - C_1 - C_k$	64.5 - 92.88	1390 - 1737.4	$A_{p1} - A_{p2} - B_w - B_k - C_1$ 40.1 - 9.8 - 3.3 - 9 - 14.1	76.6
Typic Hapludolls	0-80	O - $A_1 - B_{w1} - B_{w2}$	20.19 - 70.64	1000 - 1782.7	$A_1 - B_{w1} - B_{w2}$ 57.7 - 12.8 - 33.7	105.3
Typic Udorthents	0-81	O - $A_1 - A_2 - B_k/R$	46.92 - 84.23	1000 - 1686.9	$A_1 - A_2 - B_k/R$ 54.8 - 41.9 - 34.4	131.1
Typic Calciustepts	0-120	$O_i - O_a - A_1 - B_w - B_k$ - C	78.89 - 91.68	1000 - 1711.8	$A_1 - B_w - B_k$ - C 28.6 - 31.5 - 15.5 - 16	91.9
Typic Eutrudepts	0-80	O - $A_1 - B_{w1} - B_{w2} - B_k/C_k - C_{k1}$	50.75 - 84.82	1063.6 - 1763.2	O - $A_1 - B_{w1} - B_{w2} - B_k/C_k$ 39.3 - 9.4 - 2 - 2.5 - 19.8	33.9
Entic Hapludolls	0-140	$A_1 - B_{w1} - B_{w2} - B_{w3} - B_{wk}$	51.10 - 81.10	1346.7 - 2353.5	$A_1 - B_{w1} - B_{w2} - B_{w3} - B_{wk}$ 64.9 - 23.4 - 6.1 - 6.9 - 6.4	107.9
Typic Calciustolls	0-100	$O_i - A_1 - A_2 - B_w - B_k$	78.88 - 81.11	1000 - 1700	$O_i - A_1 - A_2 - B_w - B_k$ 21 - 27.4 - 18.7 - 10.7 - 11.6	68.6

The SOC values down to each depth are shown in Figure 2. The number of samples decreases with depth, because some soils are shallow and stony. More than half of the SOC is stored in the first 30 cm, which stresses the importance of A horizons in soils of mountain areas.

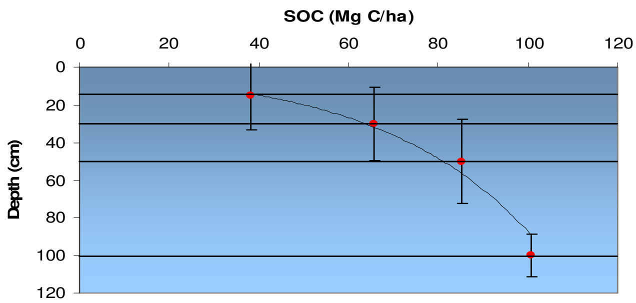

Figure 2. The SOC values down to each depth. The number of samples is 22 (10 cm), 22 (30 cm), 21 (50 cm) and 14 (100 cm). Bars show the standard deviation.

The data was checked for differences between altitudes and land use. A non parametric method (Kruskal-Wallis and Kolmogorov-Smirnov tests) was applied, since the SOC data do not follow a normal distribution. The SOC values did not show any significant difference between altitudes, but was higher at 15 cm under forest ($P<0.05$). Table 3 shows the descriptive statistics for this analysis.

Table 3. Soil organic carbon stocks to different depth (Mg/ha) according to land use

Land use	Variable	Number of profiles	Average	Median	Maximum	Minimum	Standard deviation	Variation Coefficient (%)
Agricultural	SOC15 (Mg/ha)	6	21,24	21,65	32,47	7,39	9,27	43,64
	SOC30 (Mg/ha)	6	55,67	53,72	76,67	45,08	11,65	20,92
	SOC50 (Mg/ha)	6	71,00	72,26	92,05	51,67	15,31	21,57
	SOC100 (Mg/ha)	5	86,93	97,05	102,81	65,23	18,45	21,22
Forest	SOC15 (Mg/ha)	16	44,61	33,59	187,07	11,53	41,25	92,46
	SOC30 (Mg/ha)	16	69,25	58,84	205,80	14,05	45,29	65,39
	SOC50 (Mg/ha)	15	91,08	70,06	219,01	24,88	51,31	56,34
	SOC100 (Mg/ha)	9	108,30	113,55	135,31	67,79	22,26	20,56

Conclusion

When comparing SOC between soil mapping units the soil depth has to be defined, in order to obtain unbiased estimations resulting from soil surveys not oriented to carbon inventories. Our results show that the standard depth of 1 meter in most of SOC inventories may not be necessary to increase the accuracy, since more than 50% of SOC is found in the upper 30 cm. Land use is affecting SOC storage, in the sense that agricultural soils have less SOC than forest soils at the surface. This fact increases the vulnerability of forest soils because they can lose the capacity of storing carbon after a forest fire or erosion episodes more rapidly.

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